The Effects of LOP/Pinch Culverts/Weirs on complex Water Networks – A case study on a water system in the region Twente

Maximilian Hehenkamp
s1854178
4th July 2019

University of Twente -
On the behalf of
waterboard Vechtstromen
ET Faculty
Civil Engineering
Supervisors:
J.W.M. Kranenborg
B. Zhang
B. Worm

ABSTRACT

The study presented in this report investigates the effects of LOP/pinch culverts/weirs in water networks.
The last decades the problem water and moisture deficit rise due to the climate change consequences in western Europe. With this change, the weather is foreshadowed to get more extreme in both extreme rainfall events and drought periods. The report introduces this context and gives a board insight into the changes which are foreshadowed for the policy area of the waterboard. To counteract these effects the waterboard Vechtstromen want to search for solutions that can be implemented within the water system.
To determine the effects that the measures can have on the water system a background study is done which showed that LOP/pinch culverts/weirs offer a theoretical solution the problem of the moisture deficit and the extreme discharge peaks for the region. This is achieved with the storage and conservational effects these measures offer following study of (van Bakel, et al., 2013) and (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001).
To determine if the findings are reproducible in a different environment, thus in the policy area of the waterboard, a case study is done. The policy area was analysed and possible interactions with the environment and other factors that have an influence on the measures summarised. Based on this analysis a study area was chosen that faces moisture deficits and has a fast draining speed. These factors make the area suited to indicate if the chosen measures influence the water system.
The method chosen to determine the effects of the measures is a modelling study. The model contains a 1-dimensional representation of the surface water network, thus the trench system, and is done in SOBEK 2.14. The study identifies changes in the discharge pattern of the study area. Additionally, the water height at different locations is measured and analysed to give further insight into the conservational effects of the measures implemented into the model.
From the results follows that the measures have a positive effect on the discharge of the study area since the maximum discharges are decreased while the continuous discharge increases. This is beneficial against the more occurring flooding issues and the moisture deficit since water is kept longer in the system and discharge. This finding from the discharge pattern is further supported by the results found at the water height measuring locations. The model indicates that water is conserved in the trenches and therefore permanently stored in the systems since water heights increased during the experimentations.
The study suggests that further research on the influence of LOP/pinch culverts is sensible since the measures show overall positive effects on the chosen indicators and hint that the implemented measures can be effective in dealing with the upcoming problems of extreme weather conditions in the future.

1 CONTENT

2 INTRODUCTION

Chapter 3 introduces the problem context and its urgency for the current water management in the Netherlands. After the problems are introduced, the current water management strategies are explained by the mechanisms that are available to face the flooding issues in the water systems. In the end, the research objective of this report is explained, and the research gap of this study and the current management is given. Last a short general structure of the report is presented.

2.1 Problem Context

Climate change has an increasing impact of the surface temperature and the water network in Europe and especially the Netherlands. During the last century, the average surface temperature on the earth rose by an average of 0.74°C due to the greenhouse effect of carbon dioxide (CO_2) (Verweij, Wiele, Moorselaar, & Grinten, 2010). This increase in temperature has widely impacted the Dutch landscape and water systems. The last 50 years an acceleration in the warming trend is observed which make a higher raise of temperature more likely in the future. Further, the air temperature of the Netherlands increased with twice the speed of the global average due to the geographic position and topographic characteristics (Verweij, Wiele, Moorselaar, & Grinten, 2010). This development in temperature rise leads to a significant impact on the metrology of the Netherlands and therefore the water systems.

The meteorological environment of western Europe is predicted to get more extreme. Different scenarios of the future foreshadow an increase in precipitation in winter of 4% up to 14%. In summer the rainfall could increase by 3% or in the worst scenario a decrease of up to 19% (Verweij, Wiele, Moorselaar, & Grinten, 2010). While the average temperature and the rainfall increase additionally the extreme weather conditions will increase in occurrence and intensity. These extreme conditions are intense precipitation, heat waves and drought. (Zwolsman & Senhorst, 2005).
The raised intensity of the rainfall during winter is expected to increase the discharge of the main river in the Netherlands from 3% up to 20% over the following decades in respect to the lowest and highest increase in average temperature in the climate scenarios of (Koninklijk Nederlands Meteorologisch Instituut, 2014). With higher chances of flooding for the nation (Verweij, Wiele, Moorselaar, & Grinten, 2010). Even in summer, an increase of the discharge maximum by 5% is expected due to extreme rainfall, while the average discharge in August-October of the river is assumed to decrease by 30% in average (Zwolsman & Senhorst, 2005). This increases the chance of flood damages on yields. At the same time, the freshwater demand increases due to higher temperatures and evaporation (OECD, 2013). The water deficit in summer is expected to rise from 360mm to 440mm in the worst scenario that (Koninklijk Nederlands Meteorologisch Instituut, 2014) foreshadows. The yield damages due to heatwaves and drought could lead to economic losses in agriculture of more than 10% (G.J. van den Born, 2013). It follows that the rest of the changing weather conditions lead to a less arable landscape with increased water demand.

2.2 The current strategy in Dutch water management

The current strategy of the Dutch administrates to approach these problems in the freshwater systems consists of a three-step plan to delay the discharge to decrease the maximum discharge in the Dutch rivers (Deltacommissie, 2019) . The first is the step “Vasthouden” which will be referred to as the holding/storing method in this paper. The second is “Bergen” which will be referred to as the store or conservation method and the third step is the “Afvoeren” which will be referred to as the controlled discharge method. This part of the paper gives a short overview of this three-step method. All three steps are meant to reduce the maximum discharge of the main river systems. The three methods are related to each other and act as a unit. All the methods achieve their efficiency by focusing on different measures and effects within the water systems.

2.2.1 The holding/storing water method

The holding method describes the approach of temporally holding on or storing of the water at the source, thus at the location of the rainfall/source. This can be achieved by regulating the discharge capacity of various areas. The water is, therefore, temporally stored at the source location and discharged in a controlled manner afterwards. This controlled discharge leads to a delay of the drainage and leads to a decrease of the maximum discharge and therefore in water height in the rivers since the rainwater is delayed in arrival at the main water system. This leads to a flattening of the maximum discharge peak, thus a decrease in maximum discharge and an increase in a continuous discharge after the event (van Bakel, et al., 2013).

2.2.2 The conserving water method

The conserving method describes the approach of conserving water in artificial or natural spaces to overcome critical discharges and moisture-deficit. The water is stored for a longer period in these controlled environments. Further, this method also focuses on the (re)naturalisation of riverbeds and the water environment. A famous example is the "Ruimte voor de Rivier" (Room for the River), where the riverbeds are widening up to a more natural state to increase the comping ability of the water systems to extreme weather conditions. This method is also applied to smaller hydrologic systems. (Wolbers, Das, Wiltink, & Brave, 2018)
With naturalisation and artificial measures, the water can be conserved and stimulated to infiltrate into the ground to improve groundwater resources. Infiltration is the process when surface water sinks in the groundwater and is stored in the soil over a long period. The long-term storage of water in hydrological systems is called conservation. The goal of conservation is to counteract moisture-deficit in the soils and to enhance the resistance of the water system to drought scenarios. However, the long-term storage of water in these systems leads to a decrease in holding/storing capacity since volume that could store the water by filling the reservoir is already filled up with conserved water. Further is an increase in groundwater level negative for the storage potential of an area because higher groundwater levels lead to lower infiltration rates. Also, higher groundwater tables make surface flooding more likely in extreme rainfall scenarios (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001). Therefore, both the holding/storing and the conservation method are linked to each other, but they act counteractive. The biggest reservoir to achieve the holding and storage effect is the void space within the soil.

While the conservation of water in the ground is less controllable, the effectiveness of this process is high since the potential conservation/storage capacity is often larger than artificially built water reservoirs (Kuijper, et al., 2012). Still, the benefits of this effect occur only if the soil is not statured which is often not the case during heavy rainfall scenarios since they often occur in wet periods. (Sentis, 2002) Therefore, water conserving and holding function in the same way, but they also counteract each other since if more water is conserved in a system less volume is storable in the during massive discharge/rain scenarios. While measures which stimulate conservation or holding/storage often share the same design features the configuration of these measures determines which of the methods will be focused on. A lot of the designs are flexible to offer adaptiveness for the users. The focus of the adaptations lies on conservation in summer and the holding effect in the winter (van Bakel, et al., 2013).

2.2.3 The discharge water method

The third method is the controlled discharge of the held back and stored/conserved water. The goal is again to minimize the maximum peak of the river system during flooding scenarios and to reduce the outflow of water from certain systems, like arable land, during droughts and heatwaves. The goal during floods is to discharge as much water as the water systems can transport but to hold back/store the water exceeds the maximum capacity of the main systems. Further, the hydrologic system should discharge the minimum water required in times of heat waves and droughts. This means the method tries to control the discharge as much as possible to have a positive influence on the hydraulic systems (Deltacommissie, 2019).

2.3 Research Objective

Since the water systems are predicted to have an increasing demand of water in the future, the goal of the water management is to store/conserve water at the source to minimize drought-related damages in the environment. The aim of the research is to find different measures to enhance the adaptiveness of the water systems within the policy area of the Waterboard Vechtstromen during extreme scenarios. The focus lays on measurements that incorporate the current water management strategy and enhance the resilience of the water systems to the changing meteorological/hydrological environment. To achieve this the study focuses on the effects of pinching and conserving measures. The research question that this study aims to answer is: *"What influence can pinch/LOP culverts/weirs have on the water network of in policy area of Waterboard Vechtstromen to make it more resilient to the upcoming problems of moisture-deficit during dry periods and extreme rainfall scenarios?"*

2.4 Research gap and unknown aspects of the field

Since the current policy of the waterboard is focused on the flooding issues of climate change there is a lack of attention to the drought-related issues within the water system. This leads to a lack of knowledge about how to improve the current system to be more adaptable to the scenarios of flood and drought. It is necessary to change the current measures which are implemented in the water network to adapt the discharge during heat waves and therefore to make the system resilient to both effects but especially to drought. Current studies, as (Sluijter, Plieger, van Oldenborgh, Beersma, & de Vries, 2018) or (Beekman & Caljé, 2018) describe the current problems for the region, especially the drought situation in 2018 but do not mention solutions for policy area nor for the Netherlands. A need for a good configuration of pinch weirs/culverts that counteract these problems can be an opportunity to use the trench systems. Culverts which are already present in these areas can be modified. Also, a modification of the trenches which are not under the maintenance of water authorities, as the water board. These parts of the water network lack attention in the current water management in the policy area. These trenches of the water systems are mainly owned by farmers and landlords which will be further referred to as third parties or third-party members. It is urgent for the current water management in the Netherlands to reduce drought damages for society and reduce rainfall discharge during floods. Therefore adaptation of the management and the systems to the changing circumstances is necessary.

2.5 Report structure

Chapter 3 explains the theoretical background that is necessary to back up the research method that is chosen for this report. It gives a short introduction to the functionality of the pinch measurements and the environmental influences that affect the efficiency of the measurements and different designs. After the background is clarified a geospatial analysis of the study area is presented in Chapter 4 which introduces the study area for the model study.
After the geospatial analysis in Chapter 5, the report explains the methodology and the modelling process which forms the main part of the research method. The model is created in Sobek 2.14 is a one-dimensional model that represents surface water channels in the study area. The model will indicate the effectiveness and possible influences the implemented measures.
In Chapter 6, the results of the model are presented, and the possible conclusions are given. This is followed up by the discussion of the results with a short explanation of the assumption, points of interest and the strength/weaknesses of the model in chapter 7. The report will be finalised with a conclusion in Chapter 8 which will conclude all chapters and gives suggestions for further research.

3 THEORETICAL BACKGROUND

3.1 The influence of Pinch culverts/Weirs

This chapter of the report gives a brief overview of the functionality of the measures which are going to be implemented into the model and the design differences considering prices, maintenance and effects. After that, a short introduction and background for the modelling are given.

3.1.1 The theoretical background of pinch culverts/pinch weirs

This part of the paper gives a short introduction into the topic of the measures from interest for this study and describes how these measures work together with the current strategy in Dutch water management. There are two measures that are currently from interest for the waterboard which is related to the strategies of holding and conserving water at the source. The “Knijpduikers” (Dutch) which will be further referred to as pinch culverts and the “Knijpstuwen” (Dutch) which will be further referred to as pinch weirs. Pinch culverts and pinch weirs are measures that conserve the water in an area by regulating/limiting the discharge of the water system. Both measures function in the same way, the only difference is that pinch weirs are an artificial wall which is built into the water system (Figure 2) and pinches culverts are plates which are attached to drainage pipes to regulate the discharge as shown in Figure 1 below.

Figure 1 - Example photo of a pinch culvert (Titico, 2019)

The difference between the two measures is a constructional and not a functional (Waterschap De Aa, De Dommel et al., 2004). Therefore, the two measures will often be referred to as one when the effects and influences of them are discussed and analysed. The pinch effect is achieved by limiting the water discharge to a height certain level. That means the water is held up to the height where the pinch weir/culvert allows discharge to happen. This leads to a conservation/storage of water to that level within the area and prevents the ground from drying out (van Bakel, et al., 2013). This can lead to delays in the discharge of smaller water systems to rivers and therefore achieve a decrease in maximum discharge in the main water systems (van Bakel, et al., 2013).
In different designs, there are different focuses on which effect, the conservation or the holding effect, is dominant. While simple weirs serve only a conservational purpose other designs as the

pinch hole design and the triangle design have a holding influence. This is achieved due to the fact that the water is limited in discharge that can flow through the hole and therefore water is held back and discharge in a controlled manner during periods of high water volumes (van Bakel, et al., 2013).

3.2 Different design of Pinch culverts/weirs and their influences

This part of the paper introduces the three different basic designs of pinch culverts/weirs. It describes how they work, what the design features advantages and disadvantages. The pinch measurements are defined as technical solutions for the issues described in chapter 2.1. While natural solutions are possible to face these problems most of them are expensive and time-intensive in the maintenance. Therefore, natural solutions are excluded since the third-party members, as landlords and farmers which are not directly related to the water board but are in charge of most of the trenches affect by the measurements are expected to have limited resources and motivation to apply thee measures to their properties.

3.2.1 Landbouw ontwikkeling plan duikers/stuwen (LOP-Weirs)

The in Dutch called “Landbouw ontwikkelings plan duikers/stuwen” (Agaric development plan culverts/weirs) will be further referred to as LOP-culverts/weirs (Figure 2). The design of these culverts/weirs is simple, an artificial wall is created in the water channel with a wider discharge gap in it. This gap can be closed to certain height levels with wooden/steel/concrete blanks that have the purpose of stow water to a certain height.

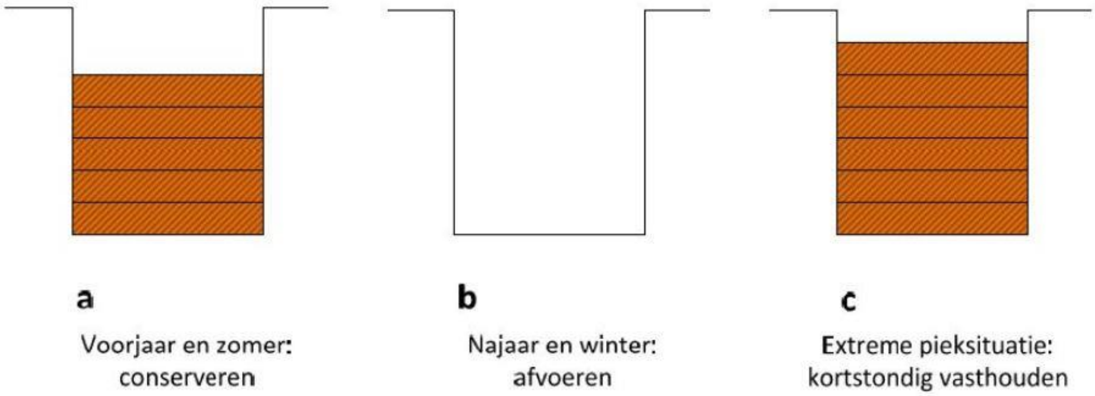


Figure 2 - Structure and dynamic maintenance of a LOP-weir (Figure in Dutch)

This achieves a conservation effect of water behind the culvert/weirs and stimulates the infiltration into the ground. If the water height exceeds the set height of the culvert/weir the water starts to flow over the obstacle (van der Schoot, Hagenaars, & Meijers-Sgroot, 2018). Therefore, no control over the discharge is possible if the water height reaches the top of the culvert/weir, then no holding effect can be achieved. The only possible holding back effect can be created dynamically adapting the height of the weir in extreme situations. The configuration of these culverts/weirs in most cases need to be changed by hand at least two times a year and more often in extreme years as seen in figure 2. Case a describes the spring and summer configuration that is focused on the conservation of the water, case b is the fall and winter configuration that is only focused on the discharge of the water. The third case c is the configuration needed in extreme rainfall scenario. Because these changes in configuration need to be done by the third-party members dynamically over the year, at least two times per year, they are often described as inconvenient and ineffective. This design was an approach of the Dutch governance to decrease the amount of irrigation needed during the summer by offering a simple solution for the framers to handle and be responsible for (van Bakel, et al., 2013). The design is cheap and applicable to most of the trenches in rural areas and is also provided by some waterboards (van der Schoot, Hagenaars, & Meijers-Sgroot, 2018).

3.2.2 Fixed Pinch culverts/weirs with a discharge hole

The difference between a LOP-culvert/weir and a pinch culvert/weir (Figure 3) is that the pinch measurements are focused on both the holding back and the conserving effect. This can be achieved through a hole which is drilled through the blank to allow a limited discharge from a certain level of water height behind the measure. This leads to a conserving effect up to the height of the hole and to a holding effect above that height since the amount of water is limited by the size of the hole (van Bakel, et al., 2013).

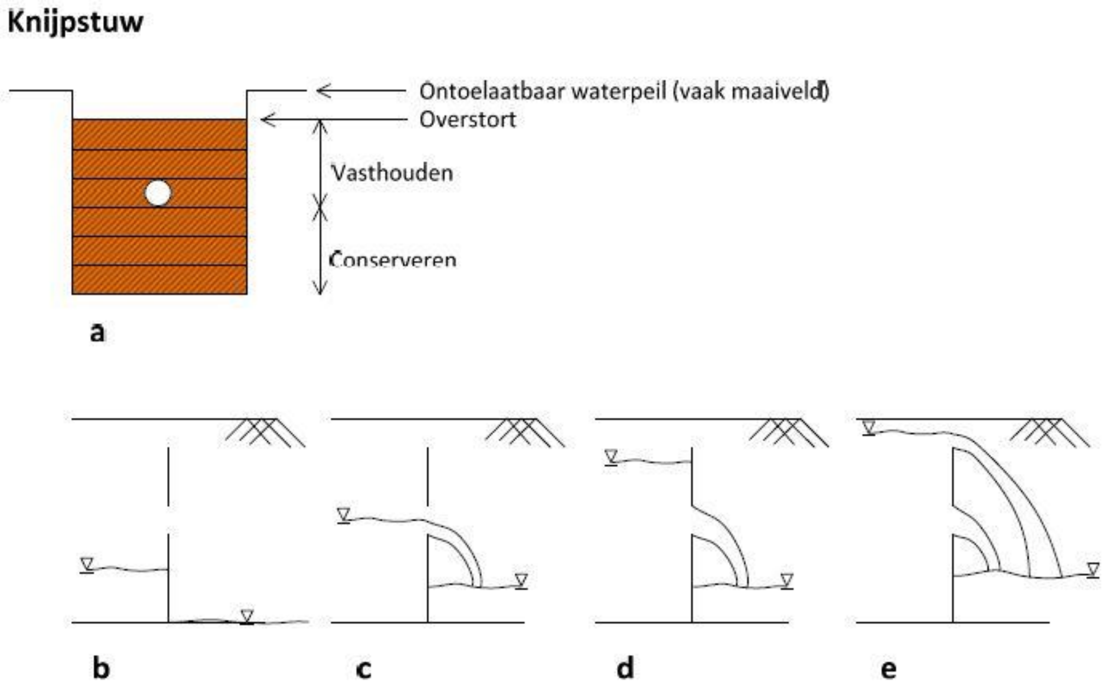


Figure 3 - Explanation of the Conserving and storage effect of pinch culverts/weirs (Figure in Dutch) (van Bakel, et al., 2013)

Therefore, the configuration is key when designing effective pinch culverts/weirs. The most influential factors are the height of the hole, the size of the hole and the maximum holding height of the culvert/weir (Louw & Vermeulen, 2000). To achieve a robust design the holding back and the conserving effect needs to be balanced in a way that the effects occur in the desired seasons and that no configuration by hand is necessary. The determination of this configuration is complicated and expensive, but pinch culverts/weirs with hole show a higher impact on both of the effects and are less intense in maintenance (van Bakel, et al., 2013).

3.2.3 Flexible (smart) pinch culverts/weirs with a discharge hole

Smart or flexible culverts/weirs are measures that react to a change in water level, either up or downstream, by changing the discharge of the water stream. This can happen through an extern power source, like an electrical or mechanical gear with sensors, or a self-regulating system as swimming weir that is moved up and down with the upstream water level. They show a positive effect on both the conservation and holding effect and are highly effective (van Bakel, et al., 2013). An example of a smart flexible pinch construction is given in Figure 4 below.

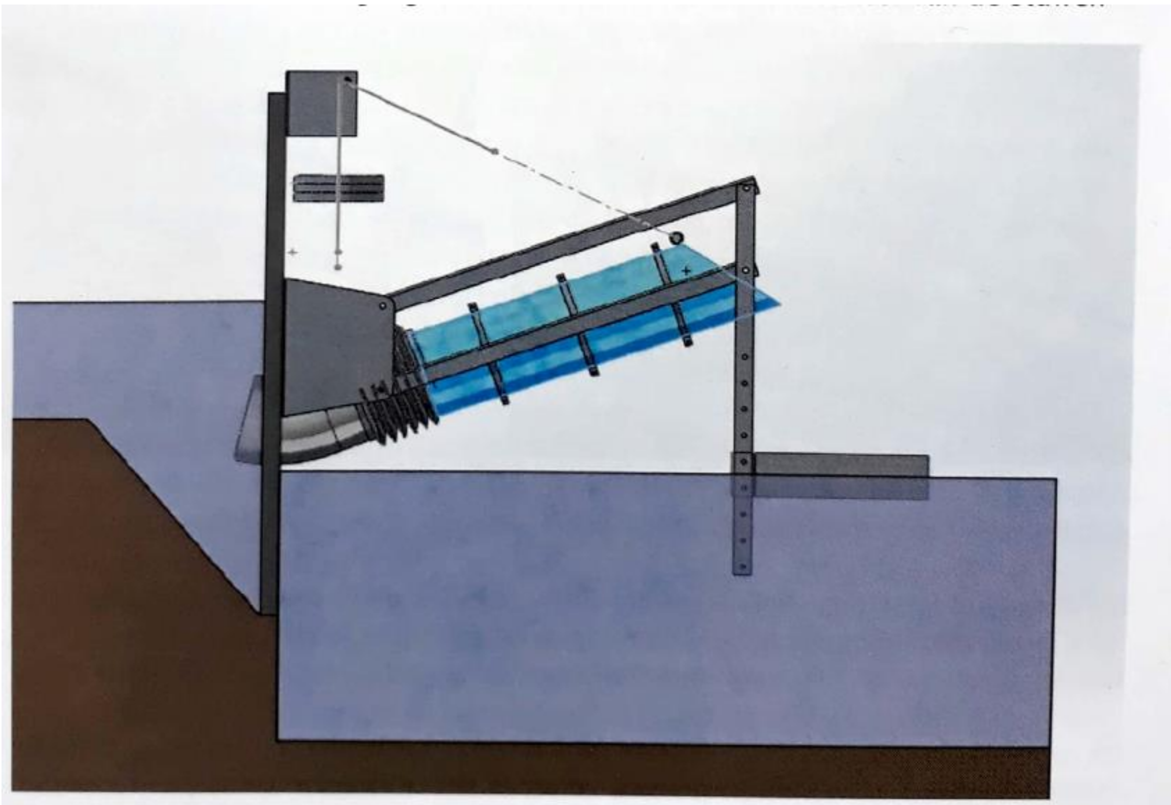


Figure 4 - Example of a flexible weir (van Bakel, van den Eerwegh, Worm, & Mensink, 2019)

These kinds of culverts/weirs are mostly found in larger water systems that are maintained by the waterboard or governance because of their expense and the need maintenance. No use of smart culverts/weirs are made public from third parties and there often considered to be too expensive and only suitable for wider, high-water flow-channel which not only serves a drainage purpose and has a constant inflow of water throughout the year (van Bakel, et al., 2013).

3.3 Influence of the environment on the effectiveness of pinch culvert/weirs

This section gives a short overview of possible influence from the environment on the effectiveness of pinch culverts/weirs. These interactions include the topographical, the pedological and the meteorological influences of the environment on the effectiveness of both the storage/holding and the conserving effect of pinch/LOP culverts/weirs.

3.3.1 Topographical influence

The conserving and the holding effectiveness of pinch culverts/weirs is highly sensitive for the topography of the surrounding environment since the height of the ground surface determines the volume of water that can be stored. Therefore, a flat topography favours these effects since the gradient in the water streams is lower and more volume can be held back by one culvert/weir and the discharge of more water can be regulated by just one weir/culvert (Artesia B.V., 2013). The same counts for the gradient of the water flow in terms of the conserving effect since the more water can be held back the more infiltration area is created and therefore more water will be stimulated to infiltrate. (Louw & Vermeulen, 2000)
The downside of a flat area is that they mostly do not suffer under extreme drought and moisture deficits since the run of and general discharge are slower and therefore infiltration is automatically stimulated. Sloped are in contrast have fast runoffs and therefore suffer more from moisture-deficits. (Louw & Vermeulen, 2000) This leads to a higher urgency for conservation in an area with higher gradients. So, the pinch effect is needed in areas where the effect cannot be easily achieved. This leads to a conflict in interest between cost-efficiency of measures and the needs of the actors.

3.3.2 Pedological influence

The infiltration of water into the soil is highly dependent on the infiltration properties, thus the graduation of the soil, the amount of void and the structure of the soil matrix. These properties are often collected under the hydraulic conductivity of the soil, thus in m/day of water infiltration into the soil matrix. The higher the hydraulic conductivity of a ground type the more efficient is the pinch culvert/weir in conserving the water and thus in increasing the moisture in the soil and the groundwater level. This effect is the key aspect for pinch culverts/weirs to counteract the drought issues in an area (Louw & Vermeulen, 2000).

Further is the conservation effect of pinch culverts/weirs dependent on the entry resistance of the water, thus on the resistance that is applied to the groundwater when it wants to rise to the surface in a vertical way. The entry resistance determines if and how much water can drain into a trench and is a part of the drainage resistance (Massop & Gaast, 2006).

Another coefficient that plays a role is the radial resistance, thus the resistance that water in the soil needs to overcome the stream horizontal through the medium. This coefficient is the second part of the drainage resistance of a trench. (Massop & Gaast, 2006)

Also, the storage coefficient has a high influence on the effectiveness of the conserving effect since it indicates how much water is stored in the ground, therefore how high the groundwater level is. This influences how much water can infiltrate into the soil and therefore which amount of the water gets conserved (Louw & Vermeulen, 2000).

Further is the height and macrostructure of the soil important. If the layers of highly permeable soil reach deep under the surface level and no impermeable layers are present up to deeper distance this highly favours the above-named coefficients and therefore stimulates the infiltration and conservation of water (Louw & Vermeulen, 2000).

3.3.3 Hydrological influence

Since more water can infiltrate if the pores in the soils are empty the effectiveness of the conservational effect is dependent on the storage coefficient that indicates how much water content the soil contains. From that follows that conservation is more effective if the ground is dry and more water can enter the ground.

That makes water which is conserved in water channels more valuable during heatwaves and drought since more of the surface water enters the groundwater reservoir. This leads to the conclusion that pinch measures, in general, perform better in a period of drought than in wet periods (Louw & Vermeulen, 2000).

Further can be concluded that a higher water level within the storage volume increases the pressure of the water against the soil particles and therefore stimulate the water infiltration. Further is the drainage resistance increase since the suction of the trench is minimised due to the presence of water. This leads to less drainage from the soil into the trench while the entry resistance is high. (Sentis, 2002)

On the other hand, the conservation of water in the water channels is limited by the water inflow to the system. During drought and heatwaves, a larger number of drainage trenches lie dry due to a lack of inflow and therefore no water can be conserved. An exception of this are areas with a constant water inflow through the year, as systems with groundwater sources, a connection to a bigger hydrologic system as a river and other systems which are constantly providing a water inflow. Thus, is the pinch effect the most effective during the periods it has no resources to work with (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001).

3.4 Theoretical background hydrological model (Sobek 2.14)

In this part the model that will be used is presented with its characteristics, weaknesses and strength, the data needed and already provided and the uncertainties in working with the model software. The software is provided by the water board to help with the decision-making and configurations in the case study area.

Sobek Suite is modelling software that is used for hydrologic system analyses to guide water-related engineering designs to more optimal states and to improve the efficiency and the cost-effectiveness of different measures. (Deltares, 2019) It offers a variety of application within the

software from one-dimensional (1D) river and water flow analysis to more complex two-dimensional (2D) application for water storage, flooding, evaporation and infiltration. The model software is capable to analyse water systems in urban, agriculture and natural reactional areas. It can simulate water flows through pipes, open water channels and scenarios as urban flooding or dyke breaches (Ipp-Hydro-Consult, 2019). To do that the model works with a numerical algorithm that can compute mass conservation and water in sub- and supercritical flow in water channels while considering the retention and emptying processes based on digital landscape models (Ipp-Hydro-Consult, 2019). Therefore, it is also suited to calculate flooding and drying of channels without the use of an artificial method (Deltares, 2019) . This makes it suited for the simulations needed in this case study. While the program is integral in usage the model is highly sensitive to many factors and quickly get complex. A clear plan of how to structure and build the model is necessary to remain clear results. Also, the validation is complex since a lot of factors need to be calibrated. To make the validation process easier Delates provides a couple of validation scenarios and a framework to calibrate and validate the results. (Deltares, 2019)
The simulation software Sobek 2.14 is used to produce a 1D representation of the water network in the study area to analyse the effects of the pinching effect on the surface water in the area.

4 GEOSPATIAL OBSERVATION AND ANALYSIS

This chapter gives insight into the choice of the study area and about the characteristics of the region. Further relations between the study area and the policy area of the waterboard are drawn to determine if the area can be used as a representative for the policy area. That suffers the most under the drought issues

4.1 Geographical location and attributes

The study area is in the south-east of the policy area. Right eastern from the city of Enschede and southern from the city Glanerbrug. The area has a size of 880 Hectares (ArchGIS, 2019) and is located at 52°12’5N to 52°10’40 and 6°54’25 East to 6°58’30 East (Google-Maps, 2019). The exact location within the study area is presented in Figure 5 below.

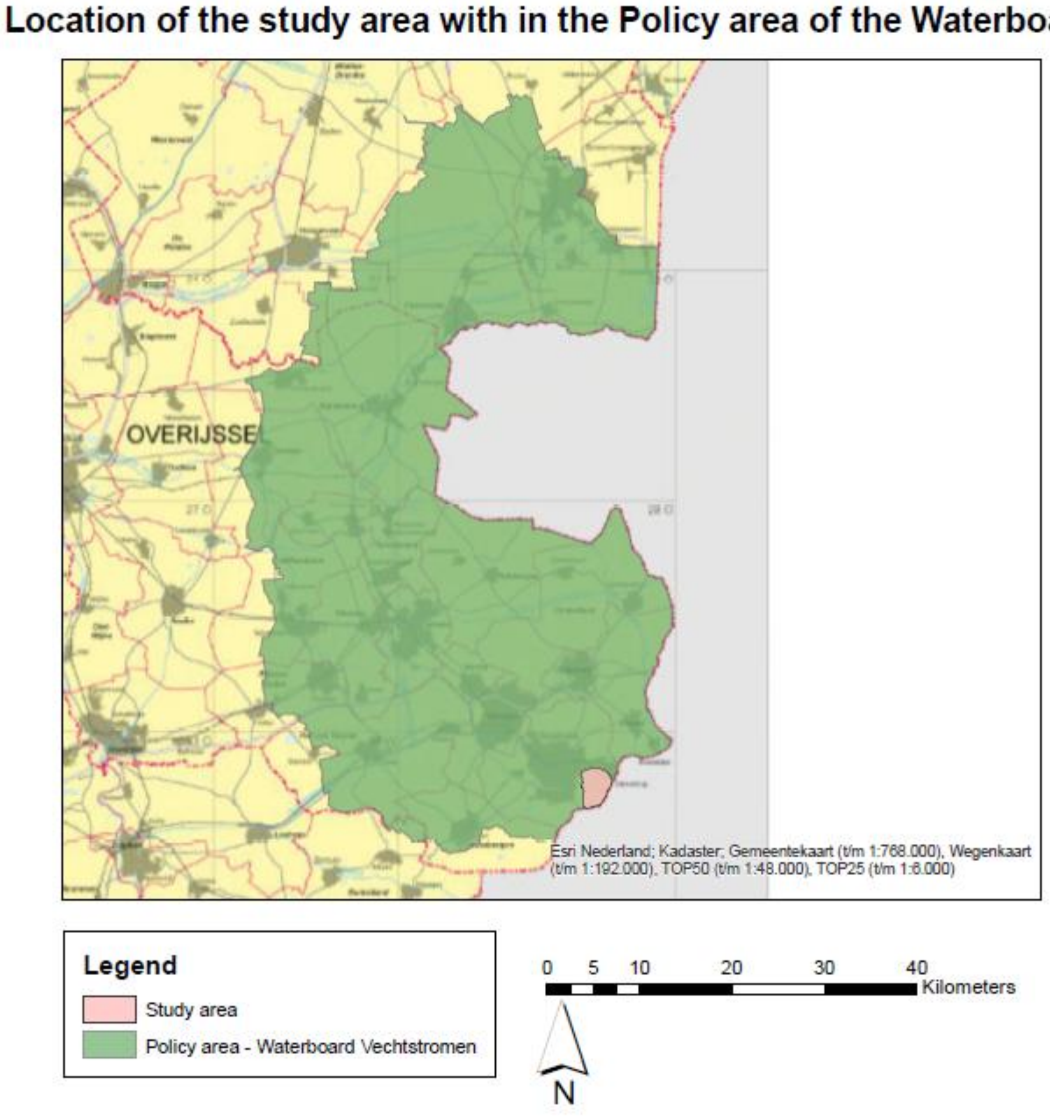


Figure 5 - Map of the policy area of Waterboard Vechtstromen with the location of the Study area

The area was defined as a focus area for drought issues (Vechtstromen, 2019) and is characterised by the necessary attributes to be an object of this study. This is further explained in the following sections.

4.2 Land use in the study area

The area is characterised by mixed agriculture, therefore by a land use of arable land and grassland as shown in Figure 6 below.

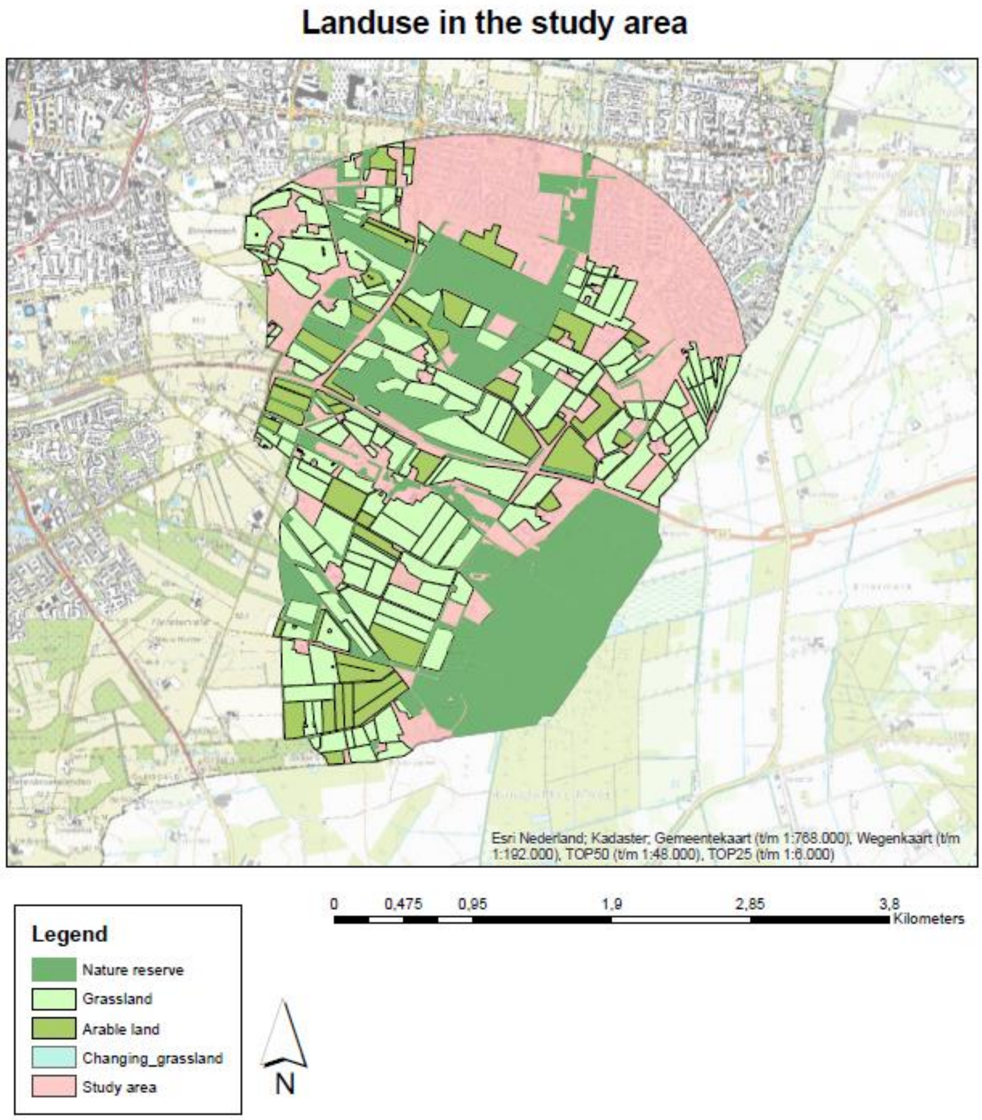


Figure 6 - Map of the land use within the study area

The total amount of agriculture area is 50% of the study area (GIS data BRP 2017 – waterboard). Of this 50 %, the amount of arable land is 10.5%. The amount of grassland in the years 2017 was 38.5% of the study area. The agriculture land use in this area is further described as a changing between grassland and arable usage. That means that in a constant period of three years the land use changes between cattle breeding and crop growing. This leads to the conclusion that the state of 2017can gives an orientation about the number of different uses within the area but the changing uses causing a constantly changing picture of the agrarian landscape.

The rest of the area, the south-east of the area contains a natural reserve with a forest/moor-like condition which is not used for agriculture. Further small areas with trees and small lakes are spread in the area (dark green areas). Since these areas are also in need of water during drought, they were included in the study area. These areas have a high potential to conserve water and to balance out fluctuations in the water resources and offer benefit for third parties because of the "water buffer" thus the high potential of water conservation.

4.3 The topography of the study area

As mentioned in the chapter of the topographical influence of the area a higher gradient reduces the effectiveness of the pinch effect greatly. The study area is sloped from the west with the highest point of 56.93m to the east in direction of the border to Germany with the lowest point of 37.58m above sea level. The height profile of the area is presented in Figure 7 below.

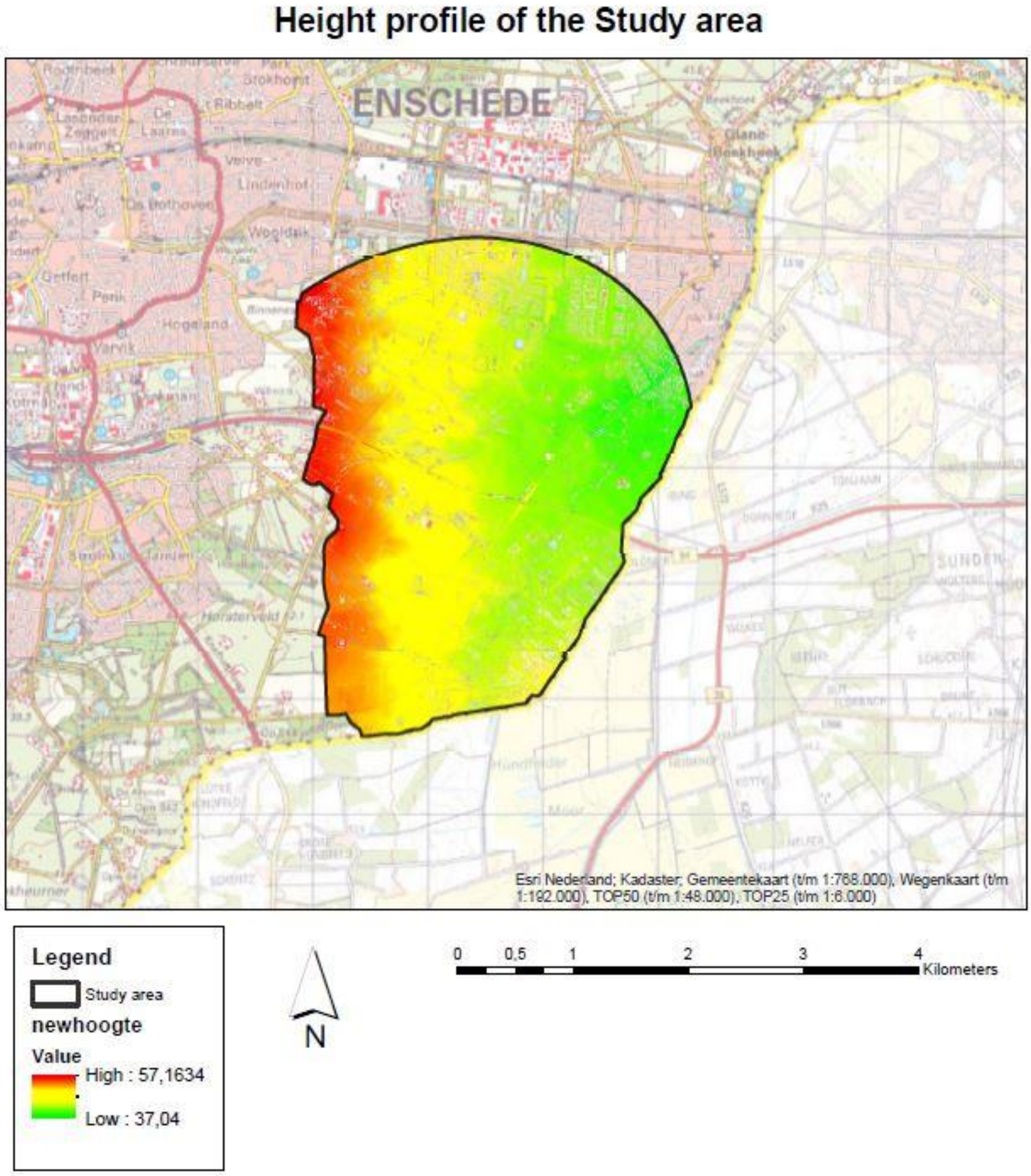


Figure 7 - Height profile of the Study area

Due to the higher hill formation in the west of the area, the drain/hydrological border can be defined clearly at the western part of the study area. This clear separation isolates the system from hydrological influence from the further western parts and reduces the not controllable factors that need to be considered from a hydrological perspective. Further is a height gradient from the southern to the northern part of the area visible which mainly defines the flow direction of the main water channels, as the Glanerbeek, while the west to east gradient mainly determines the flow direction of the smaller drainage trenches. This was also shown by (Waterschap Vechstromen, 2014).

4.4 Hydrological characteristics of the study area

The hydrological characteristics make the study area suitable for the model study since the area is quite isolated in terms of the water connections. The eastern drain border is drawn by an elevation that clearly cut the area as visible in Figure 7. Further is the area separated by the national border between the Netherlands and Germany which leads to the circumstance that over the most length of the border the water channels do not pass this border which isolates the area even further. Also, is the area restricted from an urban area in the north which makes it good to simulate. Also, there are measure points present which measures the main inflow that reaches over the border in the south and the outflow which passes the through the Glanerbrug in the north. These measure points give a good assessment of the extern factors that influence the hydrological relation is the area. The figure below shows all water channels, thus channels that are maintained by the water board and chancels that area in possession of third parties, mainly farmers.

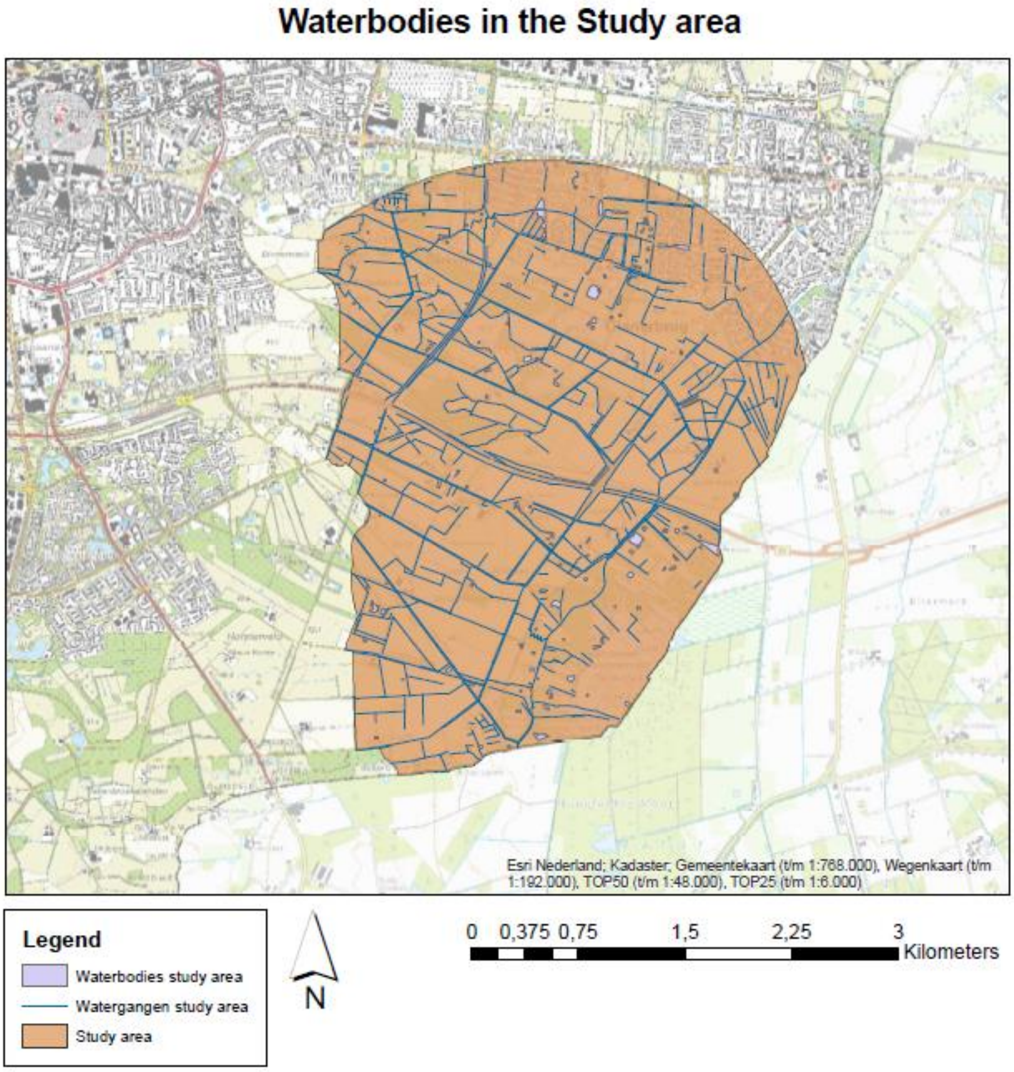


Figure 8 - Waterbodies in the Study area

Figure 8 shows that the area is crisscrossed by more than 800 small trenches and creeks which are mainly drainage trenches of the agriculture land in the area (AHN, 2016). Further is visible that the natural reserve areas contain a lower density of drainage trenches since they are more natural environments and artificial drainage is not as necessary.

4.5 Conclusion

The area has several characteristics from interest to perform a case study in it. The first main aspect is the suitability of the area since it is hydrologically isolated from the surrounding environment and historical data is available for a period of the last 6 years. Furthermore, has the area a dense water system that provides a variety of options to implement different configurations of measurements.

The second aspect is the pedological characteristic since 70% of the area is characterised as sandy grounds with a shallow aquifer the drainage speed of the area is quick which makes this area vulnerable to drought problems since water cannot be conserved naturally. Also is the region Twente mostly embedded on shallow sandy grounds with make the area a representative sample for a big part of the region that suffers the most under the drought issues (van den Eertwegh, Bartholomeus, Witte, de Louw, & van Dam, 2019). This is further emphasised by the fact that the area has a sloped height profile which increases the draining speed further. The area is isolated from the main water systems which make an artificial supply of water difficult. This leads to the circumstance that the area suffers under drought-related problems, especially under a moisture-deficit in the soil (Goijer, Heuven, Luijendijk, Overbek, & Runhaar, 2012).

These two reasons are a highlight of this area in comparison to other areas within the policy region of the Waterboard Vechtstromen considering the topic of this study. This leads to the conclusion that the area is highly suitable to perform as a study area and that the area is in urgent need of an intervention to increase the effectiveness of the agrarian sector and the water system.

5 METHODOLOGY AND MODELLING

Chapter 5 give insight into the modelling process and the methodology that is used to obtain the results from Chapter 6. Chapter 5 starts with the explanation of the modelling process and the verification that is done to support the model assumptions. After that, the historical data used to create the model is introduced and the fitting process of the simulated data is explained. At the end of this chapter, the experimental configurations and indicators are explained.

5.1 The modelling of the water network in the Study area

The basis of the model used in this study is an existing surface water model which was created for the main water channels within the study area. It consists of the water channel which is under the management of the waterboard with detailed cross-section, friction coefficients, culverts and weirs located at these water channels and the heights of the water channels to related to NAP. Since the model did not contain information about the trenches which are not maintained by the waterboard, over 800 trenches needed to be added to the model. The process of this is described in the following sections.

5.1.1 Dimensions of the cross sections and categorisation

The water channels which were not included in the basic model were made with the data provided by the (AHN, 2016) Top 10 Water Channel map. If the information of the dataset was not complete the model was optimised based on satellite images out of the GIS database of the waterboard (ArchGIS, 2019). If the information was still insufficient more information about the water channels and interactions with the water network was gathered on the field trip.
To handle the high amount of different data needed, the missing water channels were categorised into 4 Categories the properties of the categories are presented in Table 1 below.

Table 1 - Categorisation of the trenches

Category	Bottom width (in m)	Maximum flow width (in m)	Status of maintenance	Manning coefficient (in $s/m^{(1/3)}$)	Depth (in m)
Category 1	0.8	3	Good maintenance, vegetation trimmed	0.027	1.5
Category 2	0.4	2.5	Good maintenance, vegetation trimmed	0.027	1.2
Category 3	0.2	1.5	Good maintenance, vegetation trimmed	0.027	0.8
Category 4	0.2	1.5	Bad maintenance, vegetation reaches surface level	0.08	0.8

The assumptions for the dimensions of the cross-sections were based on a field measurement in the area. After the measuring of 4 samples per category, the average value for the measurements was taken to represent the water channels. The separation of the different water channels is described in Figure 9 below.

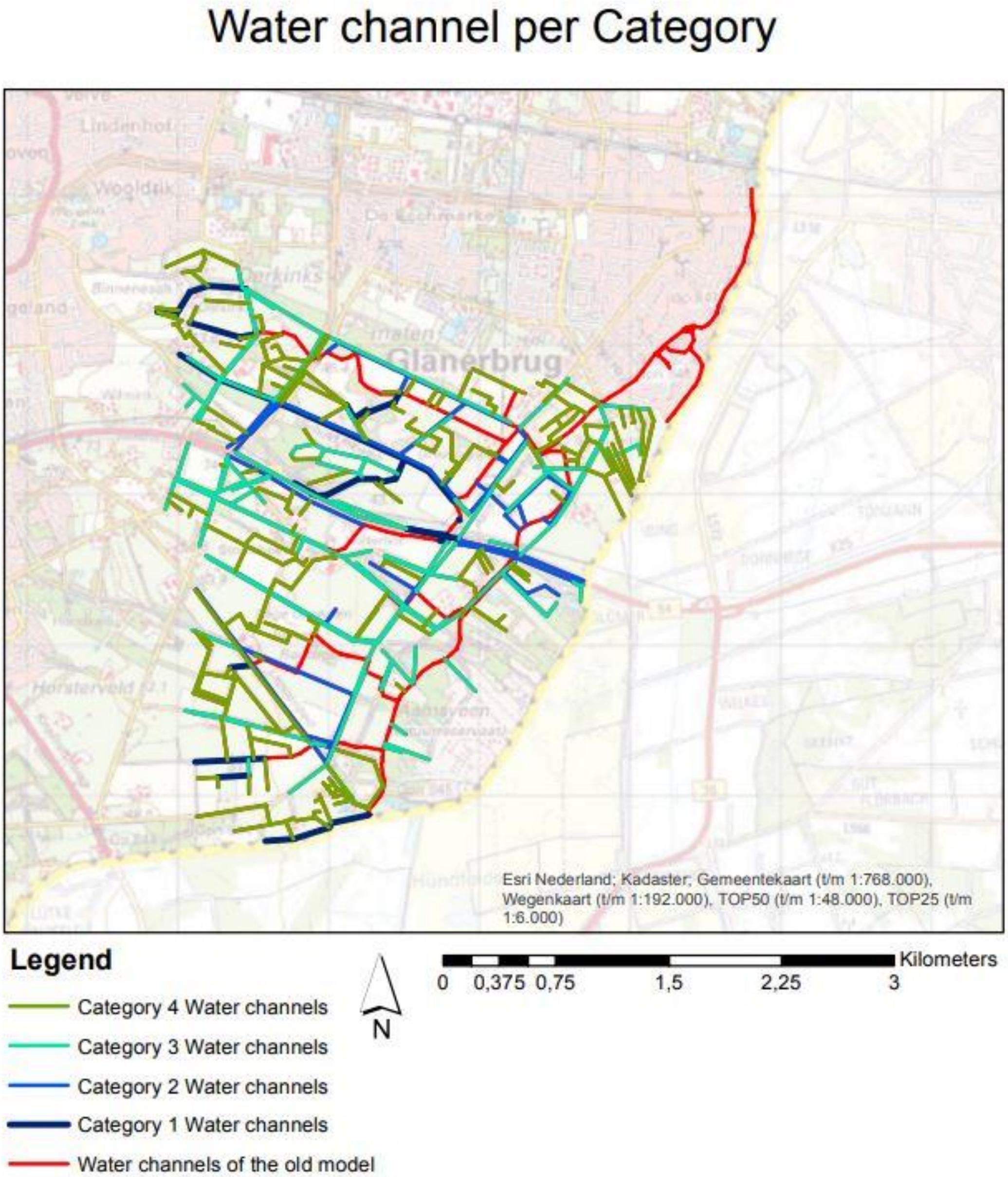


Figure 9 - Map of the categorised trenches

The red channel is the trenches which are maintained by the waterboard and for which all the data necessary was already included in the model. The dark blue lines represent water channels which form the main drainage network in the network. They are mostly extensions of the water channels from the waterboard and form all channels in category 1. Category 2 is are the drainage trenches along the main road which mostly offers a surface water discharge for the streets. These channels form category 2. Category 3 and 4 share the same dimension and form the trenches which lay along smaller streets and that cross the arable land. The main difference between these two categories is the amount of maintenance which high differs. Therefore Category 3 has significantly less flow friction than 4. The friction coefficients are taken from (Chow, 2019). The high categories, as 4 and 3 are also mostly located next to the agrarian land and conservation of the water would be from higher advantage for the farmers to deal against lack of soil moisture in these categories. The water system is made in a way that the higher categories 3 and 4 drain into

trenches of category one or trenches maintained by the waterboard. The category definitions of the trenches are made based on the observations of the field trip.
Each water channel contains three points where the cross-sectional dimensions are implemented in the model, the starting point of the reach, the centre point and the endpoint of the reach. Each cross-section point contains information about the dimensions of the flow channel and the height related to the NAP. A figure of the all cross-section point within the model is given in 10.2.

5.1.2 Dimensions and position of the Culverts/weirs

To model the culverts/weirs that are already present in the area the same method as for the cross sections was chosen. Therefore, were all culverts/weirs which are included in the basic model imported into the model while the rest of the culverts/weirs which are in the side trenches. The culverts and weirs are categorised in the same way as the cross sections and therefore the category of the object is depended on the channel category where they are located. The dimensions of the culverts are based on the observations of the field trip. Table 2 below shows the dimensions per category.

Table 2 - Categorisation of the Culverts

Category	The inner diameter of the culvert (in m)	The material of the culvert	Manning coefficient (in $s/m^{(1/3)}$)
Category 1	0.8	Concrete	0.012
Category 2	0.4	Concrete	0.012
Category 3	0.25	Concrete	0.012
Category 4	0.2	Plastic (PVC)	0.01

The dimension of the culverts was based upon the measurements of the field trip where four measurements for each category take place. Since the dimension was consistent overall category besides the second the values assumed as the representative for the area. This assumption is based on the standardisation of production of culverts and of the drainage system. For category 2 inner diameters of 0.5m and 0.3m were measured. To counteract these differences in the model the average diameter of 0.4m was chosen to represent the category. The positions of the culverts/weirs were determined based on the GIS data from (AHN, 2016). If the information was unclear for the area the model was optimised based on satellite images from the GIS database of the waterboard. If the information was insufficient more detailed observations were made during the field trip. A figure that shows all the culverts within the model is shown in 10.3.

5.1.3 Height of the water channels above NAP – GIS-driven Data

To estimate the height of the different points, the cross sections and the culverts, a GIS databased (ArchGIS, 2019) was used. Since the height map of the (AHN, 2016) with a grid of 5m times 5m had too much noise and was not implementable into the model the raster with squares of a length of 25m was used to estimate the height of the points. Further was the 5 times 5m grid to precise since a lot of the measure points alongside the trenches laid in the trenches. Therefore, more action would be necessary to use a smaller grid. Also, more modifications of the flow network within Sobek would be necessary since more error would occur. The extracted data was used to represent the surface height of an area, therefore was the depth of the water channels subtracted to represent the bottom height of the trenches. The entry height of the culverts was estimated to be equal to the bottom height of the trenches. This assumption was supported by the observations made on the field trip.

5.2 Stabilisation of the model in extreme scenarios

Since Sobek needs an initial water height to start the simulation the maximum height of the smallest trench was chosen, thus 0.8m. This initial height is important since Sobek cannot handle totally dry trenches and super low (under one millimetre) water heights since it exponentially increases the calculation time for the simulation since smaller and smaller time steps need to be calculated how smaller the water height. This implicates that the first hours of the simulation do not

represent valid results since the initial water need to discharge out of the system. Further is this restriction important since the simulation of absolute drought is not possible with the program. This leads to the conclusion that an assumption needs to be made regarding the minimum inflow into the system to make the simulation runnable.
To determine the warmup period of the model two different cases were calculated. The first situation is a flooding scenario where over a period of one day the inflow of the system is 1.8l/s/hec, which represents an extreme flood condition following (Massop, van Bakel, & de Louw, 2017) , of the study area. This case provides information about the stabilisation of the model under extreme conditions and further validates the model under these conditions. Further, a scenario with the minimum discharge that the model can run without a heavy increase in calculation time is created. The discharge patterns of the model for the outflow location for these scenarios (Location of the measuring locations for the historical discharge data) are presented in Figure 10 below.

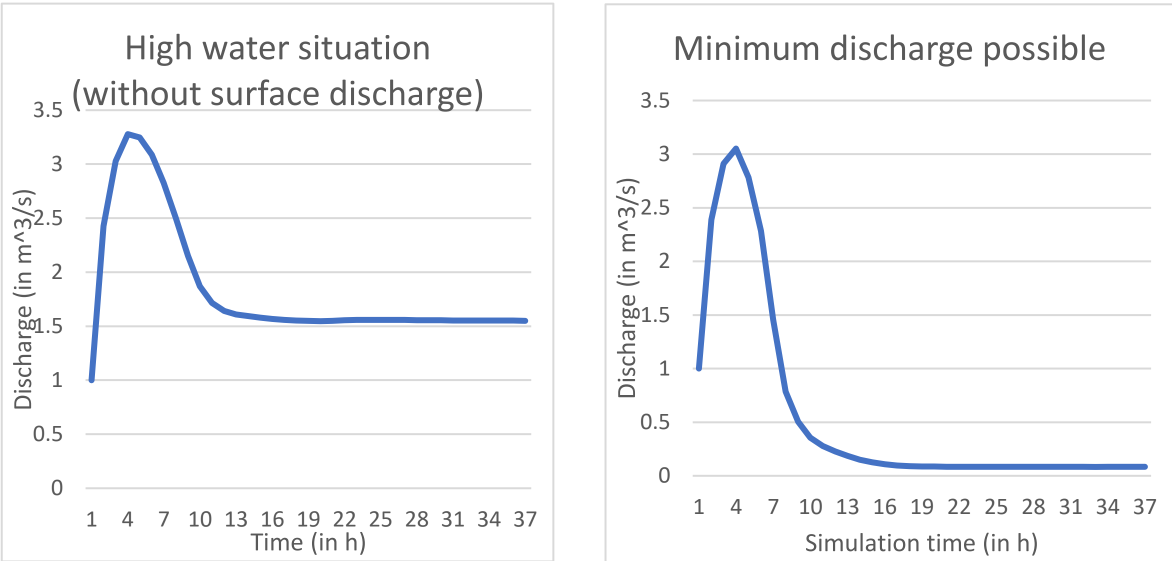


Figure 10 - Stabilization of the discharge in the high-water (left figure) and drought scenario (right figure)

Figure 10 shows that the discharge stabilises after 17 hours of the simulation on an average value of 1.501 m^3/s for the high water and 0.027 m^3/s for the drought scenario. It can be concluded that the warmup period for the model lies around 17hour before the model produces valid values. The warm-up period is necessary since the model starts with an initial water depth of 0.8m in every trench. This is necessary since Sobek is not able to start the simulation with a lower depth without increasing the calculation times significant. The discharge at the end of the stabilisation of the model can be compared to the theoretical input. This leads to the calculation error during these scenarios. Equation (1) gives the general equation for the theoretical discharge of the model.

$$Q_{Area} = A_{Study\ area} \times q_{hectar} \tag{1}$$

For which:

- Q_{Area} is the theoretical discharge considering the input
- $A_{Study\ area}$ is the area of the drainage surface of the model
- q_{hectar} is the constant inflow that is implemented per hectare

Equation 1 is applied to both scenarios (equation 3 and 4) and the theoretical discharge the scenarios is determined.

$$Q_{Area-drought} = 880hec \times \frac{0.031\frac{l}{s}}{hec} = 0.0273\frac{m^3}{s} \quad (2)$$

$$Q_{Area-highwater} = 880hec \times \frac{1.8\frac{l}{s}}{hec} = 1.584\frac{m^3}{s} \quad (3)$$

With this theoretical value it is possible to calculate the error of the model results with the equation (4) below:

$$E_{Discharge} = (Q_{Area} - Q_{steady-model})/Q_{Area} \quad (4)$$

For which:

- $E_{Discharge}$ is the calculation error in percentage
- $Q_{steady-model}$ is the model output

Wit equation 4 the errors of both simulations are determined in calculation 5 and 6 below:

$$E_{Discharge-drought} = \left(0.0273\frac{m^3}{s} - 0.0293\frac{m^3}{s}\right)/0.0273\frac{m^3}{s} = -0.07326 = -7.326\% \quad (5)$$

$$E_{Discharge-highwater} = \left(1.584\frac{m^3}{s} - 1.501\frac{m^3}{s}\right)/1.584\frac{m^3}{s} = 0.05239 = 5.239\% \quad (6)$$

The error calculation shows that both scenarios contain calculation errors in the range of 10% in each direction. This is a high amount but is justify able since Sobek starts to artificially add and remove water if the water heights reach extreme values. This led to the determined errors. Further is a lower calculation error in the model expected in the calculated scenarios since the scenarios do not contain a continuous extreme state as simulated in these events.

5.3 Historical data and the implementation of events

The study area must measure points at different locations where the discharge of the main water channels is determined with the help of measuring weirs. The location of these measurement points is presented in Appendix 10.5. From these measure points, ten years of data were available to create the model. Since the measurements were not complete for the whole time period, the datasets were simplified in different manners.

5.3.1 The main scenario for the simulation

To run the simulation and to get representative results for the study area an event was chosen that is representative of the problems that need to be considered. The choice was to have different short-term events within a bigger event over a time period of a couple of months. The rainfall events should represent a scenario that repeats 10times a year. Therefore, the dataset at the Melodie-Straat was analysed to determine a representative discharge event that occurs in the time between spring and summer. So, the scenario should contain showers that have discharge around the value of 1.2 m^3/s and 2 m^3/s. Further was important the showers which are simulated are from different forms. That means that they have different amounts of volume and duration to show the effects of the pinch culverts/weirs to these different scenarios. Considering these requirements, the time period from the 27-04-2014 to the 15-04-2014 was chosen since the event contains 3 peak showers with discharges between 1.39 m^3/s to 1.94 m^3/s of different forms. The discharge pattern of the event is presented in Figure 11 below.

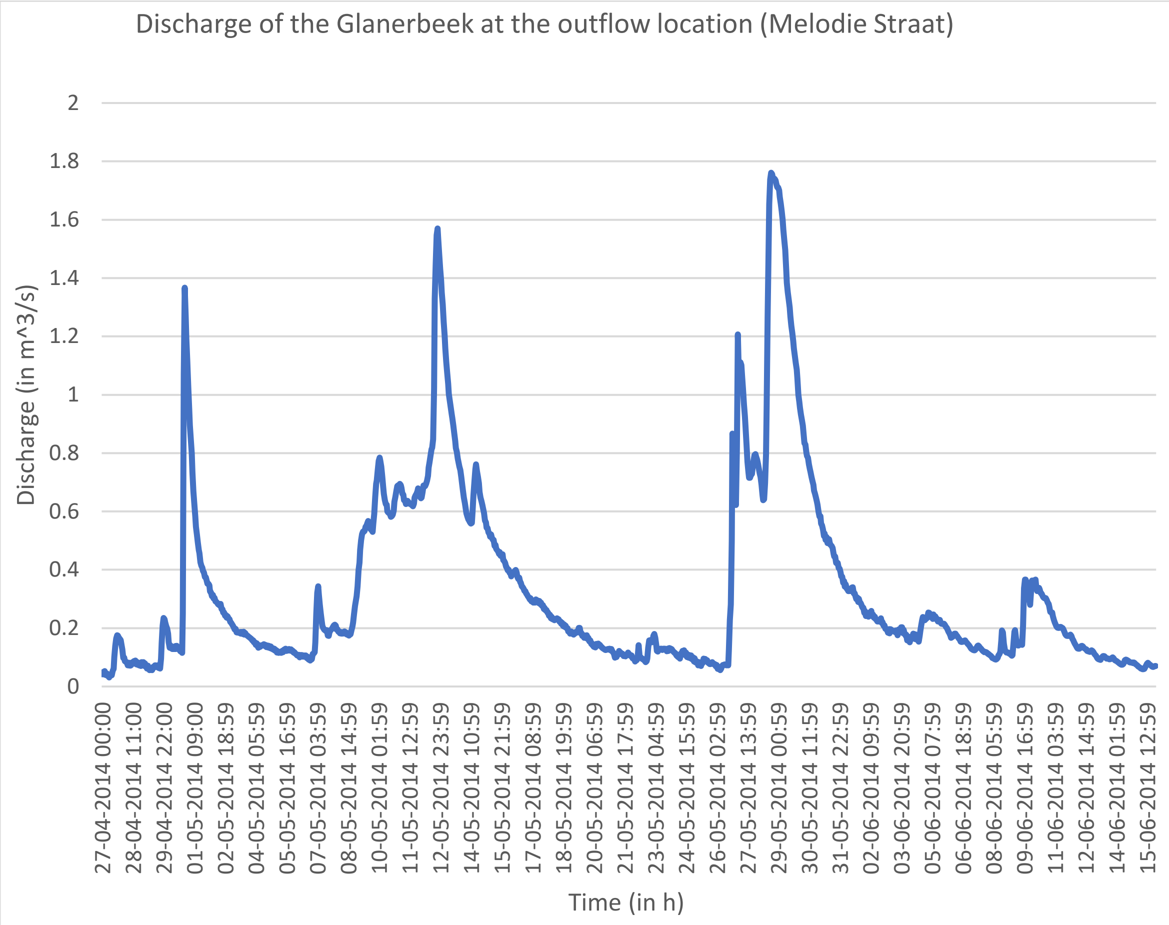


Figure 11 - Measured discharge at Melodie Straat (Main scenario)

As Figure 11 shows are the first discharge peak steep and the duration are quite short. This is followed by a drought period of 5 days which is suited since the effects of pinch culverts/weirs should be visible in both the peak discharge and drought periods. The second peak has more volume over a period of 13 days and a maximum discharge of 1.58m^3/s again followed by a drought period of the 5 days. The last discharge peak is a high-volume discharge over a longer period, 8 days, followed by a drought period of 13 days. This scenario is suited to show the effects of the installed measures and the reaction to the changes in the experiments. The implementation process of the scenario into the model is explained in Appendix 10.7.1.

5.4 Calibration of the data

Since the assumption was made that the discharge is translated into rainfall the drainage speed of the area is important to compensate for the time which the water needs to reach the measurement location at the outflow. To determine the drainage speed the model data was fitted to the historical data by estimating that the model is in average 3 hours slower in creating the discharge than the real data due to the drainage speed. The indicator to determine the best fitting for the two datasets was the Root Mean Square (RMS) deviation of the datasets, which has a minimum, of 0.031m^3/s if the model data can be estimated to be 3hours later than the historical data. For a visual comparison to the two datasets is present in Figure 13 below.

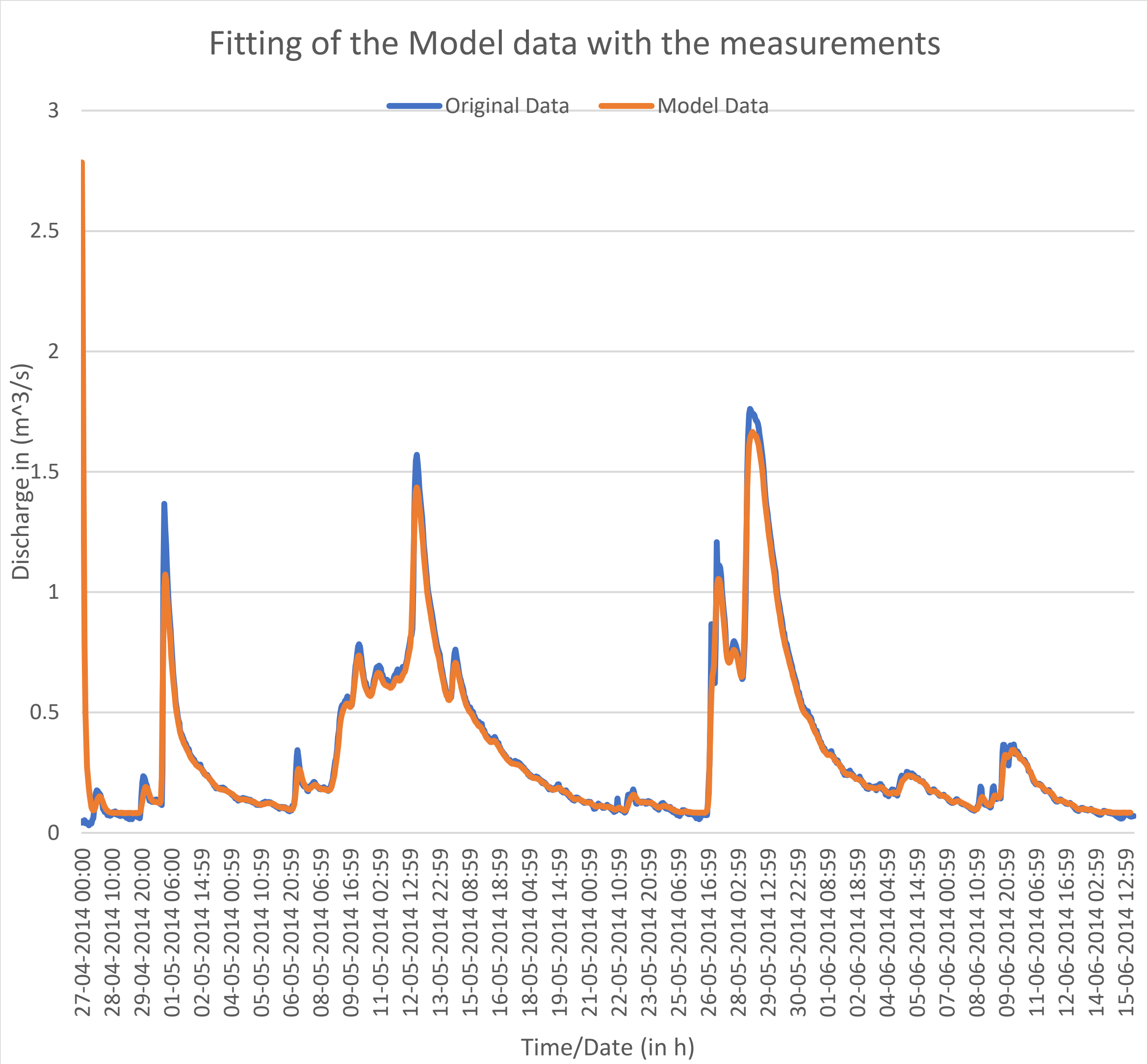


Figure 12 - Comparison of the model with the measurements (Location Aamsveen – Main scenario)

The figure shows that the two datasets are heavily correlated as the RMS deviation already implied. This can be logically concluded due to the method which was chosen to model the rainfall event. It is visible that the peak discharges are always lower in the model data than in the basic data. This can be explained since the rainfall is equally distributed over the area and the water does not reach the measuring point at the same time in the real situation. Therefore, this simulation concludes logically out of the assumptions made for the model.

5.4.1 Validation of the fitting and model assumptions

To further validate the assumption made to create the model and especially for the data fitting a second rainfall scenario was created with the same assumptions as in the chosen event. This scenario is further called the high-water scenario. The discharge will be simulated for the period of the 15-02-2017 to 15-04-2017 to see if the discharge pattern is correlated in the same way as for the chosen event. This period was chosen since it has a long-time difference to the chosen event to make sure both events are independent of each other. The results of this validation run are presented in Figure 13 below.

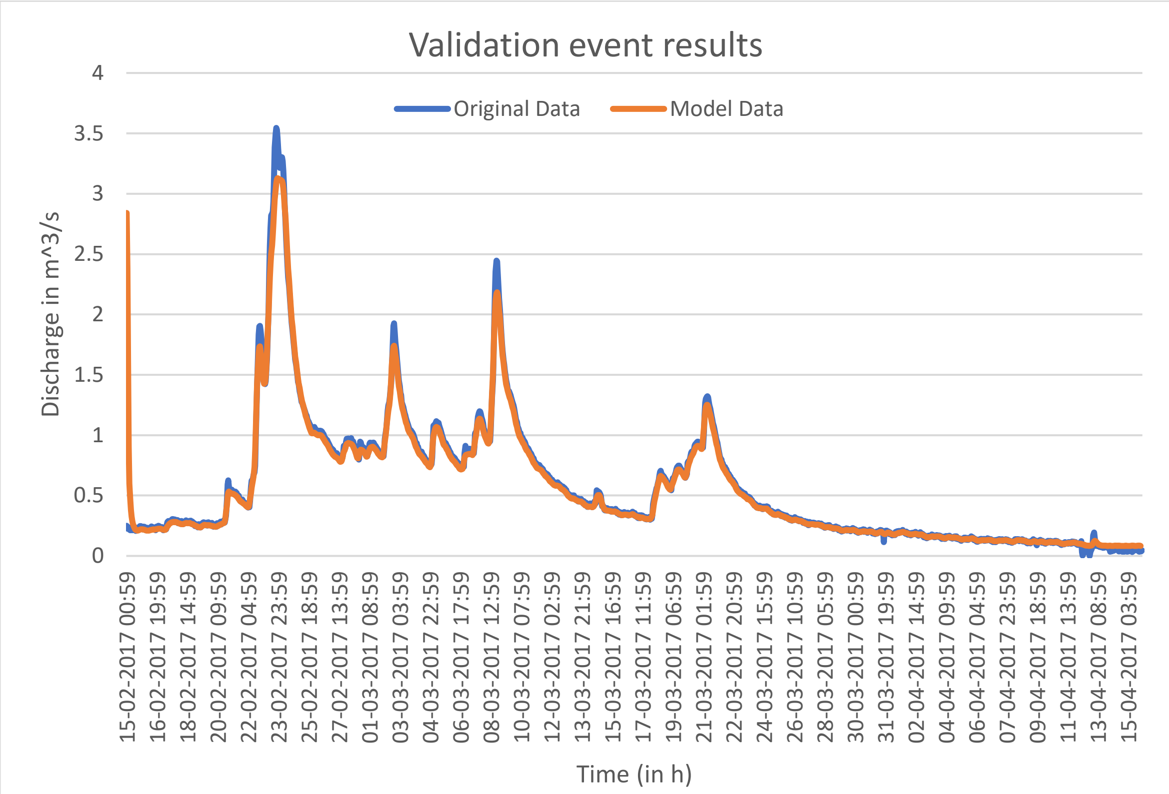


Figure 13 - Comparison of the model data and the measurements (Location Aamsveen - Validation scenario)

As Figure 13 show is the model data still heavily correlated to the basic data with an RMS deviation of 0.041 m^3/s. Further, is the same pattern of error visible as for the scenario event since the maximum peak of discharge is generally underestimated in the model. This again can be referred to the model assumption and is logically coherent with the design of the model. Further the shows that the model is capable to simulate different scenarios in a reliable way and shows that the model handles the imported data in a logical manner.

5.5 Experimental setups

The goal of the experiments is to analyse if the implemented measures make a significant difference in the study area. To determine the influence of different configurations and designs the implemented measures and the effects of these measures are evaluated with the experiment indicators. The goal of this process is first to determine which effects occur when different measures are implemented and how these effects can be used to optimise the system against the challenges of drought and high-water scenarios.

5.5.1 Experiment indicators

To determine an optimal configuration of the measures within the study area evaluation indicators are necessary. The indicators used in the evaluation of the experiments are described in this chapter.

Height of the surface water in the trenches

As described in chapter 3.3.3 is the water height of the surface water in the trenches highly influential on drought-related issues since it affects the infiltration of the surface water to the ground and the drainage resistance of the soil around it (Louw & Vermeulen, 2000). These relations make the water height a suitable indicator for the infiltration of the water and the suction of the trench on the soil around it. Further, are other factors which influence the infiltration of the surface water not changeable with pinch culverts/weirs. Therefore, was the water height chosen to give an indication

for the drought-related problems as a moisture-deficit and too much drainage from the soil to the trench.
For the location of the water height, 5 points of interest are analysed in the experiments. The location which is chosen is presented in Figure 14 below.

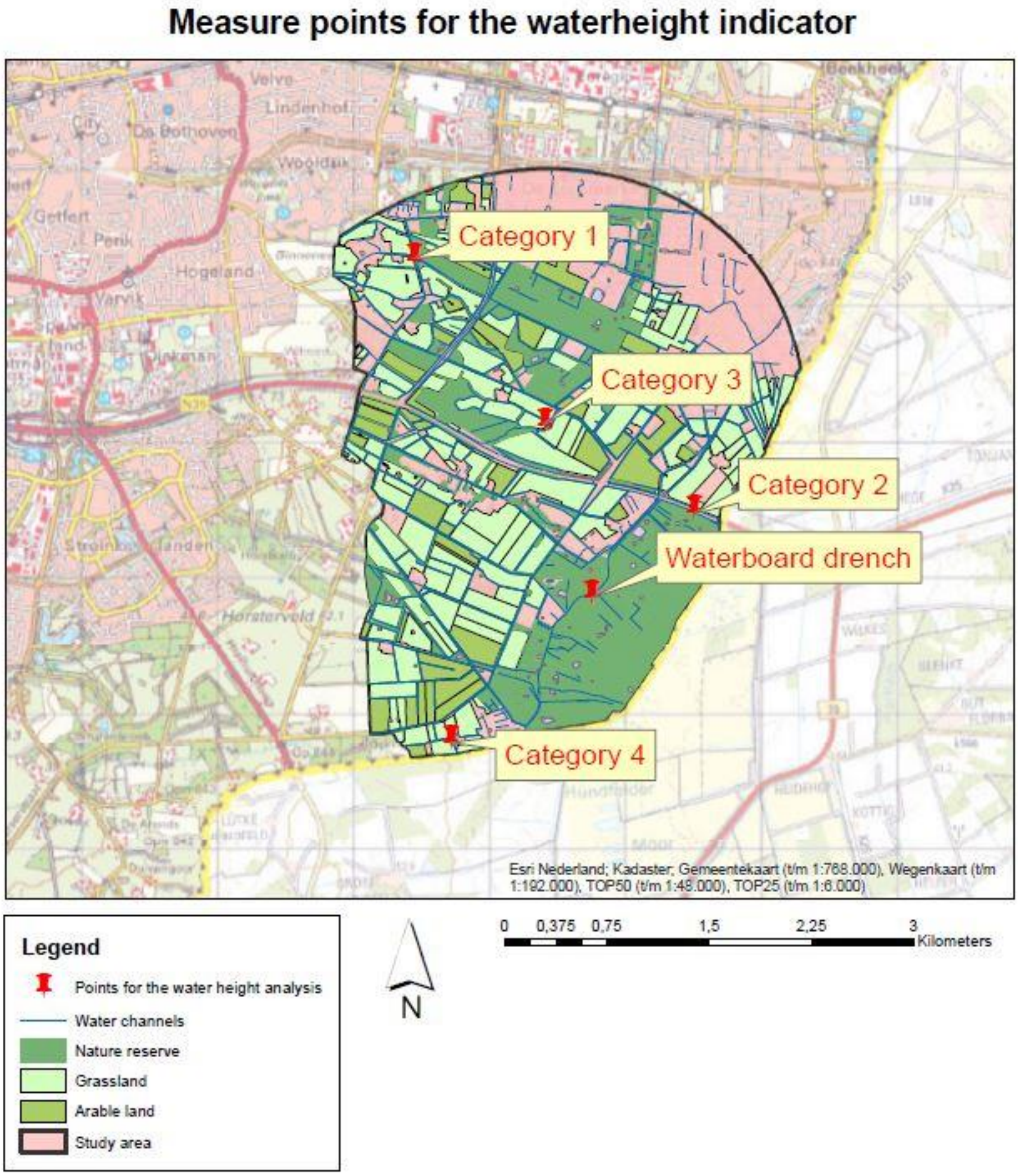


Figure 14 - Map of the measuring locations for the water height

As Figure 14 shows are the measurement points for the water height spread over the study area. The measured location for category one is surrounded by a natural reserve downstream (to the east) and agrarian ground upstream (to the west). The point gives, therefore, information about the amount of conservation that occurs in the trenches flowing through the agrarian ground. Further is the culvert connecting an isolated water network to the main part which makes results at this location from interest (ArchGIS, 2019).

The measured location of the second category is located at an isolated Trench in the south-east of the region. It is surrounded by agrarian ground to the north and the federal road N35 to the south (ArchGIS, 2019). Since the culvert is will not be modified the results from this measure point show possible interactions of modifications in the water system to not modified parts.
The third measure location is placed at a trench which drains an isolated part of the water system in the centre of the study area surrounded by agrarian ground and grassland. Since this culvert forms a bottleneck the results for the water height are from interest for the study.
The measuring point for the fourth category is located to the south and drains an isolated part of a built-up area mixed with grass and agrarian land. This location is again interesting since it forms a bottleneck for the drainage system.
The location chosen for the trenches of the waterboard is in the south-eastern part of the study area right within a natural reserve. It is chosen since the main water channel is isolated in this area and water cannot easily redirect from this location which can form flooding issues.
All the measurement locations are chosen since they have special positions within the water system and therefore are from interest for this study. A statement over the average changes for the water height is difficult to obtain since Sobek only give the height of water per location.

Discharge at measure location

The second indicator that is used to determine the effectiveness of the measures in the experiments is the change of the total discharge of the hydrological area. Changes in the discharge pattern indicate a change in discharge pattern in the side trenches. Further, the discharge of the hydrological system indicates the effectiveness of the measurements. The indicator gives information about the flooding issues since a maximum discharge reduction or increase is made visible.
Since the total discharge of the hydrological network is from interest, the outflow location will function as a measuring location within the model. The location is given in Appendix 10.5.

5.5.2 Experimental configurations

This part describes the Eight different experimental configurations that were done within the model and the differences between them. The set up differs in the location where the measurements are placed and the design which is implemented into the model. The result of the indicators that are described is presented in chapter 6.

The full pinch configuration – Experiment 1

The first experiment focuses on the implementation of pinch culverts. The measures are implemented in at the locations of the Shown in Figure 15 below.

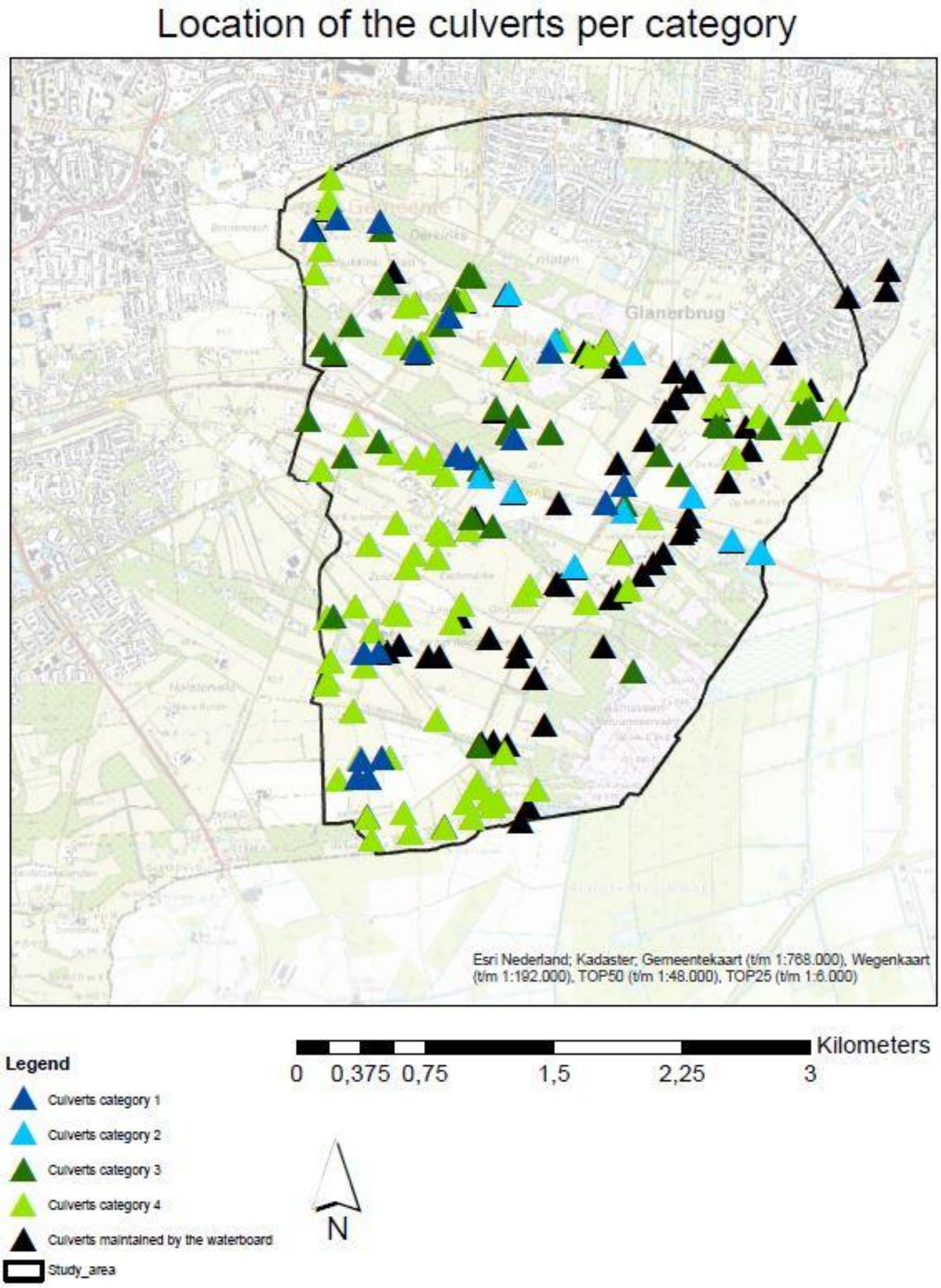


Figure 15 - Map of the locations of the culverts per category

The culverts from category 2 are an exception since they are roadside locks and any water conserved or stored in these trenches is restricted by the law since it leads to safety issues for the road users since water on the street process accidents (Ministerie van Verkeer en Waterstaat, 1988). Therefore, the measures located in these trenches remain as in the basic case. This is true for every configuration. Another reason is that the trenches are located alongside federal roads which define them as maintained by the governance and therefore out of the influence of the waterboard or third parties. Both the trenches from the third-party members, as farmers or landlords, and the trenches which are maintained by the waterboard are modified in this configuration. Category 1, 3 ,4 and the trenches maintained by third parties. The pinch culverts differ in dimension depending on the trench category where they are located at as shown in Figure 15. An example of a design used in this experiment is given in Figure 16 below.

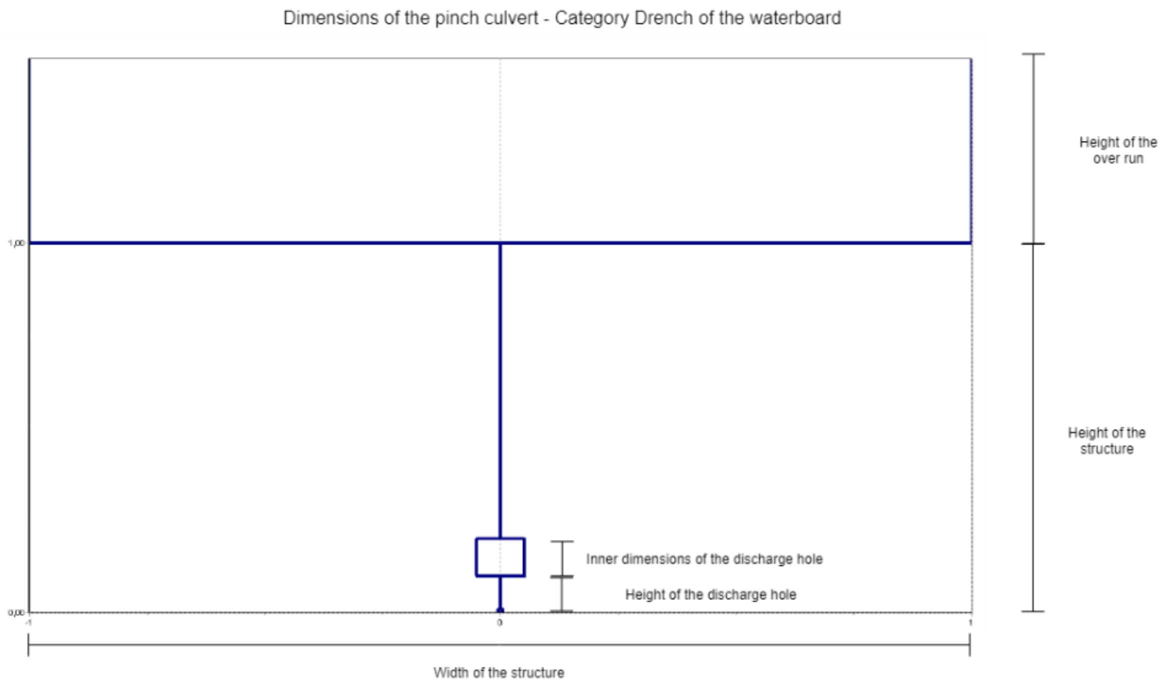


Figure 16 - Explanation of the dimensions of the measurements

A total of 231 culverts are modified in this configuration. The number and dimensions of the measures of each category show Table 3 below.

Table 3 - Dimensions of the implemented pinch culverts/weirs per category

Categories	Inner dimensions of the Discharge hole (square in m)	Height of the discharge hole (in m)	Height of the structure (in m)	Height of the over rum (in m)	Width of the structure (in m)	Number of modified culverts
Category 1	0.1	0.2	1	0.5	2	18
Category 3	0.03	0.3	0.5	0.3	1	36
Category 4	0.03	0.3	0.6	0.2	1	88
Trenches of the waterboard	0.1	0.1	1	0.5	2	89

The experimental setup focuses on the conserving effect in the side trenches and storage trenches of the water network since they have less restriction on the minimal discharge that is necessary to counteract flooding issues. Further is the water system designed to discharge water from higher categories as 4 and 3 to lower categories where the dimension of the trenches increases. Therefore, the lower categories function as the main drainage of the area while the higher categories function as drainage of smaller farmland and street. To maintain the flood resistance and to enhance the capability of the area to withstand heavier rainfall events it is necessary to have

higher storage volume in these trenches. This is especially true for the trenches under the maintenance of the water board since the whole water network is set up in the way that the water will finally drain into these trenches and from there to the main water system.
This configuration is expected to have a good conservational effect in the smaller side trenches near the agrarian land, therefore an increase in water height in the smaller side trenches during the scenarios (Category 3 and 4), and a good storage effect in the main drainage systems (category 1) and , therefore decrease of maximum discharge of the water system.

The pinch configuration (the third-party trenches) – Experiment 2

The second experimental setup tested with the model is an implementation of the same measurement design, the pinch culvert/weir with a discharge hole, but only trenches from the third parties are modified, thus category 1, 3, and 4. The effect of the conservation in the side trenches is therefore isolated and the effectiveness of these measures can be analysed on their own. A total of 142 culverts are modified in this configuration, thus only trenches of third parties excluding the trenches under maintenance of the waterboard. An advantage is that the implementation of fewer measures in the study area is less expensive in the social economic context of the project work.
This configuration is expected to have a smaller effect on the decrease of the maximum discharge and on the conservation in the main discharge trenches. Further can be expected that the conservational effects still occur in the smaller side trenches (categories 3 and 4).

The full LOP-culvert configuration – Experiment 3

This configuration focuses on the LOP design for measurements which are implemented at the culvert location in the study area. This configuration is expected to be the cheapest since the implementation of the wooden plates in front of the culverts is simple and does not require much resources nor time to install. The downside of this configuration is that a storage effect is not less achievable since the LOP-design focuses mainly on the conservation, therefore drought-related aspect, of the problems. Also has the LOP-design a high demand for time-intensive maintenance throughout the year which can create additional costs for the maintaining parties.
The design which is implemented in this setup is presented in Figure 17 below.

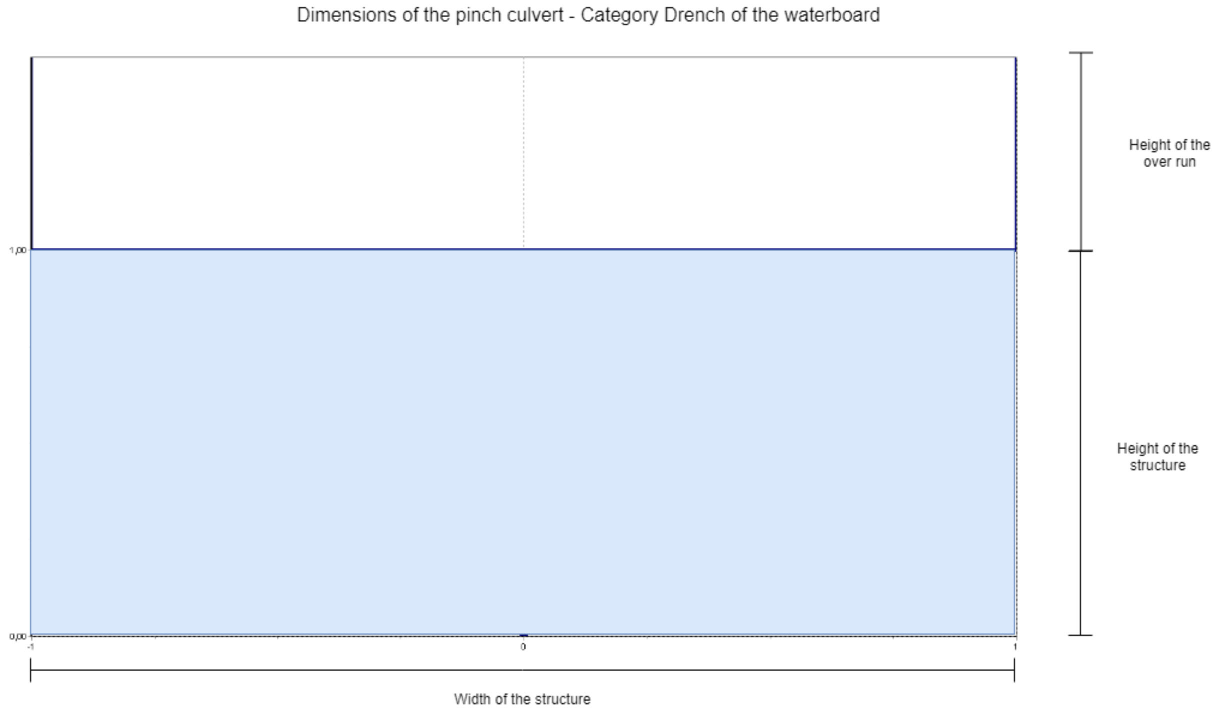


Figure 17 - Design of the LOP-design implemented in cases 3 and 4

231 culverts are modified in this configuration. The dimension of the measurement for each category presents Table 4 below.

Table 4 - Dimensions of the implemented measures for the third experimental setup

Categories	Height of the structure (in m)	Height of the overrun (in m)	Width of the structure (in m)	Number of culverts modified
Category 1	1	0.5	2	18
Category 3	0.5	0.3	1	36
Category 4	0.6	0.2	1	88
Trenches of the waterboard	1	0.5	2	89

The main difference between the LOP-design and the pinch design is that the culvert/weirs do not have a discharge hole and therefore need less production and configuration analysis since they are fewer factors to consider.

The LOP-culvert configuration (the third-party trenches) – Experiment 4

The fourth experiment again focuses on the LOP-design measures that predominantly have a conservational effect and lack storage capacity. Furthermore, are the LOP-culverts only implemented in the trenches of the third parties, therefore 142. This configuration is the cheapest one tested since the design used is the cheapest and the amount of measures placed is the smallest. It is expected to have a positive effect on the water height indicator, but no to nearly no effect on the discharge minimisation since no storage capacity is created.

5.5.3 Summarizing overview for the four experimental setups

Since the experimental setups will be referred to a lot during chapters 6 and 7 a short overview for all experimental setups is presented in Table 5 below. The experimental setups also will be referred to as cases or con1figurations in these chapters. The positions mentioned in Table 5 refer to the positions of the culverts in Figure 15 - Map of the locations of the culverts per category Figure 15.

Table 5 - Overview for the different setups

Experimental setup/Case/Configuration	Number of measures modified	Design implemented in the model	Positions of the measures
1	231	The pinch culvert/weir design	In category 1, 3, 4 and the trenches maintained by the water board at the locations of the present culverts
2	142	The pinch culvert/weir design	In trenches of category 1, 3 and 4 at the location of the present culverts
3	231	The LOP-culvert/weir design	In category 1, 3, 4 and the trenches maintained by the water board at the location of the present culverts
4	142	The LOP-culvert/weir design	In trenches of category 1, 3 and 4 at the location of the present culverts

6 RESULTS

This chapter shows the results of the modelling calculation for the two indicators that are defined in 5.5. The first indicator that is presented is the change in the discharge pattern of the whole water network. Followed by an analysis of the results. After that, the results for the water height will be presented and analysed.

6.1 Results for the water discharge indicator

The first part of the results describes the effects of the implemented measure in the study area on the discharge pattern and compare these patterns to the basic model data which is used for the fitting of the datasets that are presented in Chapter 5.4. After the general effect of the measures are explained and analysed with the example of the first experimental setup. After that, a comparison is drawn between the different configurations that are implemented during the four experimental setups. The effectiveness of the different configurations on the discharge is compared and the effects of the changes in the discharges are analysed.

6.1.1 Analysis of the first configuration – description of the effects

In this part, the effects of the measures that are modified in the model are described with the example of the first experimental configuration. First a short analysis of the discharge changes for the main scenario is presented, with two rainfall events analysed, and afterwards, a short explanation of the behaviour of the measure in the high-water scenario is given. This is followed by a short analysis of the behaviour. The results for the discharge indicator of the first experimental setup is presented in the figure below. A more detailed version of the graph is presented in 10.8.

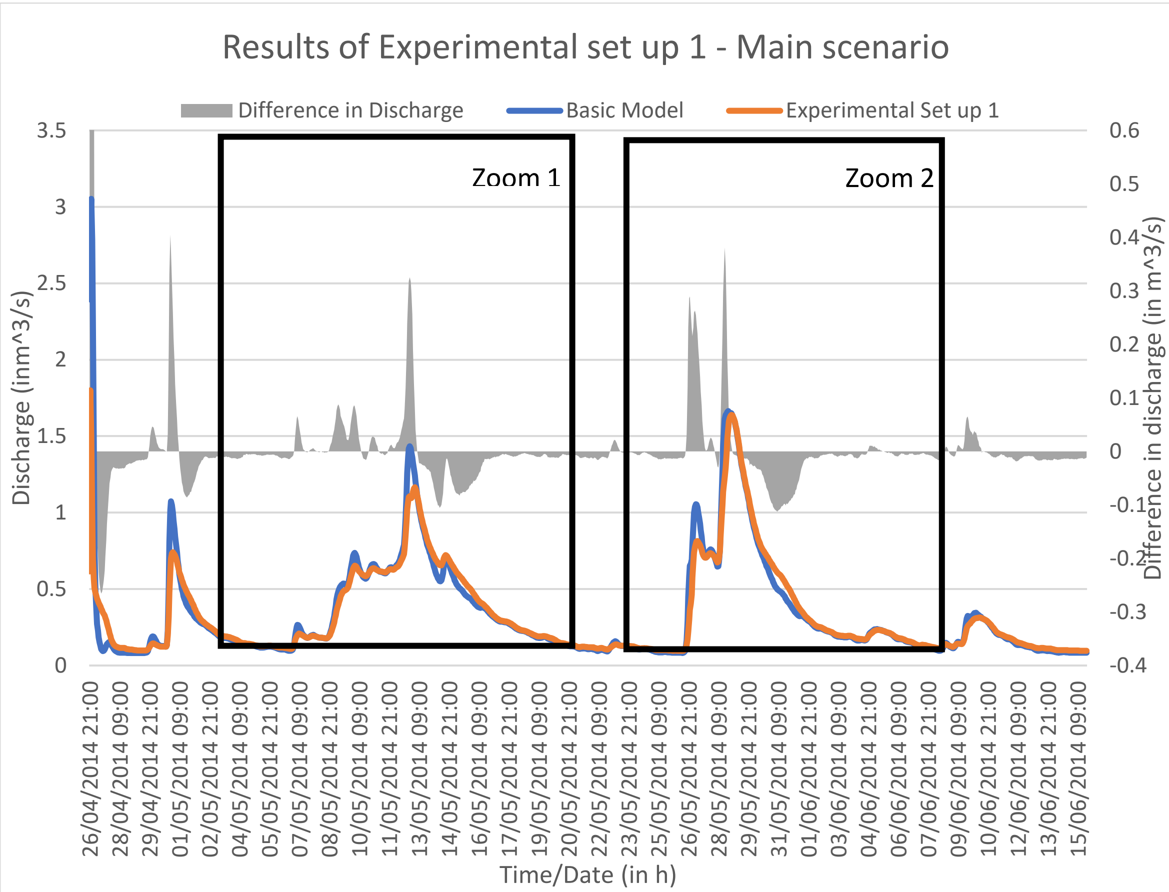


Figure 18 - Results of the Main scenario for experimental set up 1

Figure 18 shows that the measures have an influence on the discharge pattern when compared to the basic model. In general, is the statistical difference of the two datasets relatively small with an RMS deviation value of 0.0604 m^3/s during the main scenario. By observing the datasets, the discharge of the hydrological area is reduced during the (maximum) peaks of discharges in the main scenario. This is visible at the peaks around the 30th April 13th May or the 27th of May. A more detailed graph of the rainfall event around the 13th is presented in the figure below.

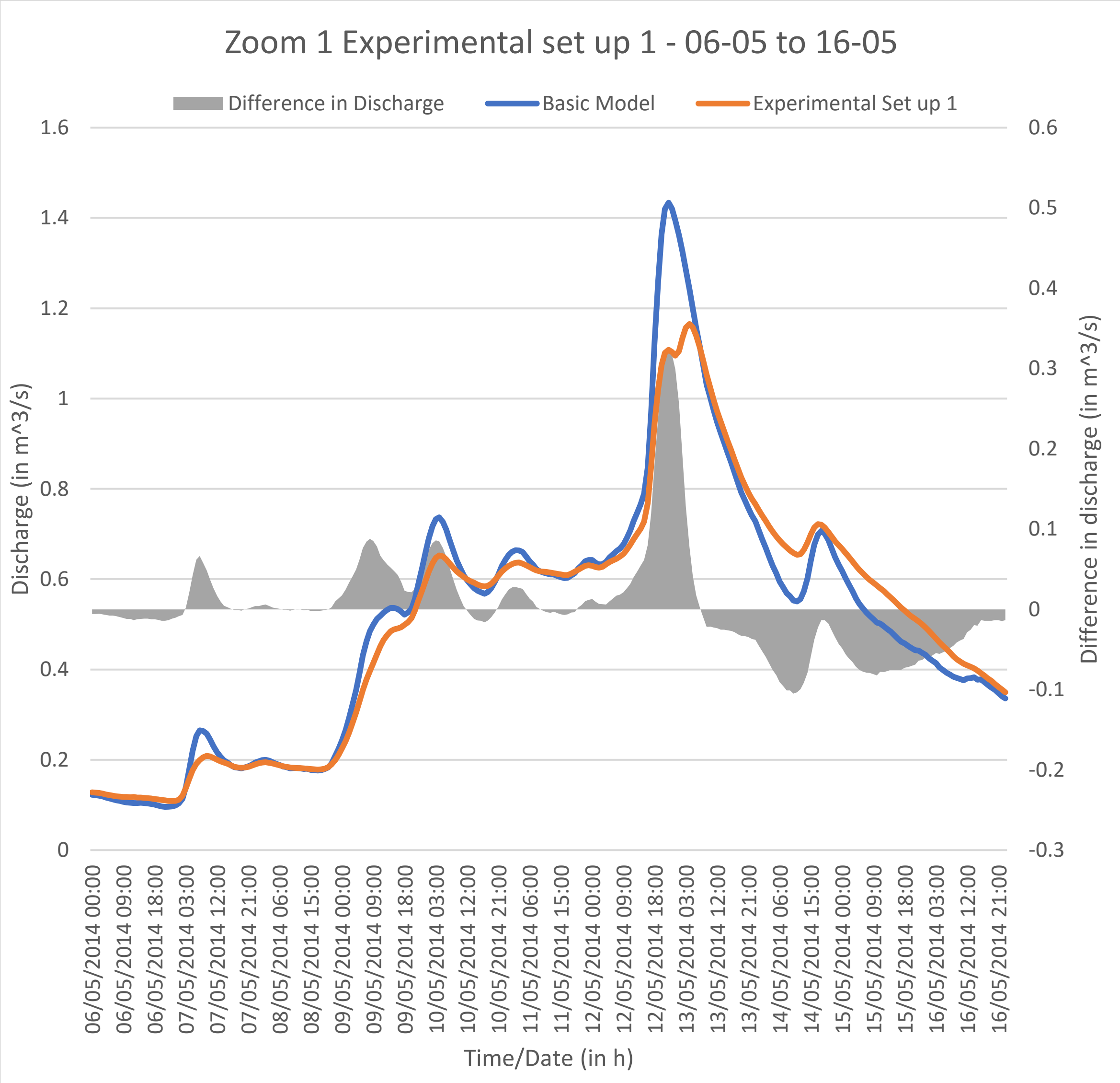


Figure 19 - Zoom on the period between the 6th and the 16th May

Figure 19 shows a reduction in the first peaks of the rainfall event at the 7th and the 10th May of 33% and 13%. Also, the main discharge at the end of the 12th May can be observed with a relative reduction of 29%. As the heavy rainfall stops after the 12th a significant increase in continuous discharge over a period of 4 days appears with an average increase of 8% compared to the basic model. Therefore, the water discharge of peaks is delayed, and the discharge of water volume happens in a more continuous manner. This is referred to as the flattening of peak discharges. After these four days, the water discharge is still increased by small amounts until a new rainfall event occurs. These are a positive effect on both the flooding issues since the maximum discharge of a hydrological area is decrease while the continuous discharge in dryer periods increases.

During the event around the 29th of June, the maximum discharge peak runs through the water system. A zoom of that rainfall event is given in Figure 20 below.

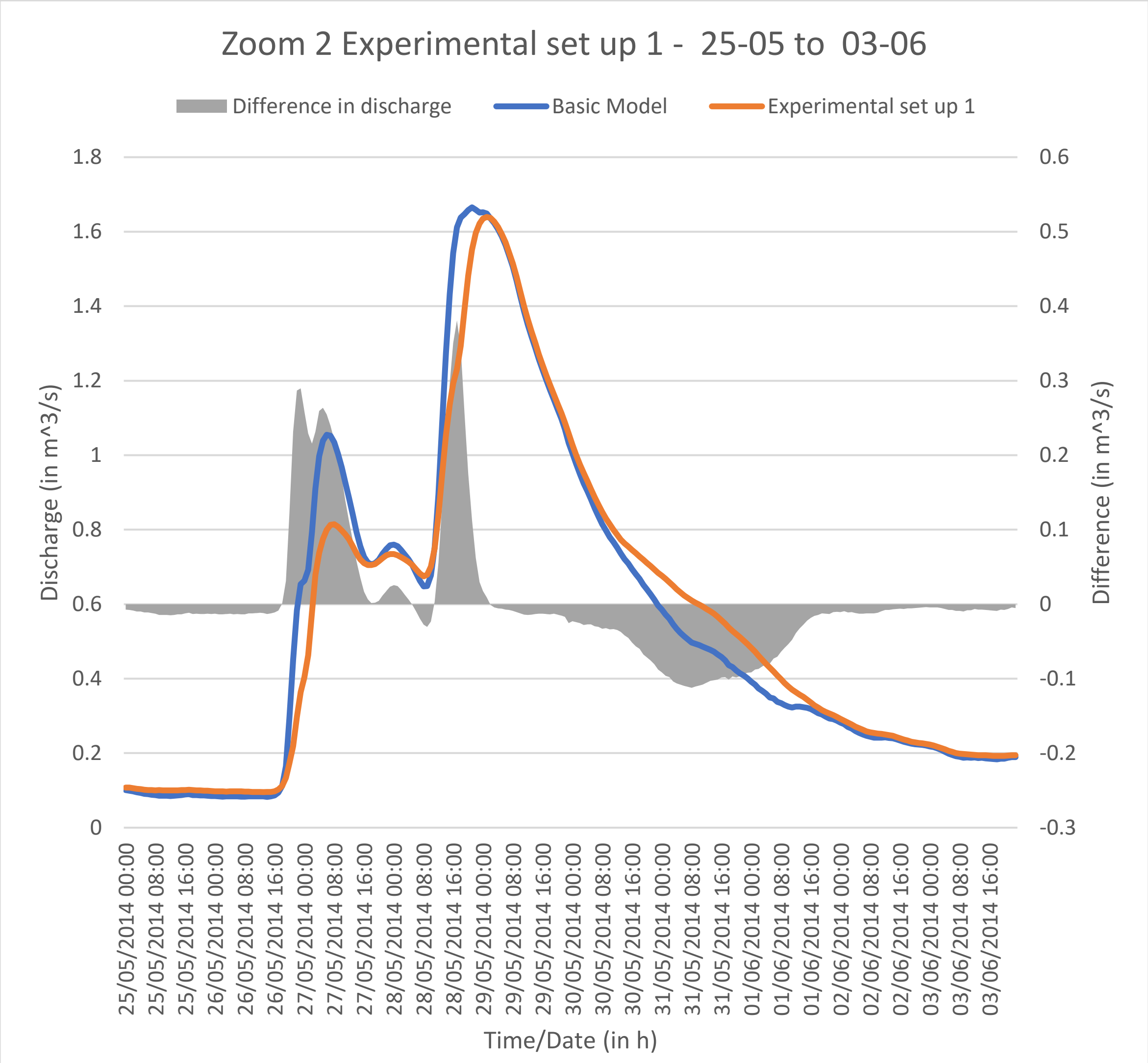


Figure 20 - Zoom on the period between the 25th May to the 3rd June

The event consists of the discharge peaks around the 27th and the 29th March, as shown by Figure 20. During the first peak, the configuration achieves a reduction of the maximum discharge of 25% in the morning of the 27th. As visible is the discharge reduced and the water volume is not discharged since the upcoming rain even, the main peak around the 29th is transitioned by a wet period with a constant inflow of new water volume. After the water volume is stored at the 27th the next rainfall event already starts with nearly full storage behind the modified measures. Therefore, the first part of the discharge peak at the afternoon of the 28th May is still delayed and stored. After the storage volume is reached the discharge of the system starts to trend in the direction of the maximum peak around the afternoon of the 27th, where the peak discharge is only reduced by 2% which is relatively low compared to the other rainfall events in that scenario. After the main peak is over the average discharge of the water system in the configuration is with a relative average of 8.5%. over a period of 4 days. This refers to the water volume that was stored form both rainfall events at the 27th and the 29th. While a flatting of the maximum discharge did not occur during the event around the 27th an increase in discharge appears the 4 days afterwards. This is related to the maximum volume that the measures can store during this rainfall event before overtopping of the measures occurs. This effect is more clearly shown during the high-water scenario. The discharge pattern of that scenario is presented in Figure 21 below. A more detailed version of the graph is presented in 10.9.

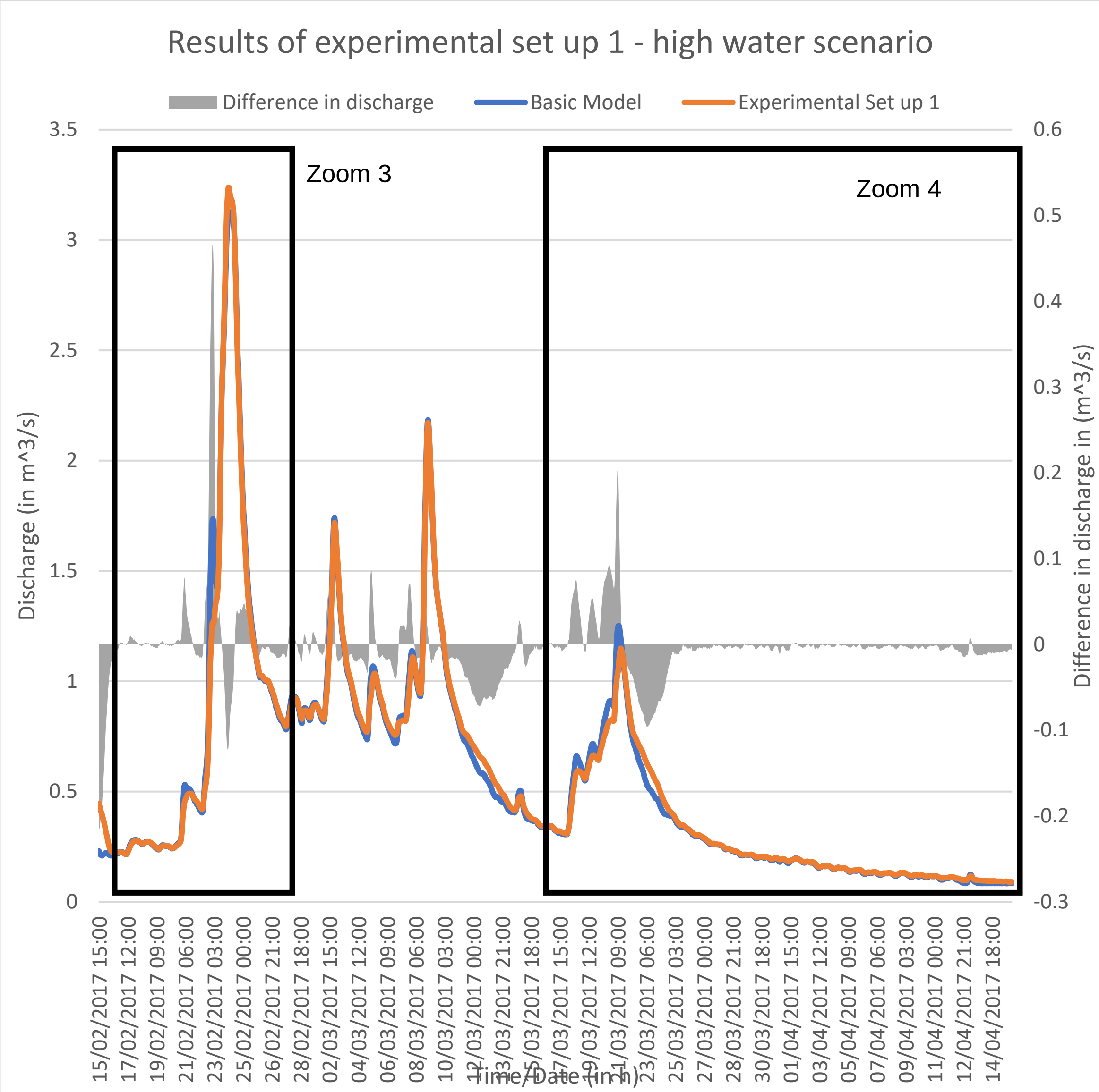


Figure 21 - Results of Experimental Set up 1 – High water scenario

By visual observation, the difference between the basic case and the experimental set up is smaller as in the main scenario than in the high-water scenario. This further supported by the RSM deviation of 0.0417 m^3/s when comparing this configuration to the basic model during the high-water scenario. Another point of interest is that the main discharge peaks around the 24th February, the 2nd March and the 9th March shown no significant decrease in maximum discharge during this experimentation, while the first peak around the 23rd February is decreased by more than 35% of the maximum peak. The zoom on that rainfall event is presented in Figure 22.

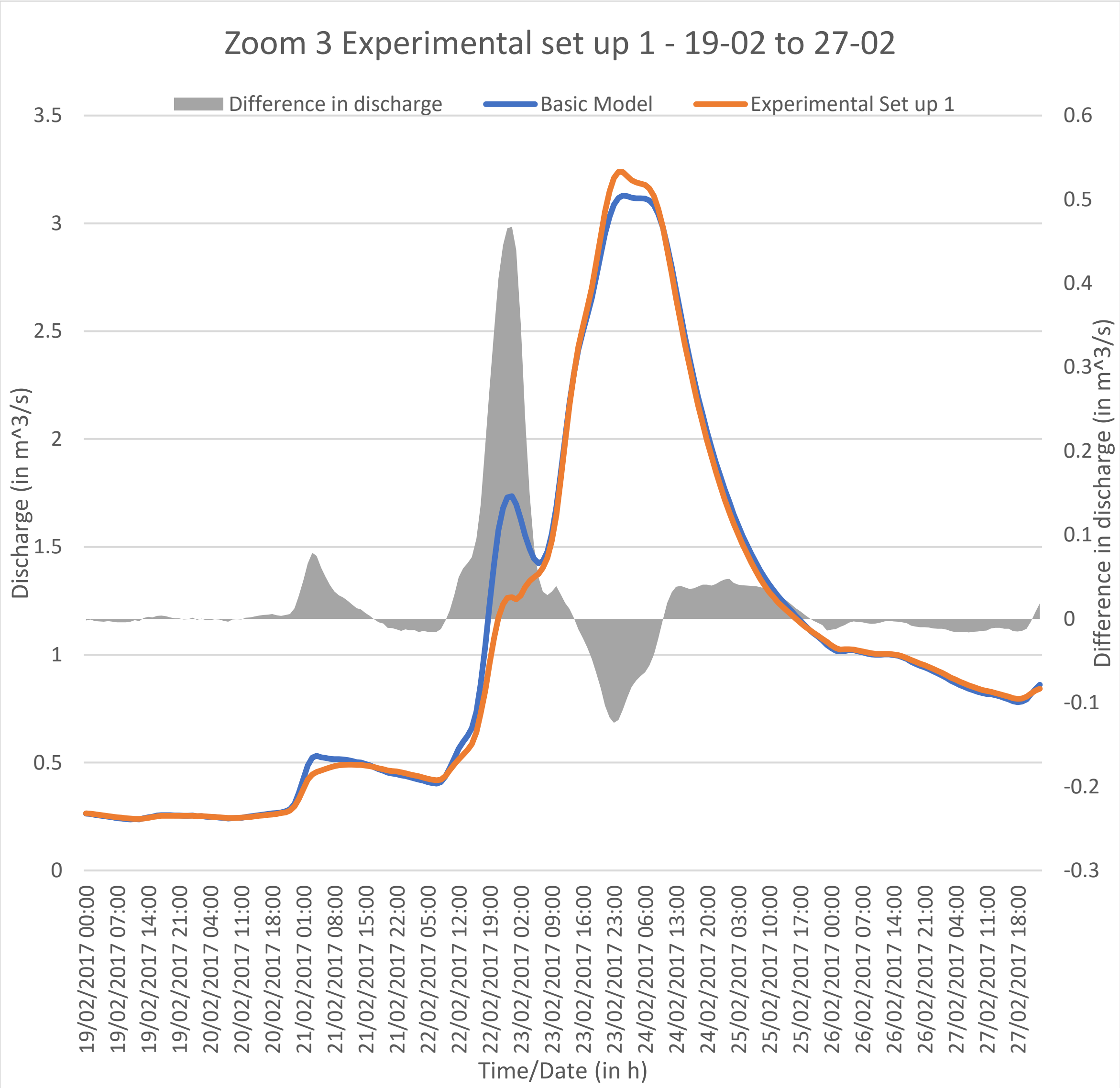


Figure 22 - Zoom in on the first rainfall event during the high-water scenario - 19th to 27th February

The graph shows that the first discharge is nearly fully stored behind the modified measures. The storage of the water starts on the 20th February and continuous to the 23rd. This is the date where the storage capacity of the measures reached, and no storage effect occurs within the simulation. The discharge pattern follows the discharge of the basic model till the end of the 23rd where the configuration discharge exceeds the discharge of the basic case by a maximum of 3.5%. In this case, the configuration acts counter-effective to the implementation purpose. After the maximum discharge, the outflow follows the line of the basic case. This is a steady state till the 9th March since the whole time period is characterised by a heavy inflow of water and the measures have no time to discharge the storage capacity. After the 9th the water system starts to discharge the stored water volume and empties the storage capacity of the measures. The period after this continuous discharge is presented in Figure 23 below.

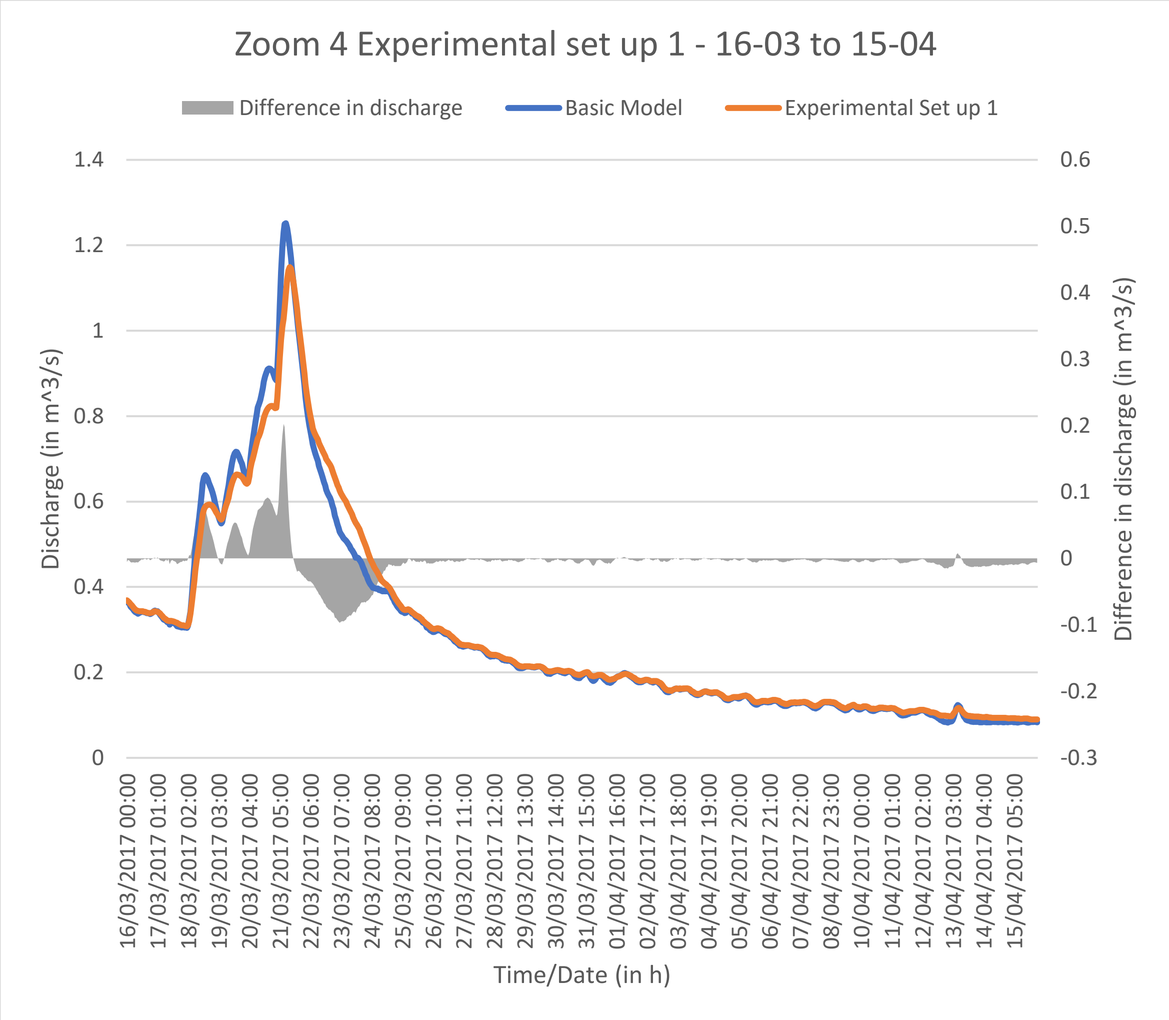


Figure 23 - Zoom in the rainfall event from the 16th March to the 15th April

After the continuous discharge of the event from the 9th to the 16th, a high amount of water is continuously discharged by the water system. The next rainfall event which causes the storage to fill up again is located around the 19th March. As Figure 23 shows is the main peak in discharge flatten by the modified measures, thus the maximum discharge is decreased by 16% relative to the maximum peak in the basic model. After the 19th March, the water system starts to discharge the stored water constantly which leads to a significant increase in discharge during the following 4 days. After that, the discharge of the configuration remains above the basic case while compensation the smaller rainfalls at the 1st and 13th April.

It can be concluded that the measures implemented in the first experimental setup are able to flatten the maximum peaks in discharge, thus reducing the maximum discharge while increasing the average discharge after rainfall events. This effect occurs predominantly on the 4 days after the rainfall, but it continues on a smaller scale till the next rainfall event appears. Exceptions to this effect are rainfall events which exceed the storage volume of the implemented measures.

6.1.2 Comparison of the effectiveness of the different experimental setups

The comparison between the different experimental set up will be started with a comparison of the first and the second experimental setup since they both share the same measures and differ only in the number of modified units.

Comparison between experimental setup 1 and 2

When comparing the two configurations to each other the same effects occur in both datasets. The main difference is the extent to which the effects occur. A graph for the main scenario with the dataset of both configurations and the basic case is presented in Figure 24. A more detailed version of the graph is presented in 10.10.

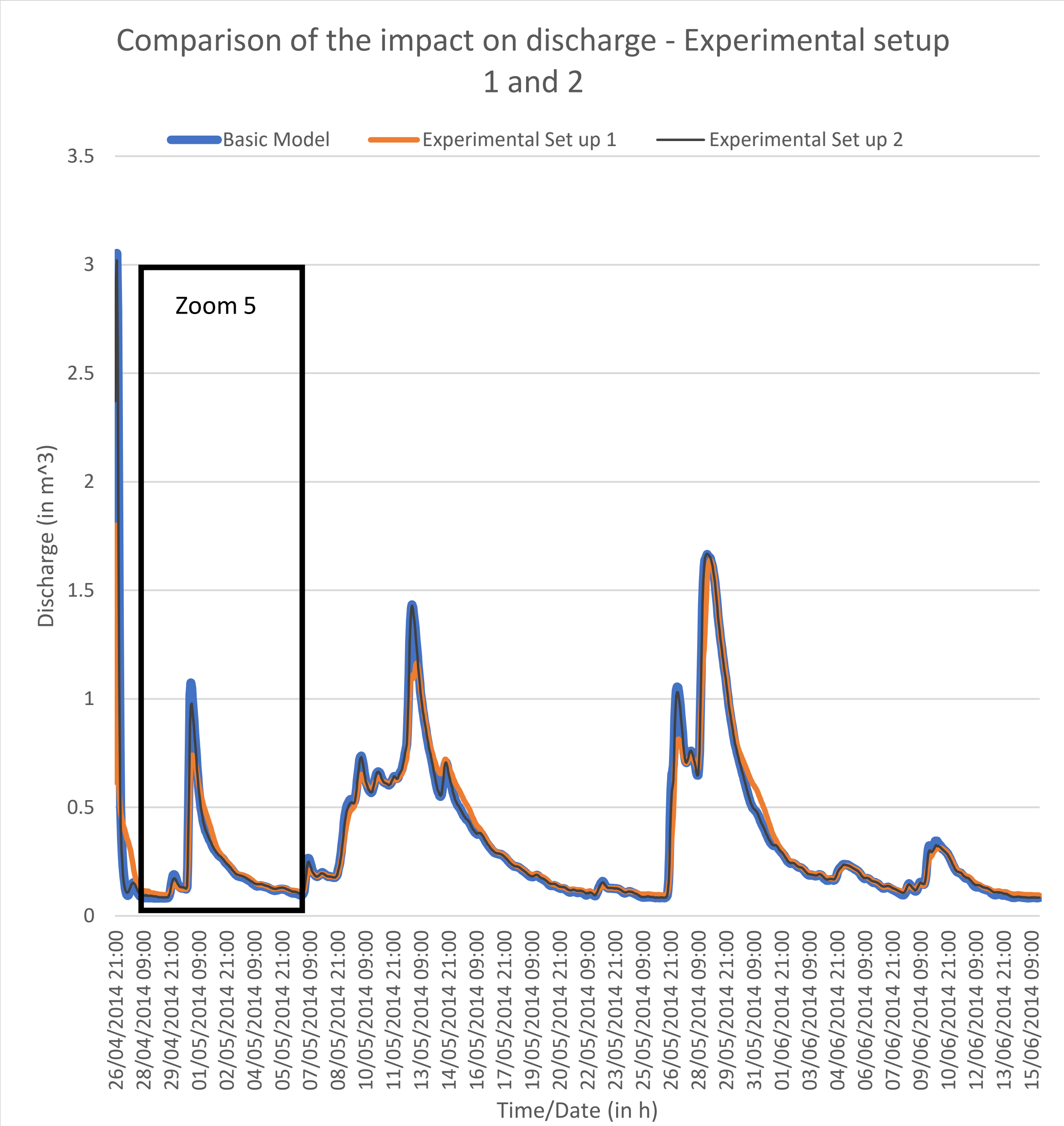


Figure 24 - Comparison of Experimental setup 1 and 2

The visual observation of the dataset shows that experimental setup 2 differs fewer from the basic case as the first configuration. This impression is supported by the RMS deviation of 0.0106 m^3/s which is six times smaller than the RMS deviation of the first case for the main scenario. Therefore, the dataset form case 2 follows the discharge pattern of the basic model. When zoomed in the same pattern in the experimental setup is visible. This is shown by Figure 25 where a zoom on the first rainfall event around the 30^{th} April is presented.

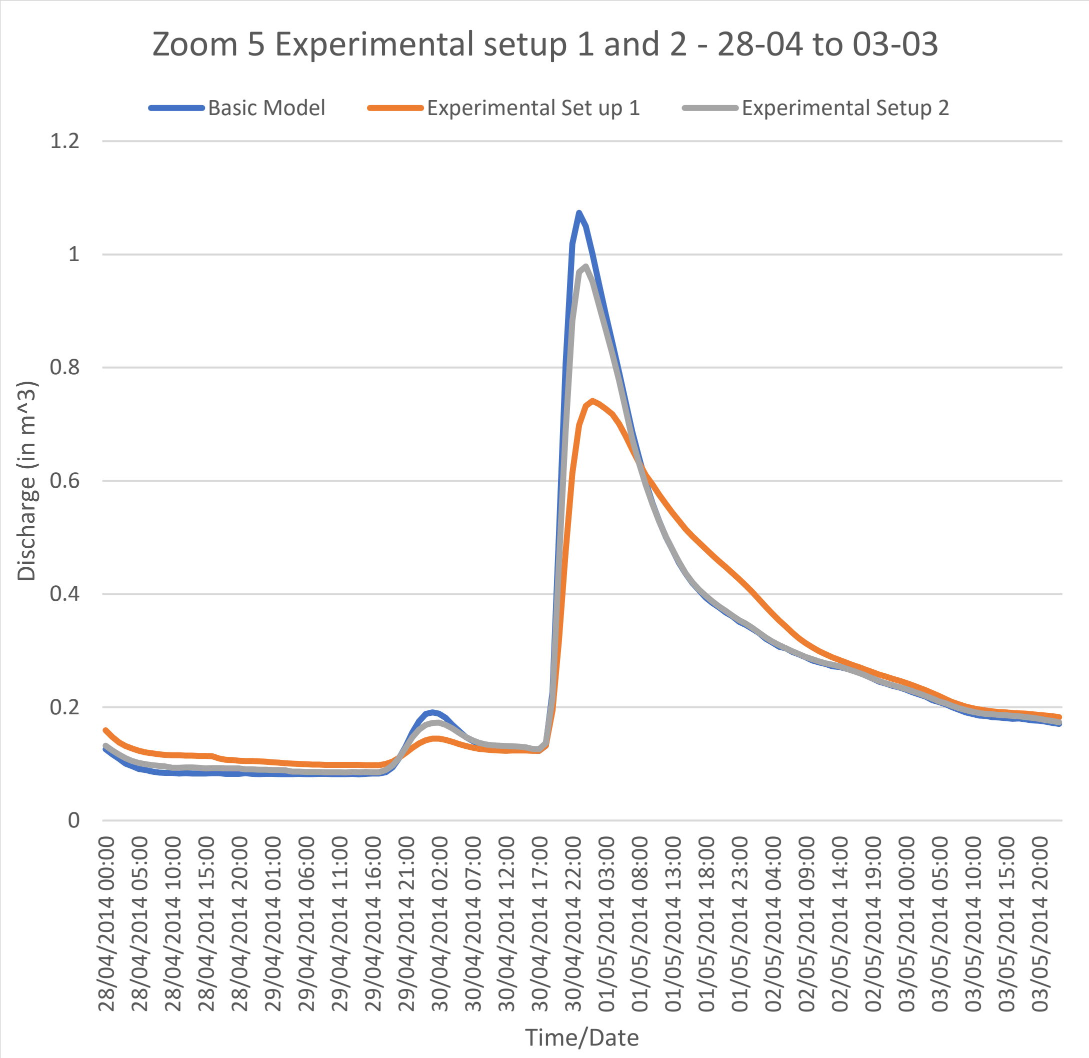


Figure 25 - Zoom in on the period of the 28th April to the 3rd May

As visible in the reduces the second configuration the first peak around the 29th April with 11% relative to the discharge, which is less than the half of the reduction of the first configuration (27%). The maximum discharge during the event at the 30th is reduced by 15% in the second configuration and 27% by the first setup. Also, a small increase of the discharge after the event is visible with an average value of 1% is observable in the 4 days after the rainfall event.
In the high-water scenario, both configurations operate in the same manner under more water volume. This means that the effectiveness of the measures concerning the storage effect decrease with more water volume. If the storage volume of the measures is reached, the storage effect is neglectable for both configurations. This relation is supported by the RMS deviation of 0.00903m^3/s during the high-water scenario which is five times smaller than the RMS deviation of the first configuration.
It can be concluded that the second configuration acts as the first, but the effects occur on a smaller scale since fewer measures are modified. This effect is enhanced by the fact that the measure which is modified in configuration 2 (Category 3 and 4) are mostly focused on the conservational effect and do not achieve considerable storage effect.

Comparison experimental setup 1 and 3

When comparison the first and the third category the first observation is that the discharge pattern follows each other with a close distance over the period of the main scenario. This is visual observable in Figure 26 below. A more detailed version of the graph is presented in

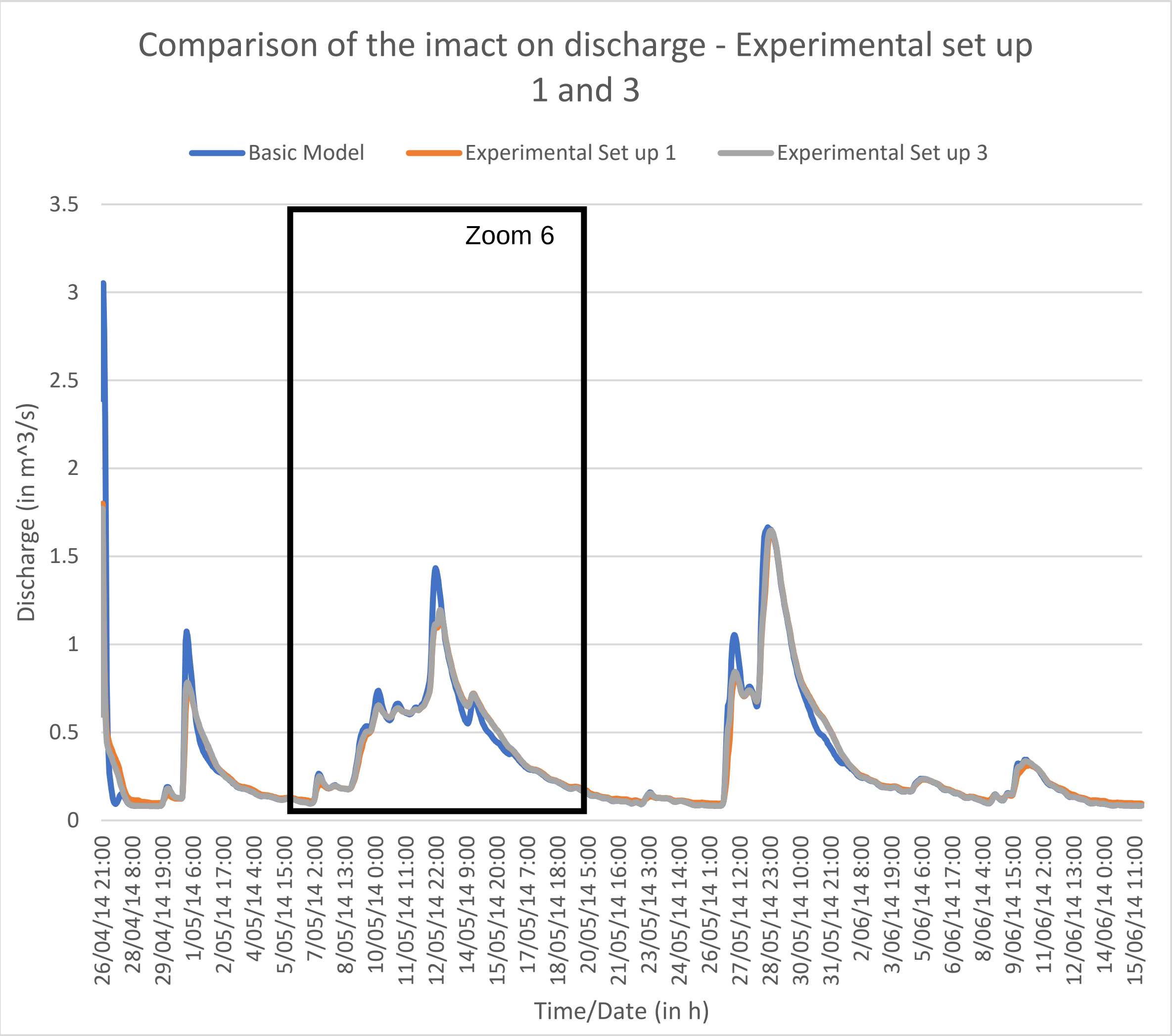


Figure 26 - Comparison between experimental setup 1 and 3 – The Main scenario

The visual similarity is supported by the RMS deviation for the third configuration which is 0.0483m^3/s and therefore 30% smaller than the deviation of the first case during the main scenario. While a lot of the effect that appears in case 1 as the flattening of the maximum discharge also happen, is the discharge after the rainfall events lower in the third case than in the first configuration. The reason for that is that nearly no water is temporally stored and therefore the volume is not discharged over a longer period. A zoom on the rainfall event around the 13th is given by Figure 27 below. It is certain that temporal storage also occurs during the simulation f the third configuration since an increase in discharge is visible in the 4 days after main rain events. This is not explainable considering the design difference of the implemented measures. Still, the difference in the dataset of configuration 1 and 3 are visible if looked at in detail.

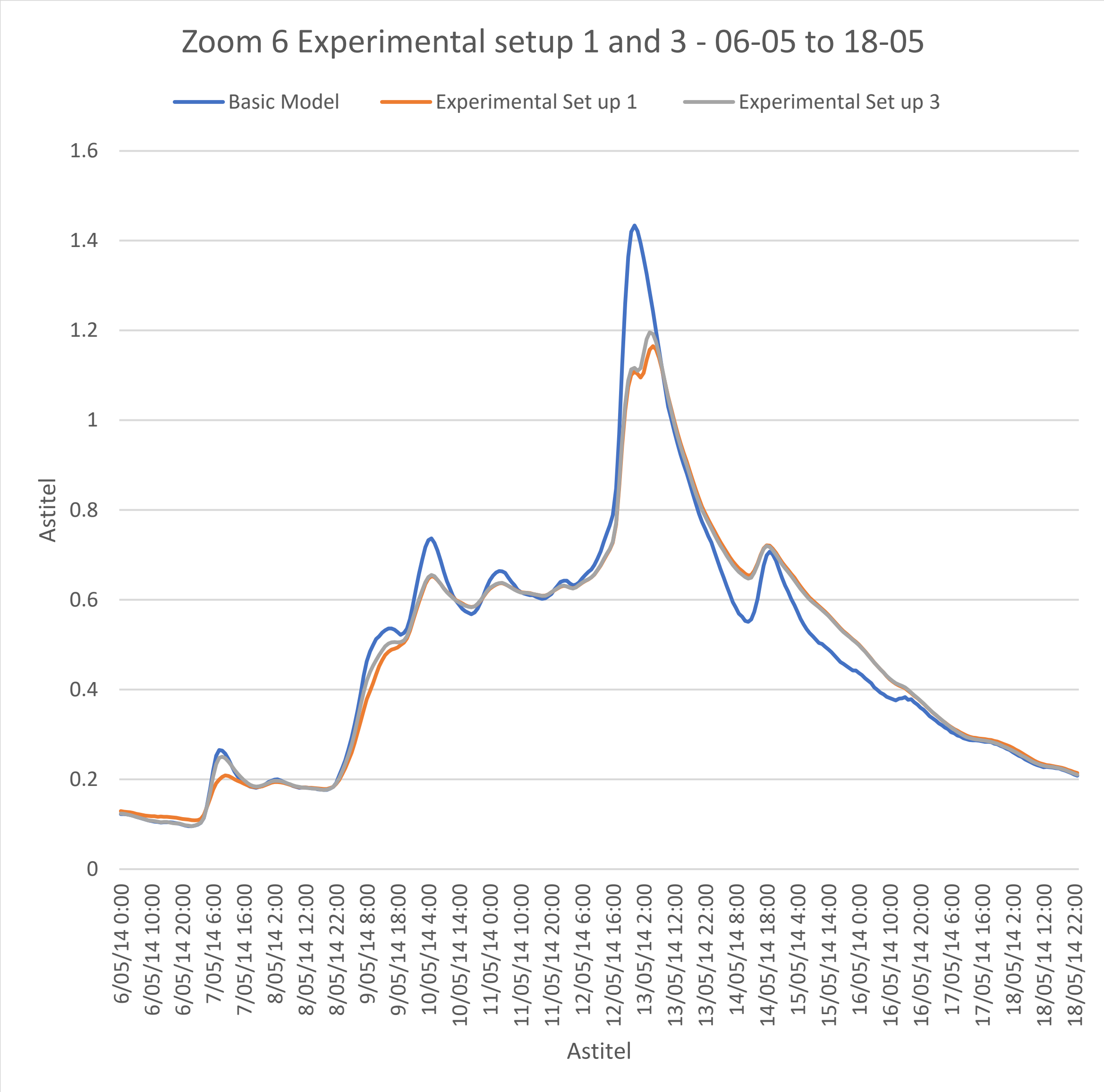


Figure 27 - Zoom in on the rainfall event surrounding the 13th May

As Figure 27 shows are their only a small difference in the two datasets of the of configuration 1 and 3. The clearest difference is observable during the small rainfall around the 7th May in the morning hours. This small rainfall peak gets nearly completely flatten out by the first configuration with a relative reduction of the peak by 33% while the third configuration only reduces that peak with 8%. After that event, the differences in the discharge pattern get small until the maximum discharge of the event is reached on the 13th May. At the maximum discharge, the third configuration reduces the peak with 12% while the first configuration flattens the discharge with 13%. Further is a small difference in the discharge pattern between case 1 and 3 visible after the main rainfall events. This difference increases if the total discharge in the system increases. This is true for both the continuous increase and the reduction of the discharge. How smaller the total discharge how bigger the relative difference between configuration 1 and 3. By observing this relation it logically concludes that the difference during the high-water scenario is smaller than in the main scenario. This conclusion is enforced by the RMS deviation of the third configuration of 0.0461m^3/s which is only 2% lower than the RMS deviation of the first configuration during the scenario high-water scenario. Therefore, the third configuration shows the same effects as the first configuration while the bigger difference between the configuration increases if the total discharge of the system decreases.

Comparison between Experimental configuration 2 and 4

While comparing the configuration to each other the visual comparison makes two different grades efficiently clear. While case 1 and 3 are impactful on the discharge pattern cases 2 and 4 are less impactful. To see the difference in effect from both cases 2 and 4 these cases will be compared in this part. The visual observation shows that there is a small difference between the two datasets. This is supported by the RMS deviation to the basic model of 0.00501m^3/s during the main scenario, which is 50% of the difference compared to case two. This difference in the scenario is shown in Figure 28. A more detailed version of the graph is given in 10.12.

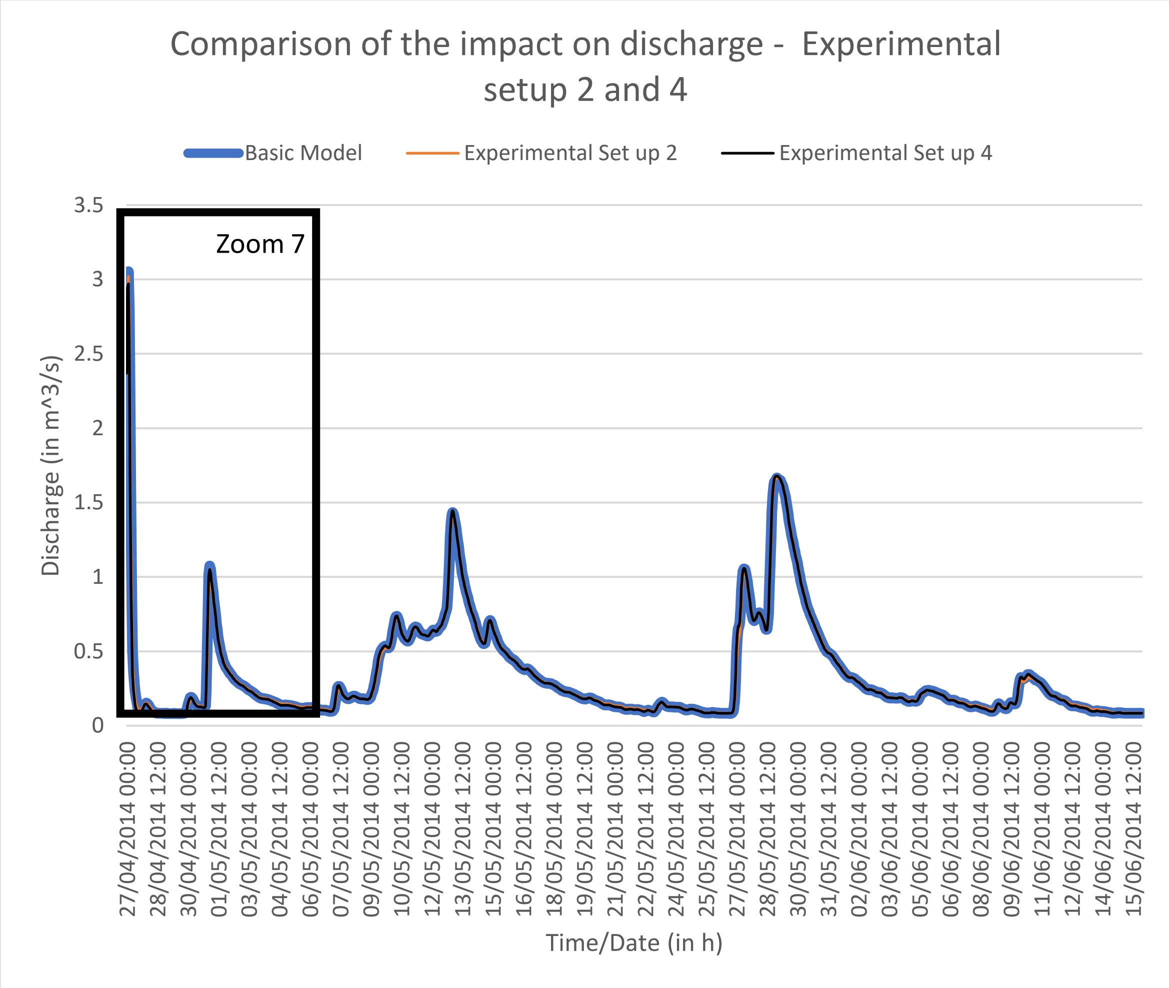


Figure 28 - Comparison between experimental setup 2 and 4 - the Main scenario

As visible in Figure 28 is the difference between the data set small. The same is true if the difference to the basic model is observed. If zoomed in on the rainfall event it gets clear that the second configuration can cope the peak discharge during the rainfall scenario more effectively than the fourth configuration. This can be seen in the rainfall event around 13th which is presented in more detail in figure

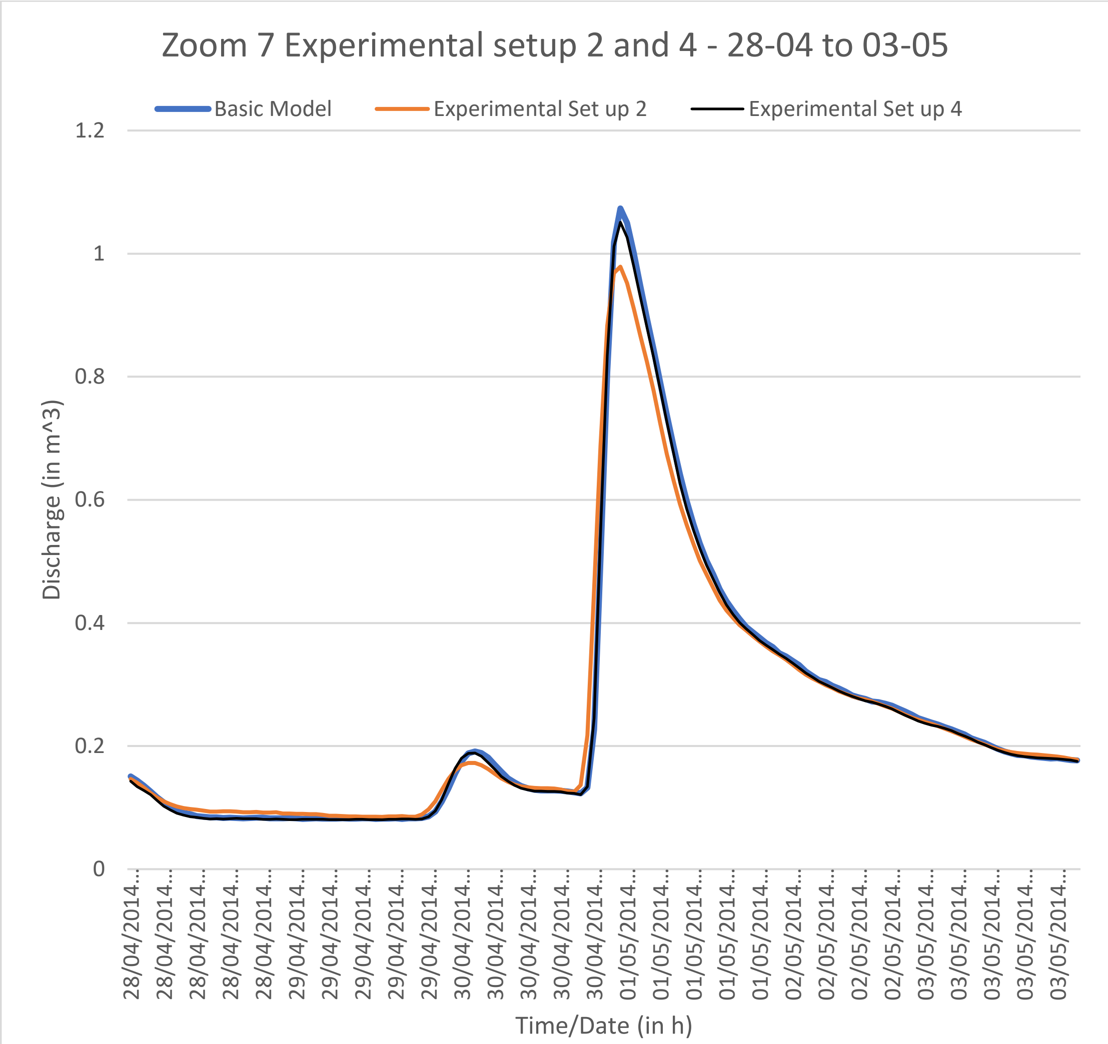


Figure 29 - Zoom in on the rainfall event between 28th April and 3rd May - Experimental setup 2 and 4 - the Main scenario

As visible in Figure 29 is the second configuration of measures able to decrease the peaks of the maximum discharge during the small rainfall event around the 30th April by 11% and the main discharge peak at the 1st May by 15% relative to the total discharge. The fourth configuration is only able to reduce the peak by 3% on the 30th and by 0.2% on the 1st May. It can be concluded that the overall effect of the fourth configuration on the discharge pattern is small and do not offer a real advantage considering the coping of high-water issues. The measures are not able to affect the discharge pattern in a significant way.

6.2 Results for the water height indicator

The water height in the trenches can be used as an indicator if the modified measures are beneficial against the moisture-deficit in the soil and if the drainage resistance of the trenches can be increased and therefore more moisture can be stored within the soil. The results of the water height in the trenches is measured 1m behind the implemented measure at the locations presented in Figure 14. The results section starts with a brief analysis. After that, a short conclusion is given for different locations. The first location that is analysed is the measuring location for the trenches under the maintenance of the waterboard. After that, category 1, 3 and 4 are analysed. As chapter 5.2 explained is the model only capable to run the simulation with an initial water height of 0.8m. Due to this circumstance, the conservation reservoir behind the modified measures is filled in the beginning of the study. This is justified by the time periods that are observed since the main scenario starts in spring and therefore at the end of the wet period of the hydrological year. The same is true for the high-water scenario which simulates the context of a wet period.

6.2.1 Results for the trenches under maintenance of the waterboard

As the visual observation of the results of the measuring location shows, share both experimental setups 1 and 3 the same features, while configurations 2 and 4 are close to the water height of the basic model. This is shown in Figure 30 below.

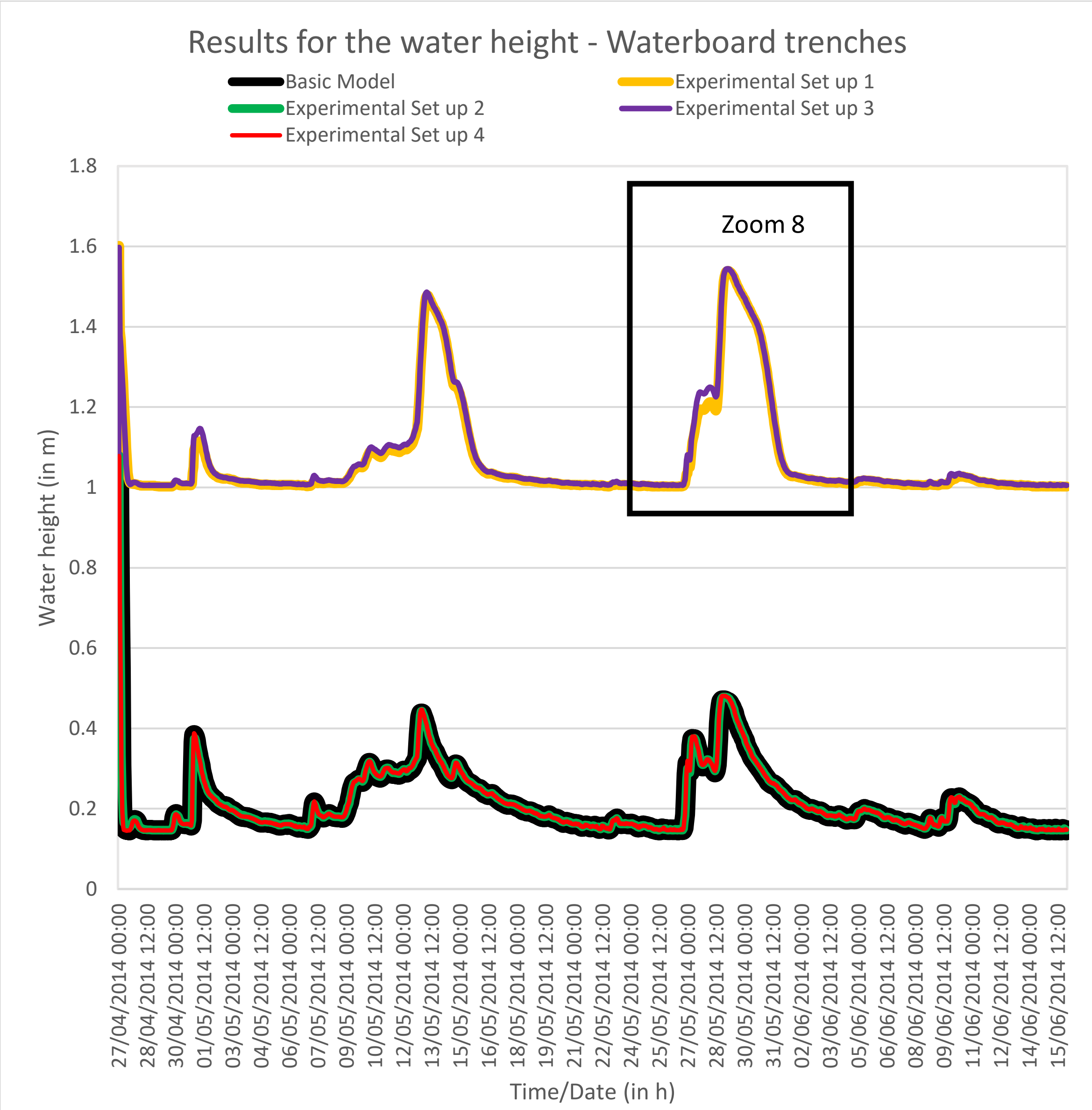


Figure 30 - Results for the water height for the measuring location at the trenches maintained by the waterboard

As the figure shows is no significant difference between the basic case and configuration 2 and 4. This is logical since no measures are modified in these cases at this measuring location. The first and third configuration shows an increase in minimal water height of 1m. Further, deformations of the water height are visible which shows a delay in the discharge pattern in configurations 1 and 3. While the results for case 1 and 3 looks similar there is a significant difference within the height measures around the 28th May. This is shown in Figure 31.

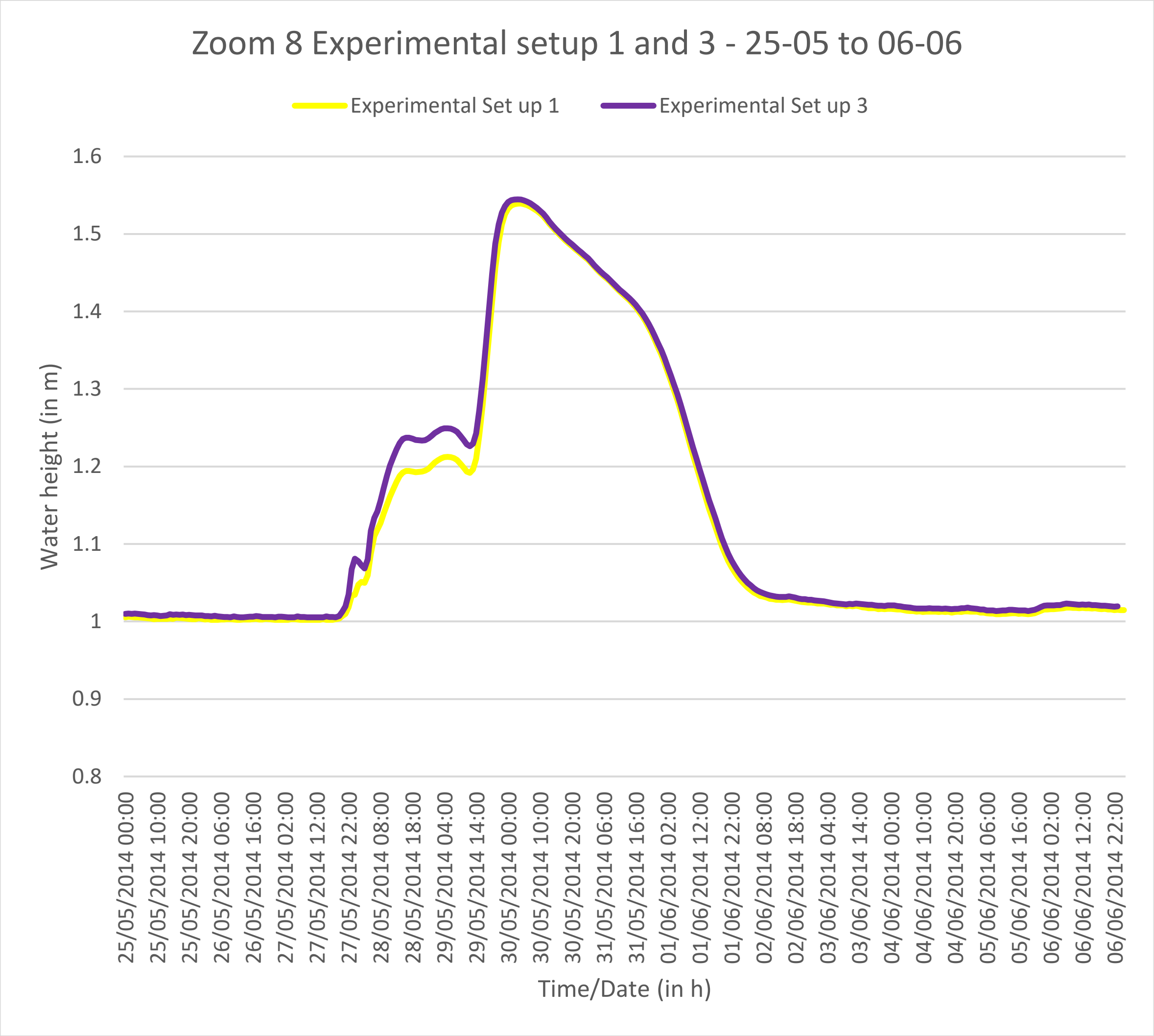


Figure 31 - Zoom in on the event around the 30th May - Experimental setup 1 and 3 – the Main scenario

As Figure 31 shows there is a difference in water height between the two configurations at the measuring location. This difference of 4cm is caused by the difference in discharge since the discharge hole design can discharge higher amounts of water in the at the same water height and the discharge of the trenches of other categories is also reduced in this configuration. Still, most of the time the datasets of configuration 1 and 3 are similar during the simulation with a small difference between them. In general, experimental setup 3 is on average 1cm higher than the water height in experimental setup 1. This is again caused by the higher potential discharge of the modified measure and the delay of the water due to the other modified measures in other categories. The similarity also shows that the water is in a constant state of overtopping and therefore the reservoir behind the culvert/weir is always filled. For the conservational effect, this is a positive influence since an increase in water height means that water can be conserved, and this has advantages effects. The design of the measures implemented in configuration 1 focus on the storage effect for this location. It can be concluded that the storage effect is not significantly present in configuration 1. The same relations occurred during the high-water scenario.

6.2.2 Results for the trenches of category 1

The results of the measuring point of category 1 contain a measuring error since the default water height for the measuring point is about 70cm higher than the position of the zero marks. This is caused by the noise within the topographical data that is used in to create the model. This affects the results in a way that the conservation reservoir is not existing, and the storage reservoir is smaller than usual. Still, the remaining 30cm of storage volume show a good representation of the storage effect. The results are presented in Figure 32 below.

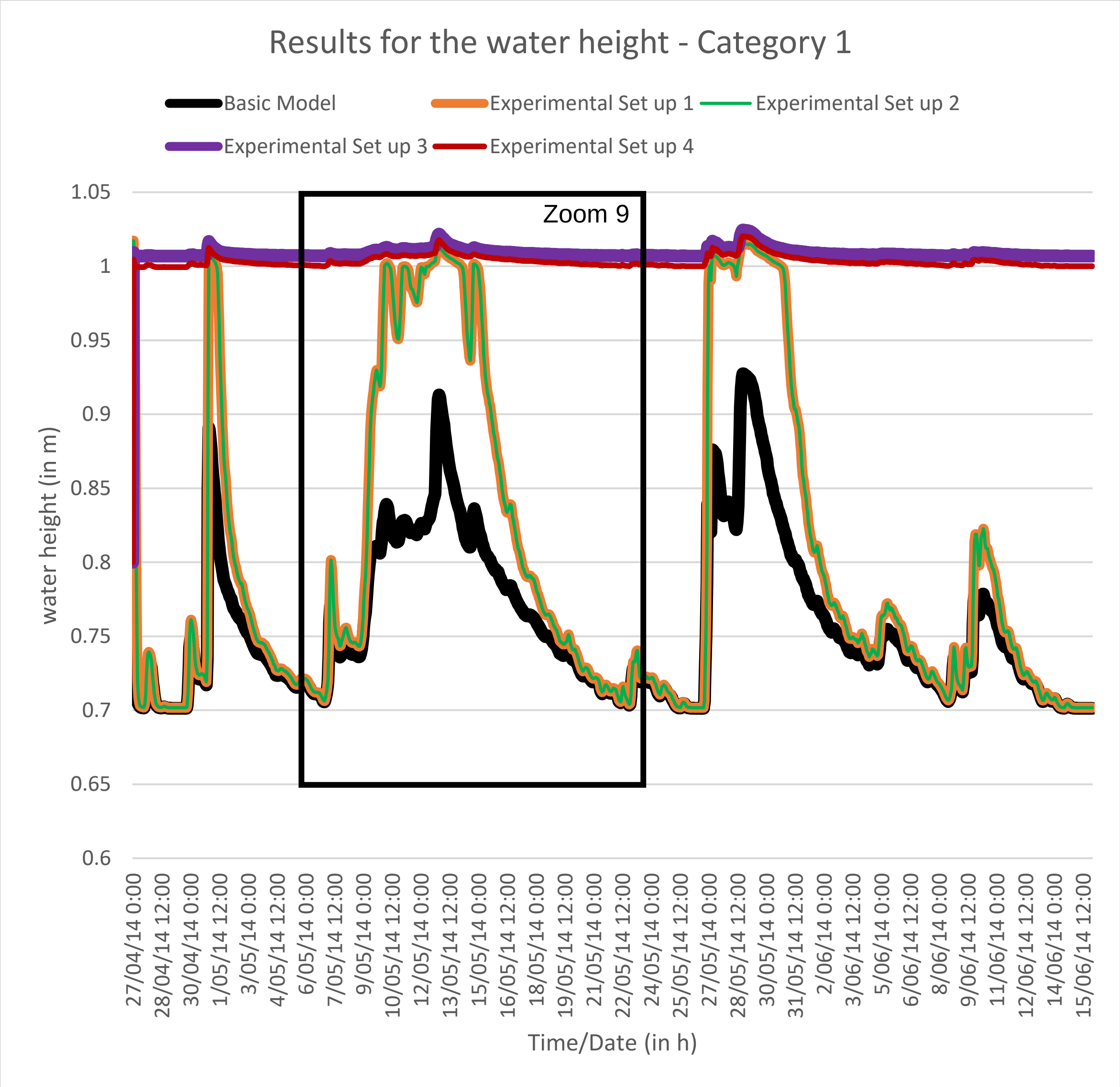


Figure 32 - Results of the measuring location for the first category

Figure 32 shows a difference for the water heights in all configurations compared to the basic model. At this measuring location configurations, 1 and 2 share the same characteristics in water height. The second and fourth are highly configurations are highly correlated but differ from configurations 1 and 2. This is logically supported by the difference in design that is implemented in the different cases. In case 1 and 2 increase of the water height behind the culvert/weirs is visible which refers to the storage reservoir in behind the implemented measure. During the increased inflow the water height stores up to the overtopping level at 1m. Since the discharge surface of the cross-section is heavily increased after this level the water height remains nearly stable and do not exceed the height of 1metre by more than 2cm. This storage effect is made visible in

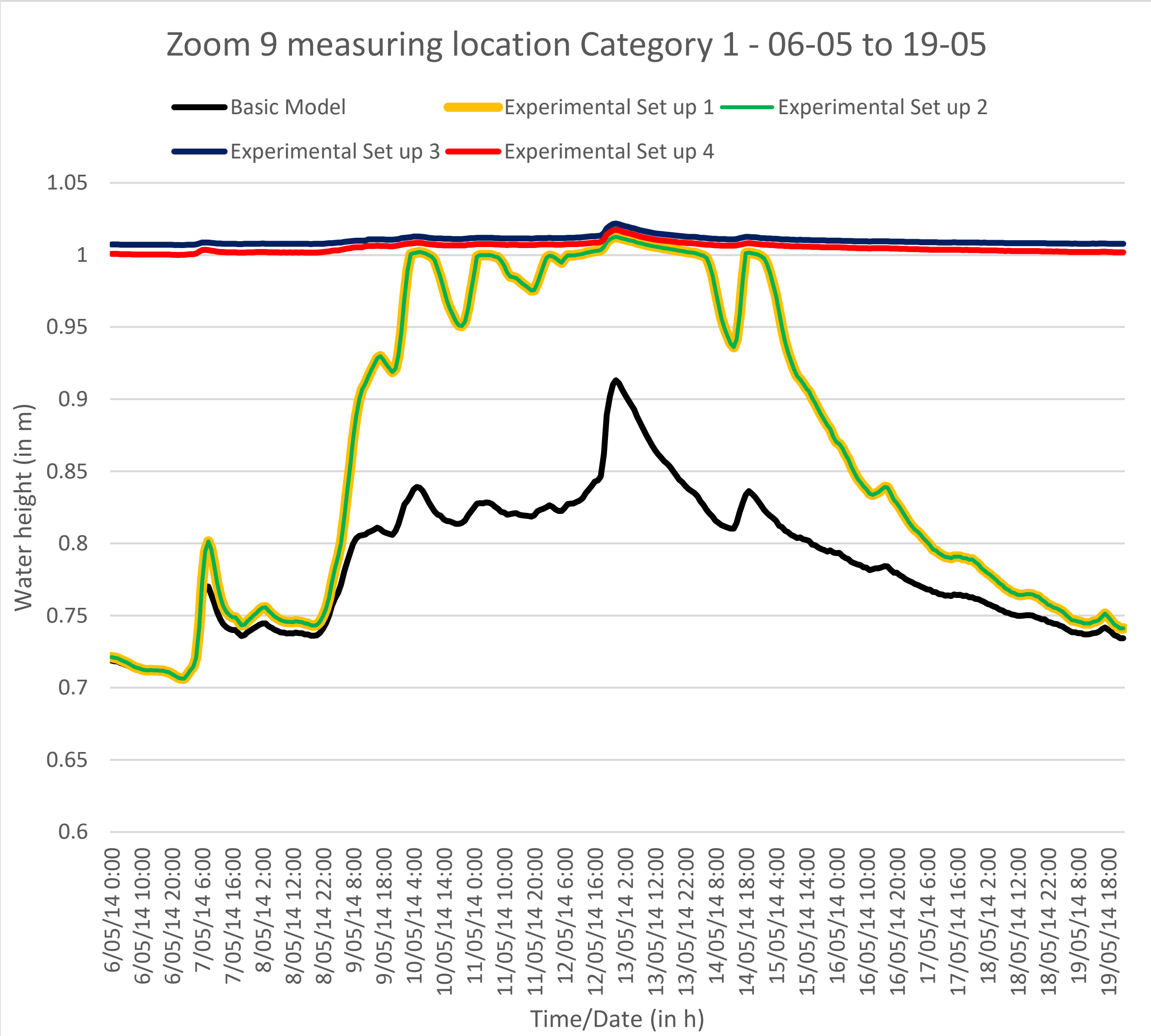


Figure 33 - Zoom in on the rainfall event around 12th May – The main scenario

The visual observation shows that the water height of configuration 1 and 2 (green and orange line) start to touch the 1m level at the 8th in the evening. As the water inflow decreases the water height behind the measure also decreases in a constant manner. This can be referred to like the effect that the temporally stored water is discharge until the maximum inflow exceeds the discharge capacity of the discharge hole. Then the water height starts to rise again until overtopping occurs. After the main rainfall event at the 13th water is held back by the culvert/weir until the morning of the 14th where a smaller amount of water is discharged again. After the morning of the 15th, the inflow of water falls below the discharge capacity and the temporally stored water is then discharged into the water network in a constant manner.
Configurations 3 and 4 do not show a storage effect at this measuring location but an increase of the water height of minimum by 0.3m and an increase of the average water height by 20cm which is beneficial for the moisture-deficit in the soils surrounding the trenches and the groundwater table. It can be concluded that the storage effect occurs at cases 1 and 2 and the conservation effect is dominant for cases 3 and 4.

6.2.3 Results for the trenches of category 3

The design that was implemented in the category 3 trenches focus on the conservational effect and have a storage height of only 0.2m in configurations 1 and 2. Further is the discharge hole design small so that this storage potential can be used for long term conservation as well. This design choice is visually reflected in the results of the measuring location which are presented in

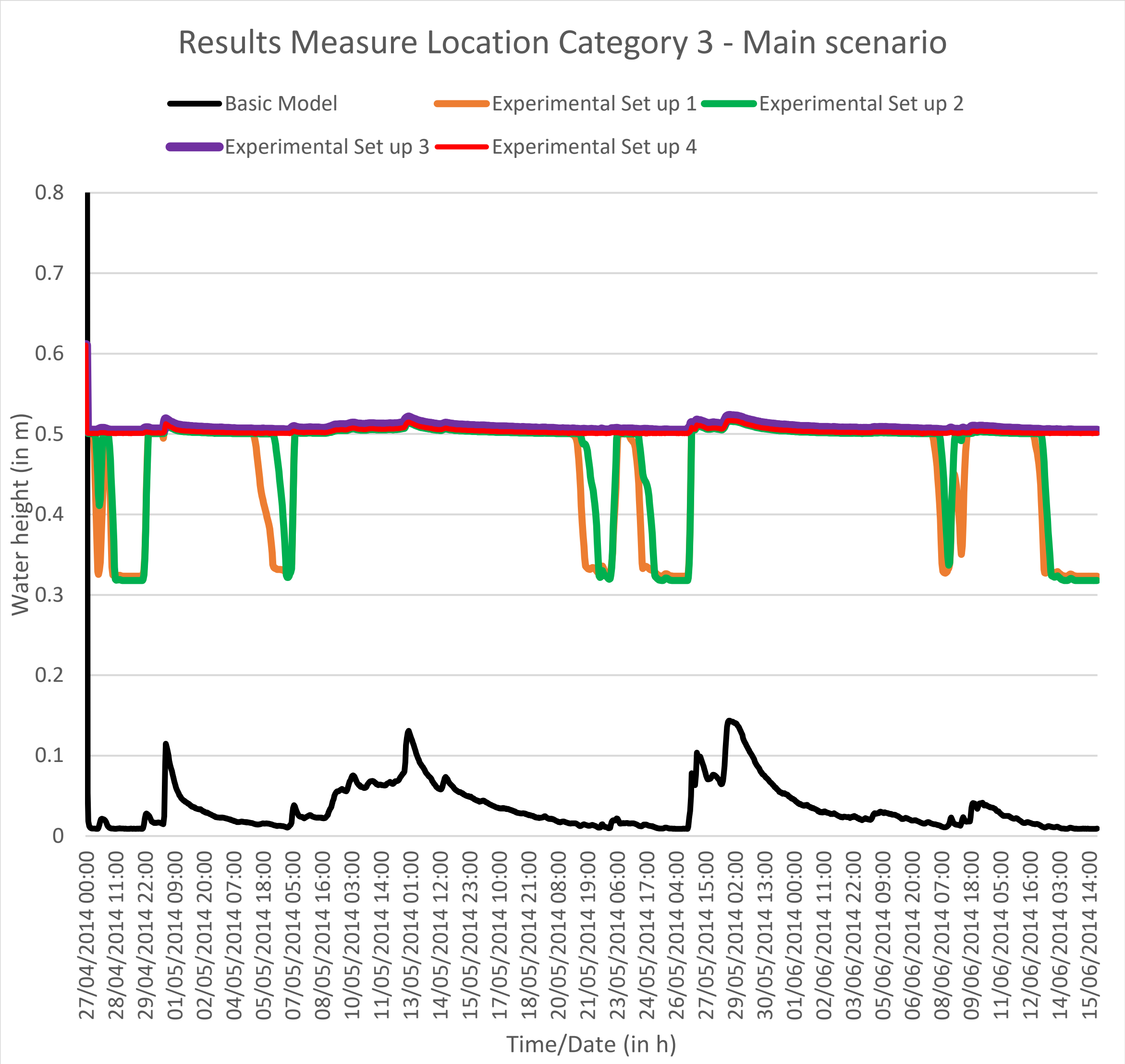


Figure 34 – Results of the measuring location for the third category

As the results show the differ all configuration heavily from the basic model. The minimal water height increases to 0.3m for configurations 1 and 2. Configurations 3 and 4 increase the minimal water height by 0.5m. Further is visible that the storage capacity of the measures is nearly always filled in cases 1 and 2 since the water height (orange and green line) only fall below the overtopping state (50cm) if the meteorological situation is dry over a period of at least 3 days. Small rainfall events as the rainfall at the 23rd May is already enough inflow to fill the storage capacity up again.

It can be concluded that the discharge holes in configurations 1 and 2 are small compared to the inflow that the trenches discharge in most of the time. The same was visible in the high-water scenario. Further storage effect visible in dry periods. Also, can be seen that the measure constantly discharges a small volume of water in dry periods. Configurations 3 and 4 achieve conservation of the water during the period of the whole scenario with an increase of the water height to a constant level around 50cm.

6.2.4 Results for the trenches of category 4

The measures implemented into the fourth category trenches during configuration 1 and 2 are designed to conserve the water up to a height of 0.3m and have a storage capacity of 0.3m above that till the height of 0.6m. This is clearly visible in the results of the main scenario which are presented by Figure 35 below.

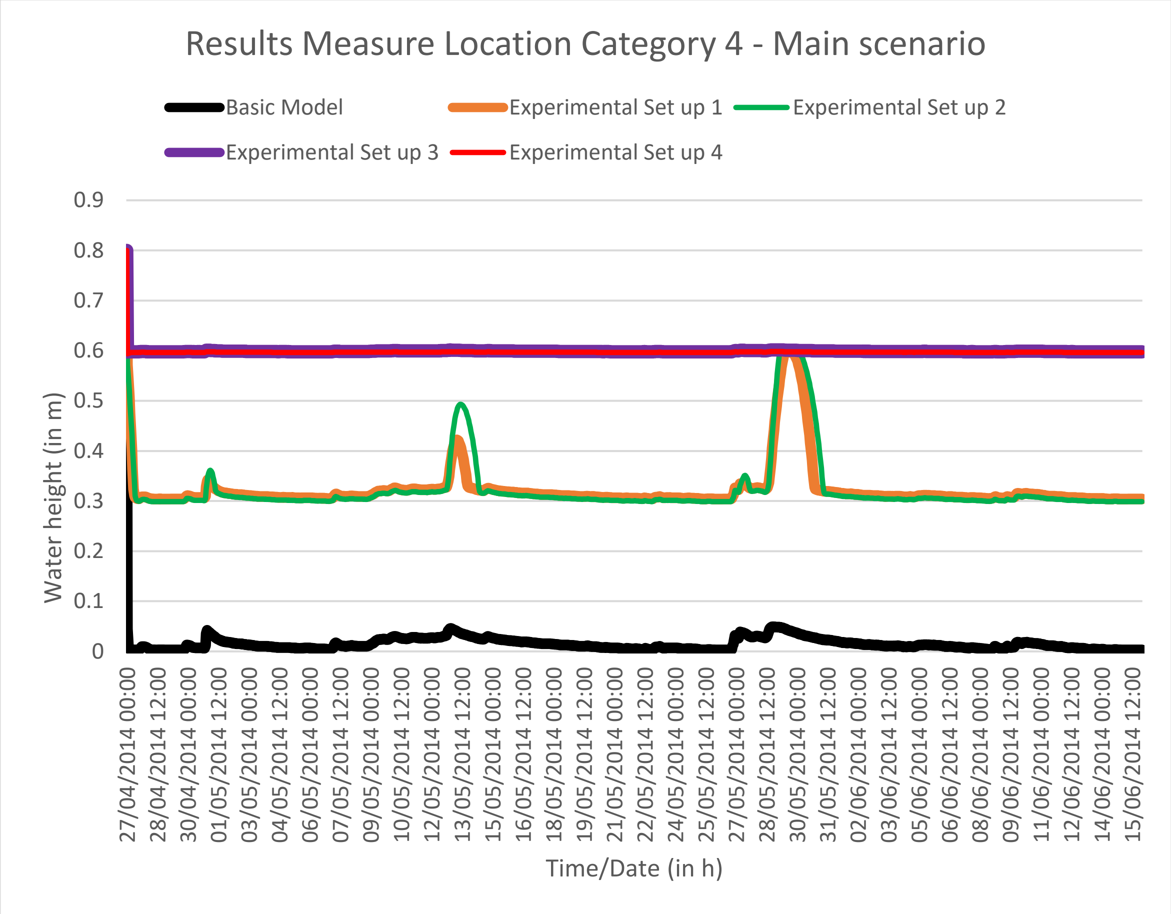


Figure 35 - Results of the measuring location for the fourth category

As visible in Figure 35 is the water height of configurations 3 and 4 constant with a minimum water height of 0.6m. This water height does not exceed the 0.62m and remains constant over the period of the simulation. Configurations 1 and 3 do differ according to the rainfall scenarios. The water height at the 30th April, the 12th May and the 30th May raise significantly above the 30cm height which indicated that the storage potential of the measures is used, and water is temporally held back. The water height is in a state of overtopping during the rainfall event of the 30th May where the water height raises above 0.6m. Further is a difference in water height between the 1 and 2 configurations visible which indicated that interaction with the increasing water height in the trenches under maintenance of the waterboard happens.
In conclusion, the storage effect of configurations 1 and 2 is clearly visible for that during strong rainfall events. For configurations 1 and 2, the implemented design is optimal since the storage effects are clearly effective at the measuring location. Further is the conservational effect in all configurations visible since the minimal water heights in all configurations is increase by the stated values.

7 DISCUSSION

This chapter of the report reflects and discusses the choices taken to obtain the results to answer the question of what impact pinch culverts/weirs have on the water network of the waterboard Vechtstromen. The question was focused on the issues of moisture-deficit in the soil and extreme rainfall scenarios.
The first aspect is that will be discussed is the choice of the study area related to the research question and if the area is suited to as study object to obtain valid results. After that, the methodology and the modelling process is reflected, and the design choices are evaluated. After the general structure of the study is discussed the results will be concluded and discussed under the perspective of current research for these issues. In chapter 8 a conclusion of the discussion is given that summarises the essence of this study.

7.1 Choice of the study area

Since resources were limited it was not possible to investigate and study the whole policy area of the waterboard. Therefore, a choice for a study area was necessary. The choice for the study is was motivated by the requirements that the methodology set in order to be suitable for an area. It was necessary that the area has a monitored discharge that can be convertible to rainfall scenarios. This limited the choice of available areas for a study within the policy region strongly. Further was a hard requirement that the area is affected by the issues of moisture-deficit and extreme rainfall events. These narrowed the options of available study areas. However, the final choice for the area is suited for the chosen methodology and shared the characteristics necessary to do the study. It was representative for the policy area, faced drought issues due to shallow sandy soil types which are presented in over 70% of the policy area (van den Eertwegh, Bartholomeus, Witte, de Louw, & van Dam, 2019) and high height gradients. Also, the area is isolated from hydrological influences which made the modelling process simpler since less external factor needed to be considered. It should be possible to extrapolate the results of this study

7.2 Model and results

Since the implementation of the proposed measure is cost intensive in the real situation and the variability in the application is wide, it was chosen to first do a model-based study on the subject since a model offers convenient variation in the implementation of different designs and configuration without a high financial commitment. The results of this study should give an impression if the measure proposed in this report has a positive influence on the water systems of the waterboard and which configuration is optimal for certain areas.
Since a model is a representation of reality, simplifications were made to achieve a result with the given time and resources. These assumptions and generalisation lead to an inaccuracy within the model when compared to the real situation as the categorisation of the trenches or imported height profile form the GIS-databases. However, the model showed reasonable results during the two testing scenarios when compared to the historical data. Another conclusion with backs up the model is that the study area has a fast reaction time to the applied rainfall events. This is typical for the shallow sandy soil types which are dominantly present in the area (van den Eertwegh, Bartholomeus, Witte, de Louw, & van Dam, 2019). The model aims to answer if the measures implemented in the study have an impact on the problems which are faced today and in the future. To achieve that the model was created as a 1d layout which represents the trenches. That means that flooding planes and interaction with the groundwater are left outside the scope of the study. These relations and interacts are from interest to answer the research, however a model of the surface water can give a first impression of the effectiveness can answer if further research on this subject is sensible.
Since this report is based on a model the results reflect the measures impact on the model. The transferability of the results is dependent on the robustness and reliability of the model and the modelling process. It was not possible to validate the occurring water heights that the model simulates since no data was available in the needed amounts to make statements on the reliability

of the produced data. The same holds for the discharge pattern within the modelled trenches. This says that the discharge distribution of the model is only estimated with the simplification of the Thiessen polygons. During all simulation and the two validation scenarios, the model shows values in reasonable ranges for both indicators. No overtopping or increase in discharge was observed during all scenarios. During the comparison of the model data and the historical data, a significant correlation between the two datasets is present at the outflow location. Since this is repeatable with different independent scenarios of the historical data, it can be concluded that the model acts as a representative simulation for the discharge patterns in the study area at the outflow location where the measurements for the discharge results are taken. The uncertainty of the historical measurements was not controlled in this study since the study will only examine if the measures have an influence and this would also be visual inaccurate rainfall scenarios, however, the shows logical reactions to the data input of the historical measurements and is able to reproduce them to a great extent.

The results of the discharge indicator showed that the measures of different designs can deform the discharge pattern in the study area in a beneficial way. The maximum discharge of the most rainfall events in both scenarios was decreased while the continuous discharge in dry periods increased over time. This effect, the flattening of discharge peaks, is also found in the studies of (van Bakel, et al., 2013) for both implemented designs with an effective decrease of the maximum discharge by 10-30% . These findings are enforced by this modelling study since the discharge peaks were decreased by 4% to 33% in different configurations and during different rainfall events. This is also logically consistent with the applied design of the pinch culvert/weir and this effect is beneficial for extreme rainfall scenarios. However, during the high-water scenario, the weirs are mainly in the state of overtopping and this can lead to an increase in drainage speed since the water flow not over the vegetation of the trenches but over resting water. This can lead to increased discharge as visible in the maximum increase of the high-water scenario. This is an increase in discharge is supported by the findings of the modelling study of (Waterschap de Dommel, 2017) where discharges increased since water flow over the top of weirs. This leads further to local flooding of the areas next to the measures. This can be both beneficial since water could be temporally stored on the surface but also cause damage to the local flooding planes (Waterschap de Dommel, 2017).

The implemented measures are and robust for more than 90% of the years therefore during scenarios that are not in the range of one in 10 years flooding scenarios. In not extreme situation they are able to reduce maximum discharges and by up to 30% and increase the continuous discharge of water in a dry period which is a positive effect against the issues during dry periods (Lerouge, Vranken, Verhoestraete, & Schuwer, 2016). During extreme effects modification of the overrun height can decrease the maximum discharge since the storage volume of all measures can be increased and the storage reservoir can be emptied. Following (van Bakel, et al., 2013) empty LOP and pinch culverts/weir reservoirs are able to decrease maximum discharges by up to 15% if maintained in the right moment. This enhances the effectiveness of the measures during extreme events but also requires third party members to participate and maintain during these events. Another finding of the study is that the numbers of implied measures have a bigger influence on the discharge pattern of the area than the design chosen. This was shown since configuration 1 and 3 shared nearly the same pattern while differing from configurations 2 and 4. It can be concluded that the quantity of implied measures highly influences the deformation on the discharge pattern of an area. Further was concluded that trenches with a bigger cross-sectional dimensional have more potential to be impactful when modified. This is logical since the storage volume of these trenches is higher than the smaller trenches. Further is the water network constructed in a way that smaller trenches drain into bigger trenches, therefore is the water discharge in these trenches higher and more water can be stored (van Bakel, et al., 2013). The difference in the effectiveness of the design is clearly visible when comparing case 2 and 4 to each other.

When comparing case 1 and 3 a difference in storage effectiveness is observable but it is smaller than expected since the third configuration did not contain storage potential as a design feature. During an observation of the model in different scenarios, it was visible that the water redirects through the water network if the water level reaches a certain level. This leads to big temporal storage in the system which then causes the discharge peaks to be flattened. If this effect would occur in the real situation is unclear and no reported research gives information about this effect. This effect needs to be analysed in more detail to enhance the validity of the calculated results. In conclusion, a beneficial effect for the discharge pattern, the flattening of the peaks and the increase in continuous discharge, is visible in most of the configurations and this effect could also occur in extreme events if the measures are properly maintained by the owning parties. Further is the position and dimension of the trench from high influence on the discharge pattern while the design is less impactful in this study. In the end, the number of implemented units also have a high impact on the positive effects on the discharge pattern.

The results of the water height indicator showed that a lot of the measuring locations are not optimised in the configuration of the pinch culverts/weirs since the storage effect properly occurred in at the measuring locations of the first and fourth configuration but was not as present at locations 2, 3 and at the trenches under maintenance of the waterboard. While trends of the effect occurred in all the configurations measuring location 1 and 4 showed the most storage usage. Further is an increase in the water height for configuration 3 and 4 dominant since the design forces the water to rise above the culvert/weir before any discharge can occur. In configurations 1 and 2 the water always filled the conservational reservoir and a conservation effect up to this height could always be achieved. This led to a continuous increase in water height in the trenches. Following (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001) this further increases the drainage and entry resistance of groundwater into the trench. Further has the conservative water the potential to infiltrate into the ground. These effects lead to a potential increase for the groundwater table which is highly beneficial against the moisture-deficit in the soil (Louw & Vermeulen, 2000). An increase in groundwater table was shown by (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001) on a local state which was highly dependent on the type of soil the slope of the trench and other factors. Since this study excludes interactions with the groundwater the water height can only indicate a positive effect. Also is the inflation and the leakage not included in this study. Both factors highly influenced the effectiveness of water conservation in the study of (Louw P. d., Vermeulen, Stuurman, & Reckman, 2001).

8 CONCLUSION

The results of the study show that further research of the subject is sensible and that the implemented measures showed positive effects for both indicators, transformation of the discharge and increase in the water height, in this study. While the study does not include the interaction with groundwater positive effects against the moisture-deficit are only indicated in this study and could not be determined with quantitative certainty. However, the results of the study high imply that a positive effect of the measures on the groundwater table is likely. Since this study will be the first part of a research project on the drought issues in the area it is suggested that the follow-up studies analyse the interactions with the groundwater table in more detail and the positive effects that these measures can offer. Also, the cost-benefit analysis of the measures should be analysed since a big part of the users are third parties that need to buy the measures and economic efficiency is the main motivation for these third parties.
The positive effects on the maximum discharges could be shown with certainty in the model. The measures have the potential to decrease the maximum discharges during rainfall peaks and increase the continuous discharge in drought periods. This is known as the flattening of discharge peaks and highly desired to increase the safety of the water network. This is both beneficial for the waterboard and the third parties. Research to optimise the configurations of the measures in the water network is advised since the results showed that optimum configuration is dependent on the local environment and is not easy to generalise. Not all occurring effects are analysed in detail, therefore, a pilot field study of the effects of the measures in complex water networks is suggested. In the end, the study is a solid foundation for further research on this topic and the results indicate that the measures have a high potential to solve big parts of the problems that the water network of the Waterboard Vechtstormen is going to face in the future.

9 BIBLIOGRAPHY

AHN. (2016). *Actueel Hoogtebestand Nederland.* Provinices van Nederland, Rijkswaterstaat en De Waterschappen van Nederland.

ArchGIS. (2019, April 24). Topographical Map of the Netherlands. Almelo, The Netherlands: Waterboard Vechtstromen.

Artesia B.V. (2013). *Effect knijpstuw Koopmansblikken - Evaluatie veldexperiment.* The Netherlands: Artesia B.V.

Beekman, W., & Caljé, R. (2018). *Doorwerking droogtee van 2018 in Overijssel.* Schoonhoven: Artesia - Water Research Unlimited.

BOFEK. (2012). *BOFEK2012, de nieuwe, bodemfysische schematisatie van Nederland.* Wageningen: Alterra.

Chow. (2019, April 29). *http://www.fsl.orst.edu*. Retrieved from http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm

Cobouw redactie techniek. (2019, March 22). *weekblad.cobouw.nl.* Retrieved from http://weekblad.cobouw.nl/digitaleeditie/2013/5/20130621___/1_08/article11.html

Deltacommissie. (2019). *Deltaprogramma 2019: Doorwerken aan de delta: Nederland tijdig aanpassen aan klimmatverandering Cpt. 4 .* Nederland: Deltacommissie.

Deltares. (2019, April 11). *www.Deltares.nl.* Retrieved from www.Deltares.nl/software: https://www.deltares.nl/en/software/sobek/#features

G.J. van den Born, J. v. (2013). *The Effects of Climate Change in the Netherlands: 2012 Cpt. 5.* The Hague: PBL Netherlands Environmental Assessment Agency.

Goijer, I., Heuven, A., Luijendijk, J., Overbek, M., & Runhaar. (2012). *Zoetwatervoorzieningen Oost Nederland.* Deventer: Tauw.

Google-Maps. (2019, April 23). *Google.com*. Retrieved from google.com/maps: https://www.google.com/maps/place/52%C2%B012'31.7%22N+6%C2%B058'29.9%22E/@52.208805,6.97279,17z/data=!3m1!4b1!4m6!3m5!1s0x0:0x0!7e2!8m2!3d52.2088049!4d6.974984

Google-Maps. (2019, March 23). *www.google.com*. Retrieved from https://www.google.com/maps/: https://www.google.com/maps/@52.7896992,6.8476026,11781m/data=!3m1!1e3!5m1!1e4

Gülser, C., & Candemir, F. (2014). Using soil moisture contansts and physical properties to predict staturated hydraulic conductivity. *Eurasian Journal of Soil Science*.

H20waternetwerk. (2019, June 27). *h2owaternetwerk.nl*. Retrieved from https://www.h2owaternetwerk.nl/h2o-actueel/grondwaterstanden-op-hooggelegen-gebieden-ook-bij-natte-zomer-nog-niet-hersteld

Ipp-Hydro-Consult. (11. April 2019). *www.sobek.ipp-hydro-consult.de.* Von www.sobek.ipp-hydro-consult.de/was-ist-sobek.html: http://sobek.ipp-hydro-consult.de/was-ist-sobek.html abgerufen

Koninkijk Nederlands Metrologisch instituut. (2019, June 6). *https://www.knmi.nl*. Retrieved from https://www.knmi.nl: https://www.knmi.nl/kennis-en-datacentrum/achtergrond/ruimtelijke-verdeling-van-neerslagtrends-in-nederland-in-de-afgelopen-100-jaar

Koninklijk Nederlands Meteorologisch Instituut. (2014). *KNMI'14 - Klimaatscenario's voor Nederland.* The Netherlands: Ministerie van Infrastructuur en Milieu.

Kuijper, M., Hendriks, D., Dongen, R. v., Hommes, S., Waaijenberg, J., & Worm, B. (2012). *Sturen op Basisafvoer - Een analyse van zomerafvoeren in het beheergebied vanwaterschap Regge en Dinkel en hoe daar in de toekomst mee om te gaan.* Netherlands: Deltares.

Lerouge, F., Vranken, L., Verhoestraete, D., & Schuwer, T. (2016). *Veerkracht voor het metropolitaan Kerngebied vanuit het perspectief van ecosysteemdiensten.* Vlaanderen: KU Leuven, Cluster landschap - stedenbouw.

Louw, P. d., & Vermeulen, P. (2000). *Waterconservering en peilbeheer in het BeNeLux-middengebied - Deelrapport 1: Uitwerking slootproeven.* Noord-Brabant: Nederlands Instituut voor Toegepaste Geowetenschappen TNO.

Louw, P. d., Vermeulen, P., Stuurman, R., & Reckman, J. (2001). *Waterconservering en peilbeheer in het BeNELux-middengebied - Deelrapport 3: Bepaling van de effecten van waterconservering.* Zwolle: Provincie Noord-Brabant.

Massop, H. T., van Bakel, P., & de Louw, P. (2017). *Maatgevende afvoer en maaiveldafvoer in Waterschap Vechtstromen.* Wageningen: Alterra, De Bakelse stroom, Deltares.

Massop, H., & Gaast, J. v. (2006). *Intreeweerstand, nader beschouwd - Procesmatig onderzoek naar de relatie tussen de drainageweerstand en de intreeweerstand.* Wageningen: Alterra.

Ministerie van Verkeer en Waterstaat. (1988, Juni). *Handleiding Wegenbouw - Ontwerp Hemelwaterafvoer.* Delft: Rijkswaterstaat.

OECD. (2013). *The Netherlands - Climate change impact on water systems.* OECD Secretariat.

Rezanezhad, F., S. Prince, J., L. Quinton, W., Lennartz, B., Milojevic, T., & Van Cappellen, P. (2016, March 11). *Structure of peat soils and implications for water storage, flow and solute transport: A review update of geochemists.* Retrieved from Elsevier.com: https://reader.elsevier.com/reader/sd/pii/S0009254116301243?token=1C4A45DD15594FEF4B840787105338113439E39EEDA839E7A2E82638F0B07B2C205CE64F77D15D855A701174BDD6081C

Sentis, I. P. (2002). Hydrological Approach to Soil and Water Conservation. *Man and Soil at the Third Millenium*, 65-87.

Sluijter, R., Plieger, M., van Oldenborgh, G. J., Beersma, J., & de Vries, H. (2018). *De Droogte van 2018 - Een analyse op basis van het porentiële neerslagtekort.* De Bilt: Koninklijk Nederlands Meteorologisch Instituut - Ministerie van Infrastructuur en Waterstaat.

Titico. (2019, March 24). *Wikipedia.* Retrieved from https://nl.wikipedia.org/wiki/Knijp: https://nl.wikipedia.org/wiki/Knijp

van Bakel, J., Bardoel, B., Boland, D., Entzinger, N., Menger, I., & van Rens, C. (2013). *Water Vasthouden aan de Bron - Bijlagen rapport deel 2.* Noord-Brabant: Waterschap De Dommel; Waterschap Aa en Maas; Waterschap Brabantse Delta; Provincie Noord Braband.

van Bakel, J., Bardoel, B., Boland, D., Entzinger, N., Menger, I., & van Rens, C. (2013). *Water vasthouden aan de bron - Praktijkonderzoek om wateroverlast te verminderen door bovenstrooms water vast te houden.* Noord-Brabant: Waterschap De Dommel, Waterschap Aa en Maas, Waterschap Brabantse Delta, Provincie Noord-Brabant et Al.

van Bakel, J., van den Eerwegh, G., Worm, B., & Mensink, J. (2019). *Slim peilbeheer in haarvaten van watersystemen met SAWAX-stuw.* The Netherlands: Nederlandse Hydrologische Vereniging.

van den Eertwegh, G., Bartholomeus, R., Witte, F., de Louw, P., & van Dam, J. (2019). *Droogte in zandgieden van Zuid-, Centraal- en Oost-Nederland.* Wagening: KnowH20.

van der Gaast, J., & Massop, H. (2008). *De hydrologie voor het beheergebied van waterschap Velt en Vecht.* Wageningen: Alterra.

van der Schoot, M., Hagenaars, A., & Meijers-Sgroot, I. (2018). *Wel Goed Watergeven.* Noord-Brabant: ZLTO.

Vechtstromen, W. (2019, March 22). *www.vechtstromen.nl.* Retrieved from https://www.vechtstromen.nl/buurt/: https://www.vechtstromen.nl/buurt/

Verweij, W., Wiele, J. v., Moorselaar, I. v., & Grinten, E. v. (2010). *Impact of climate change on water.* Bilthoven, the Netherlands: National Institute for Public Health and the Environment.

Waterschap De Aa, De Dommel et al. (2004). *Van stuw tot gronddam; Vergelijkend onderzoek; Project waterconservering 2de generatie.* The BeNeLux Area: Boerenbond, Aminal, Provincie Antwerpen, Provincie Limburg, Zuidelijke Land- en Tuinbouworganisatie, Noord-Brabantse Waterschapsbond, Provincie Limburg, Provincie Noord-Brabant.

Waterschap de Dommel. (2017). *Feitenrapport wateroverlast juni 2016 - effecten van stuwen op wateroverlast.* The Netherlands: Waterschap De Dommel.

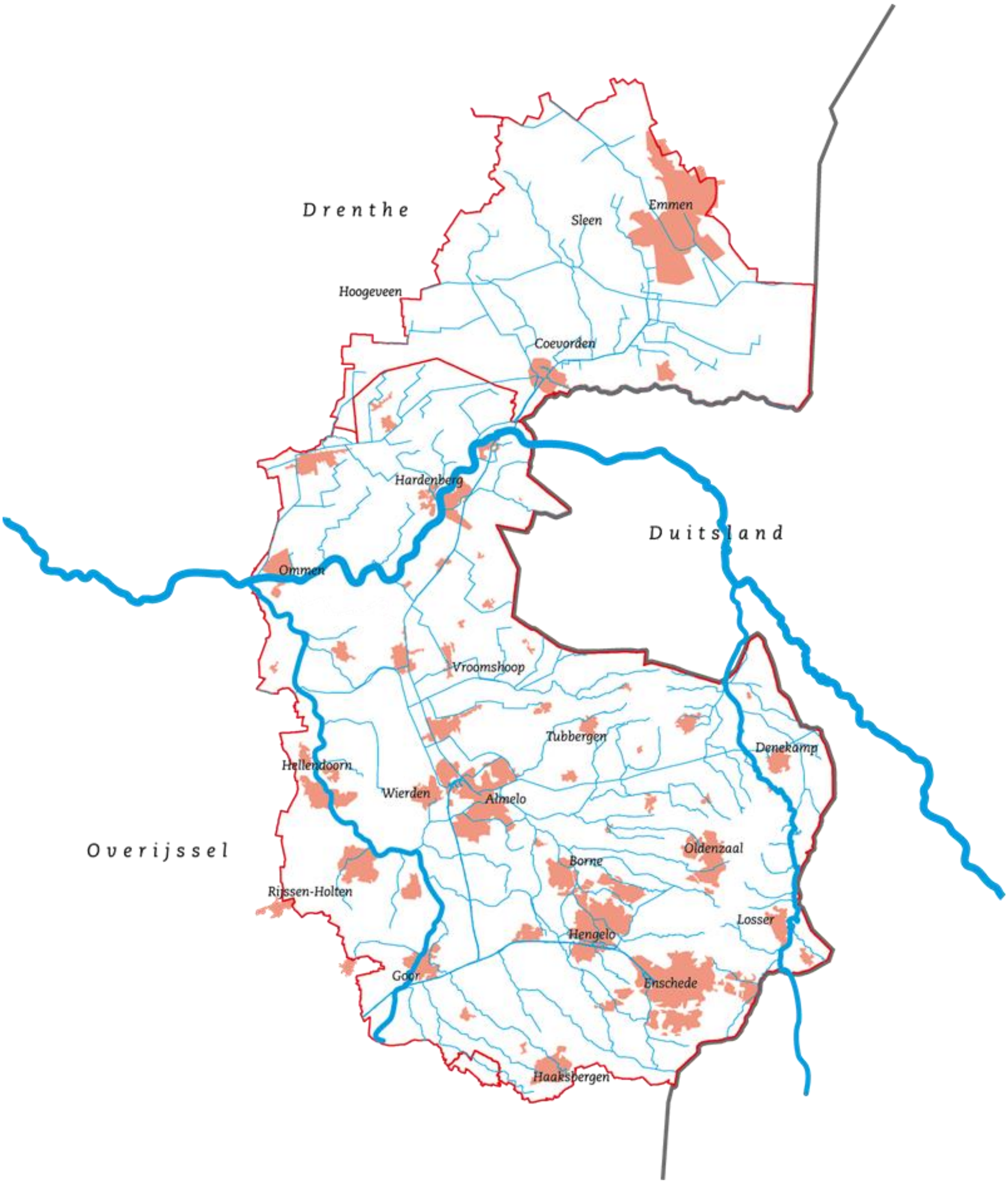
Waterschap Vechstromen. (2014). Detailafwatering. Almelo, Twente, Netherlands.

Wolbers, M. O., Das, L., Wiltink, J., & Brave, F. (2018). *Eindevaluatie Ruimte voor de Rivier.* Utrecht: Rijkswaterstaat.

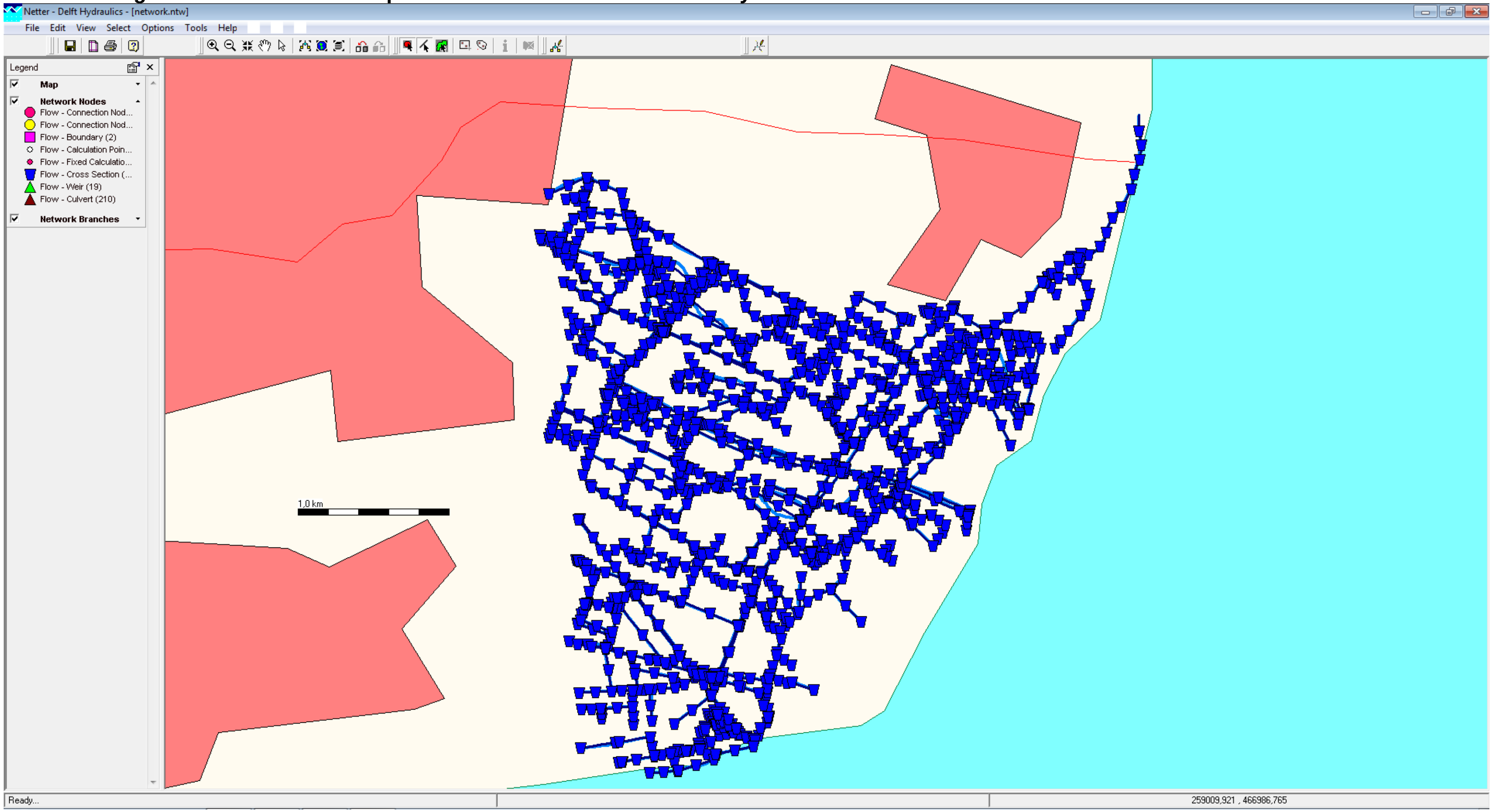
Zwolsman, H., & Senhorst, J. (2005). *Climate change and effects on water quality: a first impression.* Nieuwegein, The Netherlands: RIZA Institute for Inland Water Management and Wastewater Treatment, Kiwa Water Research.

10 APPENDIX

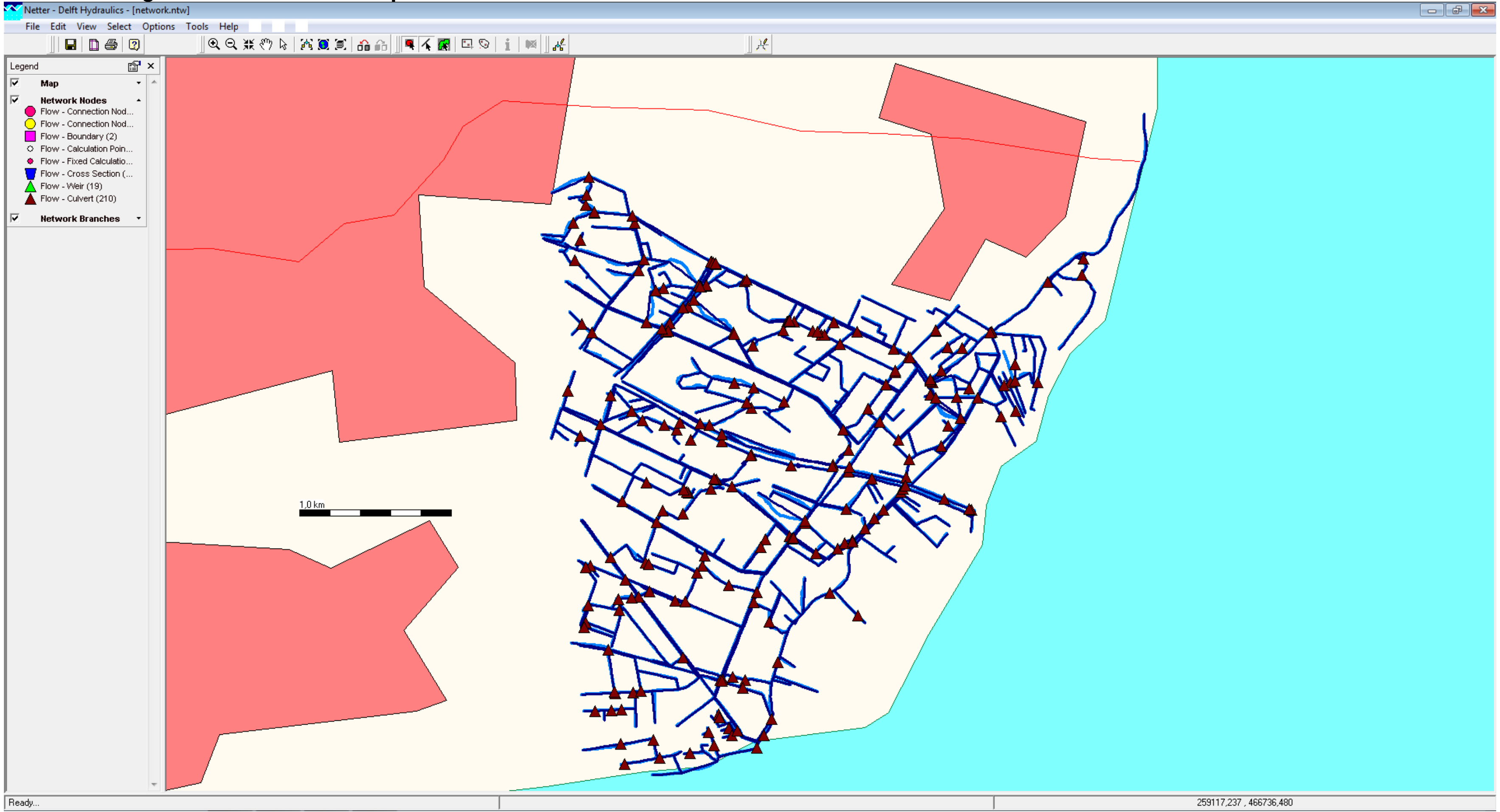
10.1 Appendix 1 – Image of the policy area of the Waterboard Vechtstromen (Dutch)



10.2 Image with all cross section points within the model of the study area

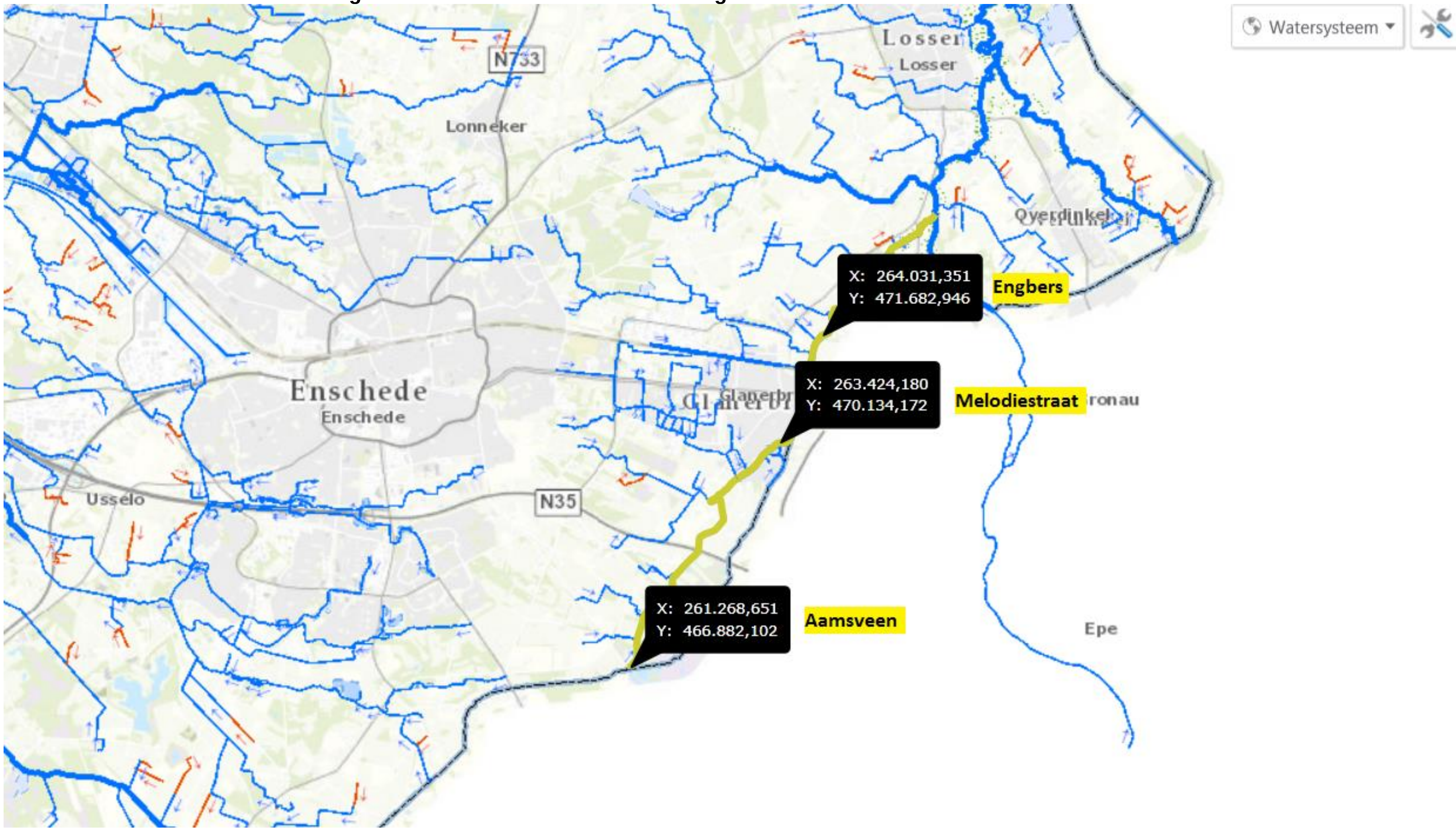


10.3 Image with all the culverts points within the model



10.4 Image of the lateral inflow points within the model

10.5 Location of the measuring locations for the historical discharge data



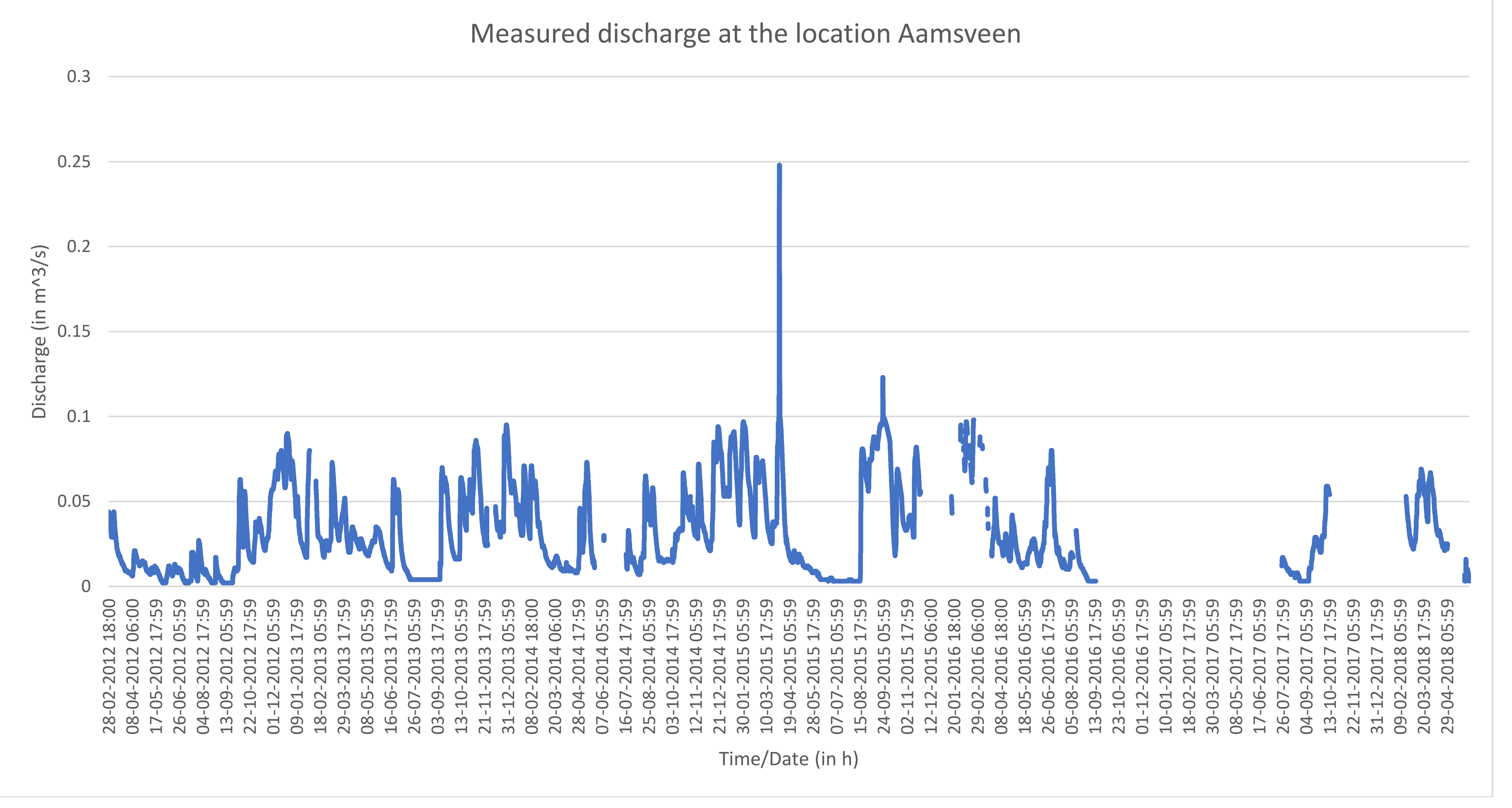
10.5.1 Measure point at the inflow location (Aamsveen)

The measuring point is in the south-east of the study area at the border to Germany. The measuring period starts at the 01-01-2012 and ends at the 31-12-2018. The measurement location marks the inflow of the Glanerbeek into the region. Directly upstream of the measured location is artificial retention storage for the region. This leads to the relation that the inflow of the Glanerbeek remains steady over the time of the measurements. This can be explained through the buffering effect of the retention storage. Also, the Glanerbeek is pinched at the location to allow for a relatively constant inflow of water that is overall from small influence on the outflow measurements (in average 3% of the outflow volume). The dataset of the measurements is presented in 10.6.

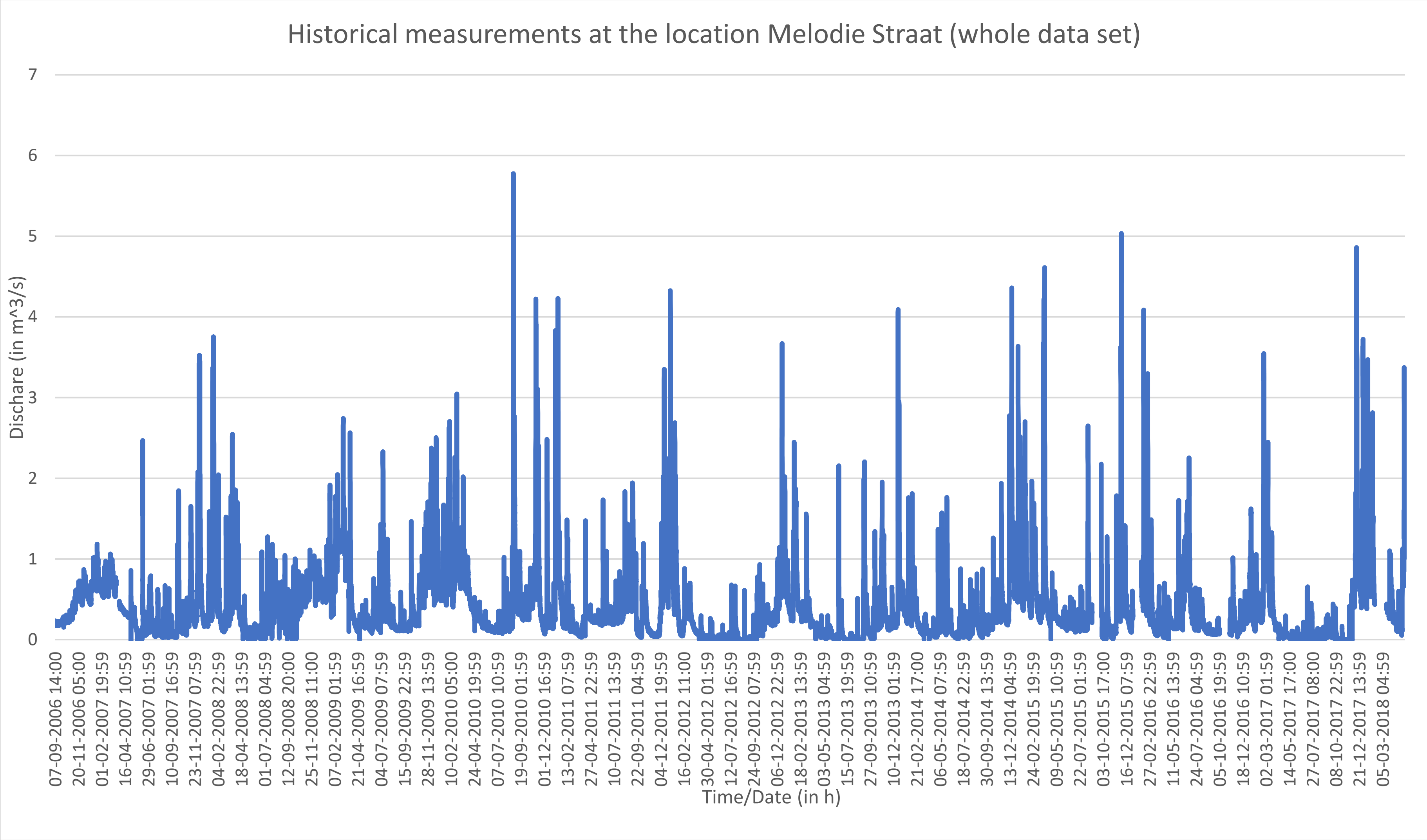
10.5.2 The measurement point at the outflow location (Melodie-Straat)

The measuring point is in the northeast of the study area directly at the inflow point to Glanerbrug, the urban part of the study area in the north. The exact location on a map is given by 10.5. The measuring point collects data of the discharge of the whole study area since the region is isolated from hydrological influences by topographical circumstances as described in the chapter The topography of the study area. The dataset contains measurements of the period d from the 01-01-2006 to the 31-12-2018. It is characterised through the typical discharge pattern for the Netherlands with high discharges in the winter and the begin of spring to lower discharges during the summer month and fall. Exceptions of this are the peak discharges in the summer period due to extreme showers. (Koninkijk Nederlands Metrologisch instituut, 2019). The dataset is presented in 10.7.

10.6 Measurements over 10 years at the Inflow location (Aamsveen)



10.7 Measurements over 10 years at the outflow location (Melodie Straat)



10.7.1 Implementation of the scenario into the model

To implement the rainfall scenarios into the model the design choice was to create drainage surfaces around the lateral inflow points in the mode. The size of these areas was determined with a map form (ArchGIS, 2019) and the Thiessen polygon function. This function separates the area around the points so that the separating line is exactly in the middle of two points. This is done on a 2d plane with respect to all the lateral points within the model shown in Appendix 10.4. The result of the splitting of the area with the Thiessen polygon is presented in Figure 36.

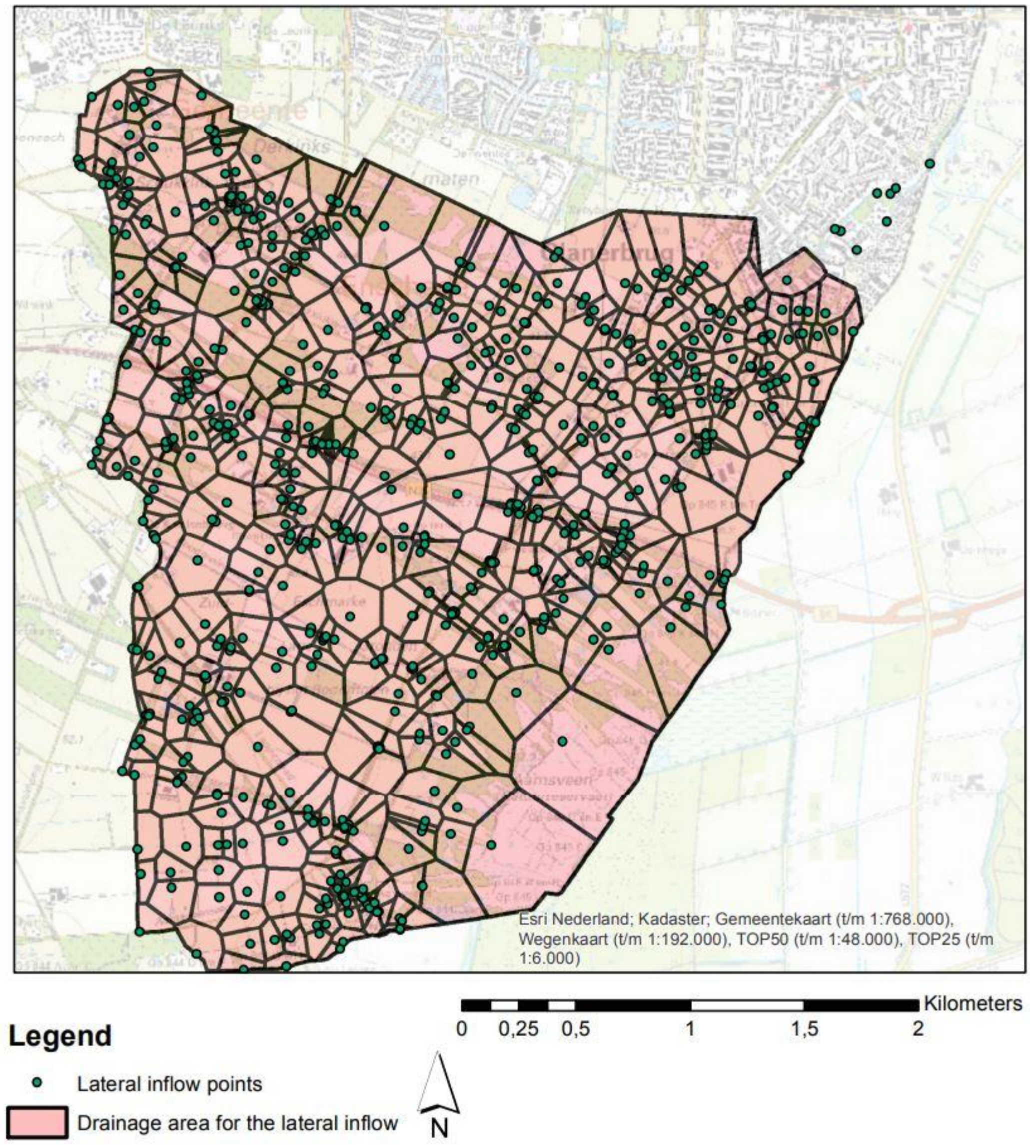


Figure 36 - Drainage surface of the lateral inflow location

The figure shows how the rainfall will be divided on to the trenches within the model. The exact area of the drainage surfaces was determined with (ArchGIS, 2019). To create a rainfall scenario, form the discharge event that was chosen the discharge per second needs to be converted into mm rainfall per hour. This is done following equation 7 below.

$$p_{study\ area} = ((Q_{outflow} - Q_{inflow})/A_{study\ area}) \times 1000 \times 3600\text{sec} \qquad (7)$$

For which:

- $p_{study\ area}$ is the rainfall per hour in mm

- $Q_{outflow}$ is the outflow of the water system in m³/s
- Q_{inflow} is the inflow of water in m³/s
- $A_{study\ area}$ is the surface area of the study region

So, to determine the amount of inflow of water into the system an assumption was made based on the dataset of the measuring point Aamsveen. Since the discharge of the measuring point was not from big influence on the discharge at the outflow and the values of the inflow been relatively stable over the measuring period of 2014 the inflow is modelled as a constant inflow in time.

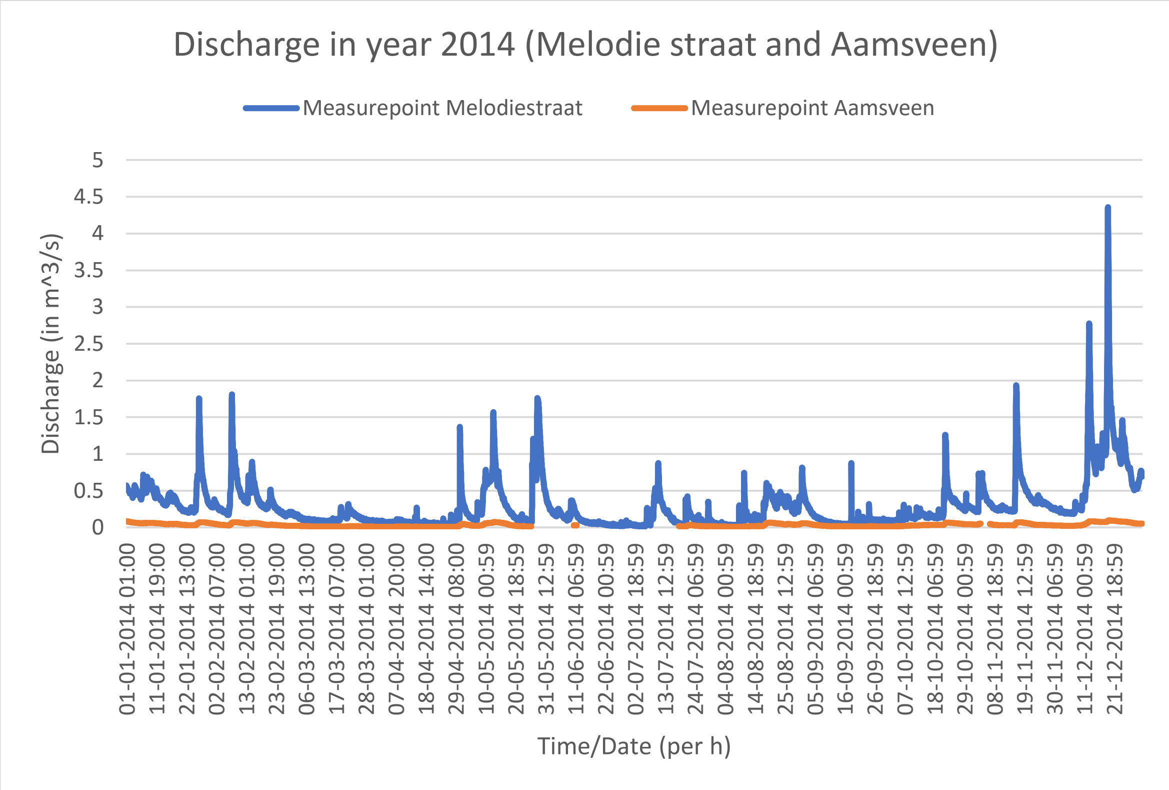


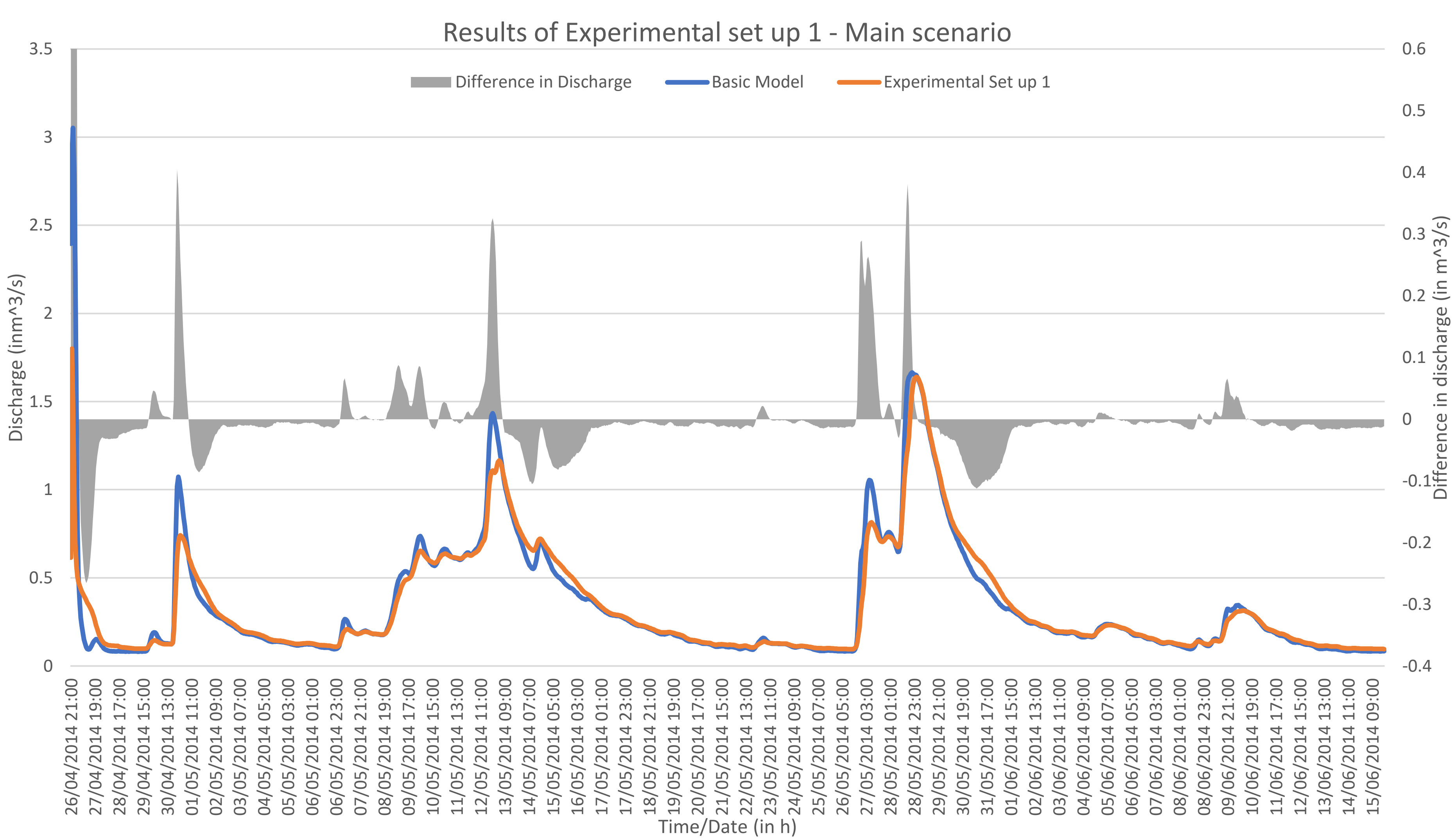
Figure 37 - Measurements of the year 2014 (both measure locations)

The volume of this modelled constant inflow is the median of the measurements of the year 2014. Figure 37 shows both measurements at the two locations related to each other during this period. Following the assumption that the inflow is nearly steady the inflow has nearly no influence on the outflow of the area as visible in Figure 37, the values for measurement of 1m³/s at the outflow location can be recalculated as rainfall by using equation (8).

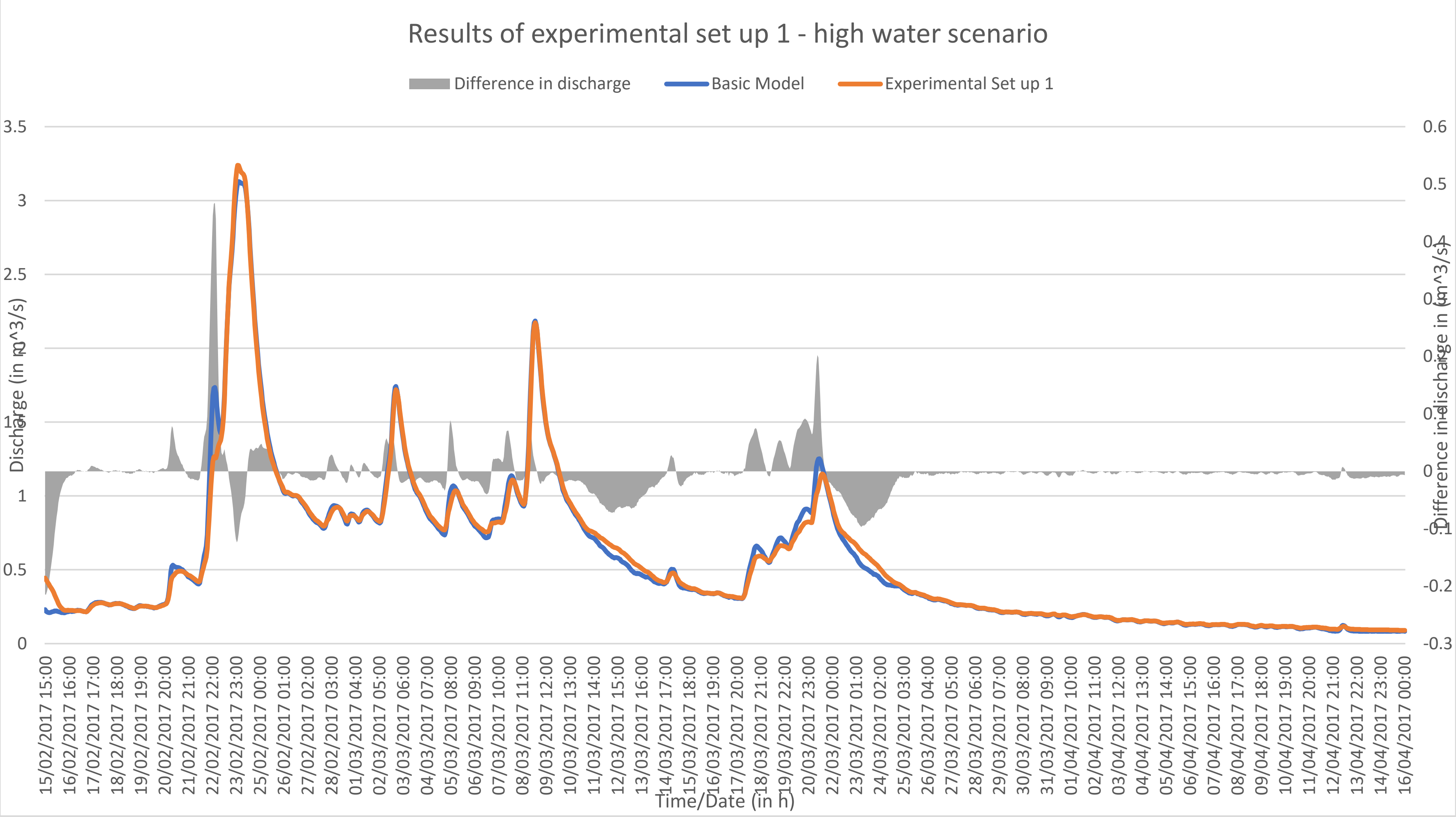
$$p_{study\ area} = \left(1\frac{m^3}{s} - 0.0537\right)/8807268m^2 \times 1000 \times 3600\ \text{sec} = 0.3868\frac{mm}{h} \qquad (8)$$

Since the model cannot fall dry at all trenches the determined minimum discharge needed to be applied to all trenches which were determined with 0.0293m³/s in chapter 5.2.
Therefore, if the rainfall during the measurement causes the discharge to be lower than 0.0293 m³/s the rainfall modified to become this exact minimum to reduce calculation times and internal errors. A rainfall event over the duration of the chosen event was created from the discharge dataset as described above. This scenario was then applied upon the model to show if the system was simulation the discharge as shown in the historical data

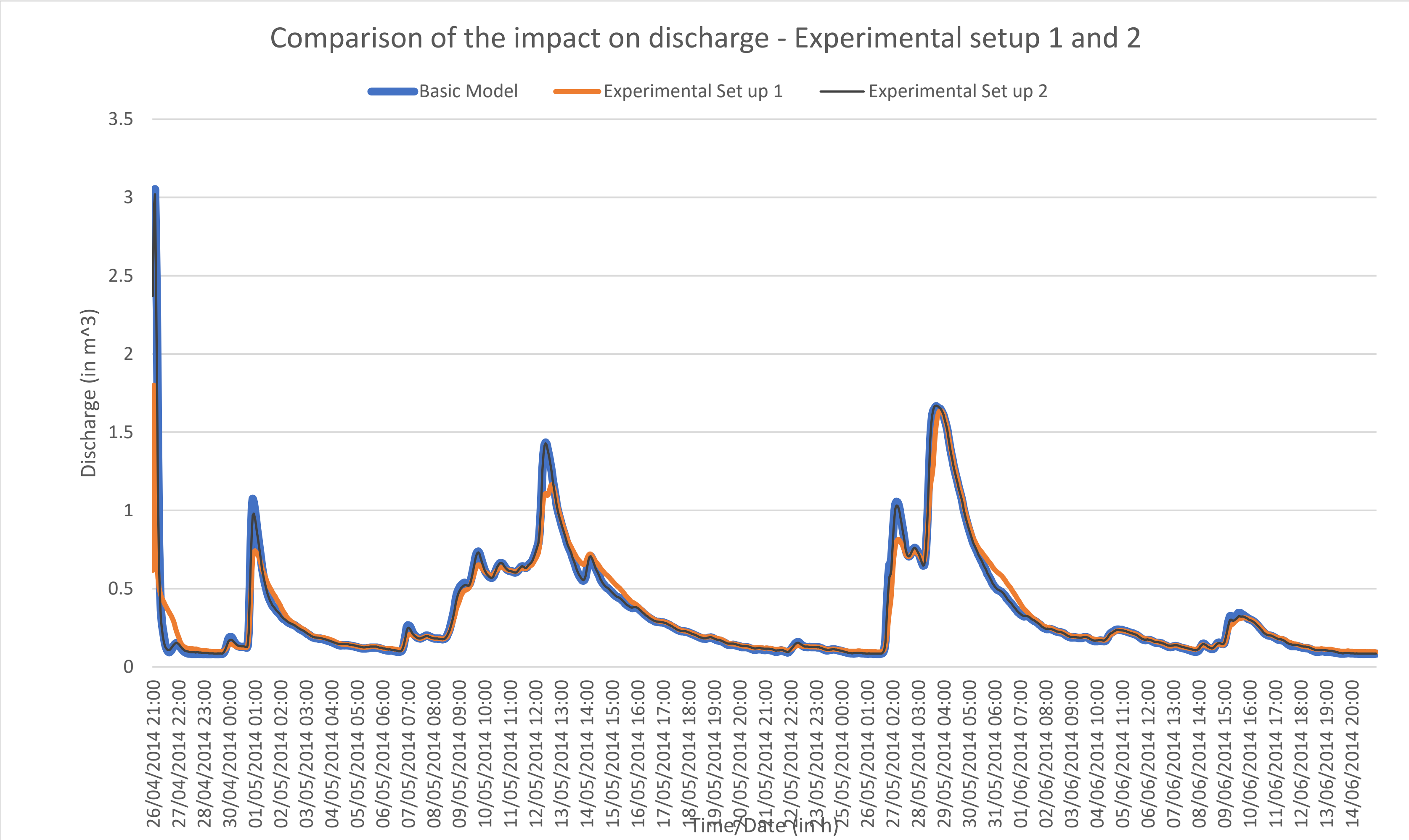
10.8 Results for the Main scenario for experimental set up 1



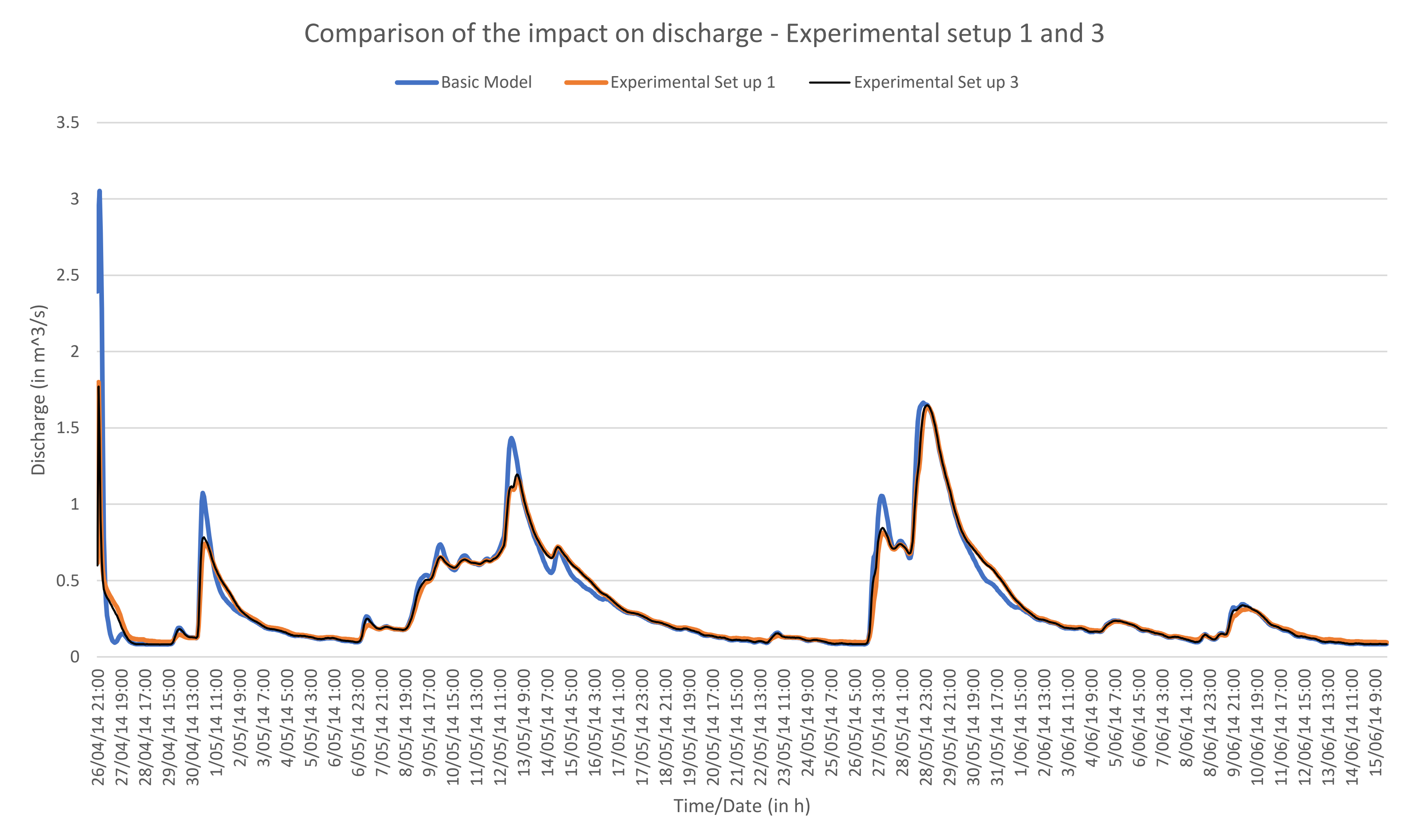
10.9 Results of the high-water scenario for experimental setup 1



10.10 Comparison of Experimental setup 1 and 2



10.11 Comparison of Experimental setup 1 and 3



10.12 Comparison between the 2 and 4 experimental setup – the Main scenario