Water retention during moderate precipitation events in rural areas

A case and comparison study regarding the Verloren Beek catchment.

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Bachelor Thesis

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Table of Contents

Table of Figures

Table of Tables

1 List of abbreviations

This thesis document uses technical and non-technical abbreviations. These are explaind below:

Abbreviation	Definition
EDR	Evenly Distributed Rainfall
SPR	Spread Pattern Rainfall
IR	Intense Rainfall
CS	Current Situation
EM	Embankments
CC	Closure of Culverts
STOWA	Foundation for Applied Water Research
NWRM	Natural Water Retention Measure

Preface

In front of you lies my thesis report 'Water retention during moderate precipitation events in rural areas' at which I have worked on the past ten weeks. The study has been done at Engineering and Consultancy firm Aveco de Bondt. It has been focused on potential measures to retain water in soil layers in a catchment located at the border of the Veluwe area. The study serves as an elaboration on prior research performed by employees of Aveco de Bondt regarding four catchments located at and around the Veluwe. Aveco de Bondt is an engineering and consultancy firm working in the field of water, infrastructure climate, built environment and sustainability. The initial research has been commissioned by waterboard Vallei & Veluwe. In this research, I have set-up and answered three research questions, aiming to overcome the research objective.

I would like to thank Wouter de Vries and Jesse Bootsma for their feedback and input over the past months. I would also like to thank Robin de Graaf for taking the role of second examiner and assessing this thesis. Furthermore, I would thank Aveco de Bondt for this opportunity and Team Watersysteem for their help and feedback during my thesis.

First of all, a small summary of the research has been provided. The first chapter introduces the relevance of the subject and the prior research. The second chapter consists of the research objective and research questions. Afterwards, the study area is explained, as well as the modelling software and available data used. This is followed by the methodology used to obtain the results, which are presented afterwards. These results are then interpreted and analysed in a broader context in the chapter that follows. The limitations of the study are addressed in the same chapter. This thesis will end with the drawn conclusions and offers recommendations for further research.

Summary

The aim of this research is to investigate the possible influences of two Natural Water Retention Measures on the infiltration capabilities of soil layers in sandy areas. This particular research is a case and comparison study covering the Verloren Beek catchment near Epe, Gelderland. Periods of drought as well as periods of intense rainfall cause the Netherlands to be prone to water damage (Deltares, 2021; ENW, 2021). Damage varying from 820 million euro's in the agricultural sector and between 140 and 380 million in the navigation sector due to the drought in 2018 are in accordance with this view (Hekman et al., 2019). There are multiple methods to avoid such periods of drought. An example is the implementation of Natural Water Retention Measures (NWRMs). Two particular NWRMs researched prior are the placement of embankments alongside waterways and the closure of various groups of culverts within the water system. The main goal of these measures is to keep the rain where it falls during the summer periods. Summer periods in particular have been chosen due to the intensity of rainfall generally being higher in comparison to winter periods. This research will elaborate upon the previous research by modelling different rainfall scenario's and making a comparison between these and previous results in earlier research. The aim of this research is to overcome the knowledge gap regarding the consequences of the implementation of embankments and closure of culverts during everyday rainfall scenario's. This has been formulated in 3 research questions.

To answer these questions, 2-D geodesign software Tygron has been chosen. This software is particularly useful as it excells at combining surface and ground water calculations in rural areas. Moreover, it is able to group large data sets, calculate the needed parameters and create comprehensible output in a fast fashion. As input, Tygron requires rainfall scenarios. These have been determined via a statistical analysis of the Epe area and combined with the national precipitation statistic (Beersma et al., 2019). Consecutive and nonconsecutive rainfall scenarios have been chosen with different intensities to get a clear insight into the behaviour of the water system with and without the proposed NWRMs. To assess the influence of the measures and the behaviour of the water system in general, the water balance as well as discharge graphs have been used. Maps indicating surface run-off times have also been generated to acquire a more elaborate insight in the effect that embankments can have.

The presented results show that there is no significant difference between the current situation and the implementation of embankments alongside waterways nor closure of tertiary culverts. This leads to the conclusion that the proposed NWRMs do not influence the infiltration capacities of the soil layers during everyday rainfall scenarios. However, during precipitation events occurring twice a year on average, a significant influence of embankments can be seen. Additionally, the implementation of embankments alongside waterways has shown to partially influence the infiltration capacities in the system for uncommon rain-events. Moreover, the nature of the rain event, either sequential or non sequential, has shown to influence the effect embankments have on the infiltration capacities of the soil layers.

The general conclusion of this research is that both NWRMs do not have a large effect during everyday precipitation events. However, embankments alongside waterways start to become influential for

rain events that are less common, but still occur on a yearly basis. Particularly the intensity of the rain events plays a large role in this influence. A suggestion for further is research to investigate the practical feasibility of these measures taking into account the stakeholders and local legislation.

2 Introduction

Water has been a key element within the Netherlands for the past millenia. Located in the delta of various large waterways, much of our daily practices are dependent on water. Not only drinking water but also agriculture, the transport sector and biodiversity amongst others are all facets where the Dutch are dependent on water systems (Rijkswaterstaat, 2023). Both periods of drought as well as periods of intense rainfall show that the Netherlands is prone to water damage as well (Deltares, 2021; ENW, 2021). Damage varying from 820 million euro's in the agricultural sector and between 140 and 380 million in the navigation sector due to the drought in 2018 are in accordance with this view (Hekman et al., 2019).
The growing economy and increasing population play an important role in the reduction of available water as made relevant in national news and shown in a recent report by the National Institute for public Health and the Environment (van Leerdam et al., 2023; NOS, 2023). Right now, drinking water is partially recovered from ground and surface water bodies, reducing the ground water table and the general availability of water for various other usage types such as agriculture and nature conservation.
The past few years have also given us a better insight into the local differences in the Netherlands during these periods of drought (Philip et al., 2020). Higher elevated parts of the country are, due to their elevation, less reached by primary waterways. Therefore these areas are largely dependent on rainfall for their access to water. This makes them more susceptible to periods of drought due to the uncertain nature of rainfall compared to water supply via primary waterways.
Such elevated areas are often sandy as well, hence their ground water levels tend to be lower and infiltration capacities higher(Deltares, 2022). This gives these areas the potential to store more water within soil layers which could be used later on when droughts occur (Ritzema et al., 2016).
This principle of water storage can be achieved in various ways. The general approach is to first retain water which can then be stored afterwards. Regarding this retention, differentiation can be made between Natural Water Retention Measures (NWRM) and grey infrastructure to retain water at specific places. This retained water can then be stored in the soil layers. Collentine and Futter (2016) classify NWRMs as follows "NWRM restore the water retention capacity of the landscape by changing the rate of the hydrological cycle through improved soil infiltration, slower overland flow, reduced channel velocity, and increased evapotranspiration"(p. 4). This definition classifies various water retention methods in two principles. One is 'Room for the river', effectively retaining water in the river. The other principle is described as 'keeping the rain where it falls'. This method aims at retaining the water in the area where it falls and reducing the discharge peak, either within the ground or by making sure more water evaporates, which reduces the discharge peak. Examples of such measures are embankments alongside waterways, increasing the roughness of the area, changing the relief of the landscape but also closing and opening culverts.
Deltares has recently also performed a large scale study on the implementation of NWRMs (Kaandorp et al., 2021). This study has been specifically aimed at retaining water at agricultural plots via various methods. It has shown that closing various groups of culverts can increase the water retention capacities of agricultural plots. Examples of other measures assessed are farmer-weirs

(boerenstuwtjes), decreasing the depth of small scale streams and adjusting the ground properties to increase their capillary capacity. These are all small implementations that are together able to influence the watersystem largely. A concept with a similar goal is 'The national watering can idea'(Het nationale gieter idee; Deltares, 2022), also introduced by Deltares. This plan describes potential ways of storing water within soil layers. One method is the reduction of run-off times which leaves more time for water to infiltrate. This is turn results in water storage in the soil layers. The concept is mainly aimed at pumping water from the rivers into these areas in stead of using NWRMs. The overlapping goal of both of these concepts is storing water in the soil layers to be able to use in periods of drought. Storing water in soil layers via the use of NWRMs has partially inspired waterboard Vallei & Veluwe as it can be of particular use in the area they are responsible for. That is, in this particular case study, a part of the area surrounding National Park Veluwezoom.

Research into this concept for that specific area has then been commissioned to Aveco de Bondt, forming a larger scale research project into the optimal adaptation of such concepts in four separate catchments in and around the Veluwe area (Visser, 2022). In this research, various measures in the area have been resembled using modelling software to get an insight into the influence of these measures on the water retention capacities of the area. Key within this prior research has been the implementation of measures in these area's them self, making sure that the changes to the area are implemented locally. Two particular NWRMs researched are the placement of embankments alongside waterways and the closure of various groups of culverts within the water system. The main goal of these measures is to keep the rain where it falls during the summer periods.
During these summer periods, longer periods of rainfall tend to be more uncommon in comparison to winter periods. However, when a precipitation event does occur in the summer, the rainfall tends to be rather intense. Hence this combination of intense rainfall followed by periods of drought in the summer is suitable for water storage to counteract these periods of drought. Therefore an intense summer precipitation event of 60mm per hour was assumed in the previous research. This rain-event has a recurrence time of once every 100 years (Beersma et al., 2019).
This prior research has concluded that embankments alongside waterways can significantly reduce area discharge, with model results varying from 15 to 30 percent. Closure of tertiary waterways has shown to be less effective, as only a reduction between 0 and 15 percent is shown (Visser, 2022; Vries, 2023).
The effect of embankments and tertiary culverts has not yet been tested against a more common precipitation event in these areas. As such events occur much more often, the consequences of embankments and closure of culverts is important to be familiar with as well. Especially their contribution to water storage during more common rainfall could impact the effectiveness of these NWRMs. Moreover, the consequences during everyday rainfall scenarios effects the implementation phase as well. Mainly because a complete insight into these consequences is needed when discussing such measures with stakeholders.

This research will elaborate upon the previous research by modelling different rainfall scenarios and making a comparison between these and previous results in earlier research. This study are is the same that has been used in previous research. Multiple rainfall scenarios are chosen to ensure a complete insight into the consequences of these NWRMs. The aim of this research is to overcome the knowledge gap regarding the consequences of the implementation of embankments and closure of culverts during everyday rainfall scenario's. Additionally, it also addresses the question for what rainfall intensities and patterns the implementation of embankments start to be influential on the water storage capacities of the soil.

3 Research objective & Questions

In this section, the research objective is stated, after which the research questions to reach this objective are formulated and elaborated upon.

3.1 Research objective

Based on the demonstrated relevance and demonstrated knowledge gap in Section 2, this study aims to pursue the following objective:

The research objective of this study is to assess the influence of riverside embankments and closure of tertiary culverts on the water storage capabilities of the soil layers during everyday precipitation events and uncommon precipitation events with higher intensities

3.2 Research questions

To make sure this objective is covered, the following three research questions have been formulated:

1. *What is the influence of embankments alongside the waterways on the water retention capabilities of the Verloren Beek catchment during everyday rainfall compared to extreme rainfall occurring once every 100 years?*
2. *What is the influence of closing culverts within the C-water system [1] on the water retention capabilities of the Verloren Beek catchment during everyday rainfall compared to extreme rainfall occurring once every 100 years?*
3. *At what intensity and rainfall time-span does the implementation of embankments start to significantly influence the water system and its water storage capabilities?*

The combination of the answers to these three research questions will reach the research objective and therefore cover the knowledge gap as stated in Section 2.

1: The C-water system consists of all waterways within the study area below an arbitrarily defined discharge threshold. This is known as the tertiary water system as well. This concept is explained in Section 5 in more detail.

4 Study area, Model used and Data

In this section, the study area is depicted, the available data is elaborated upon and the model used in this study is explained.

4.1 Study area

This sub chapter has been split in two sections. The first section covers the phyiscal boundaries and objects in the area. The second section elaborates on the relevant parties involved in the area.

4.1.1 Verloren Beek catchment

In this section, the study area is depicted. For this research, a specific part of the catchment of the Grift serves as the study area for the case study. This catchment is located to the northeast side of the Veluwe and covers the area between Apeldoorn and Heerde, see Figure 1. Due to the relatively large elevation differences, part of the rain on the Veluwe area flows to the eastern part of the Netherlands into the Grift via various 'sprengen' (small waterway; "Vallei & veluwe portaal", 2014). In this research, the sub-catchment of one of these sprengen is used as study area. This small stream is called the 'Verloren Beek' and is illustrated in Figure 2. This sub-catchment is used as it is a suitable example of a higher elevated catchment on the border of the Veluwe area, with agricultural land use as well. Moreover, The area is relatively sandy with a low ground water level. Therefore it connects to the aforementioned criteria in Chapter 2 of an area with high water storage potential.

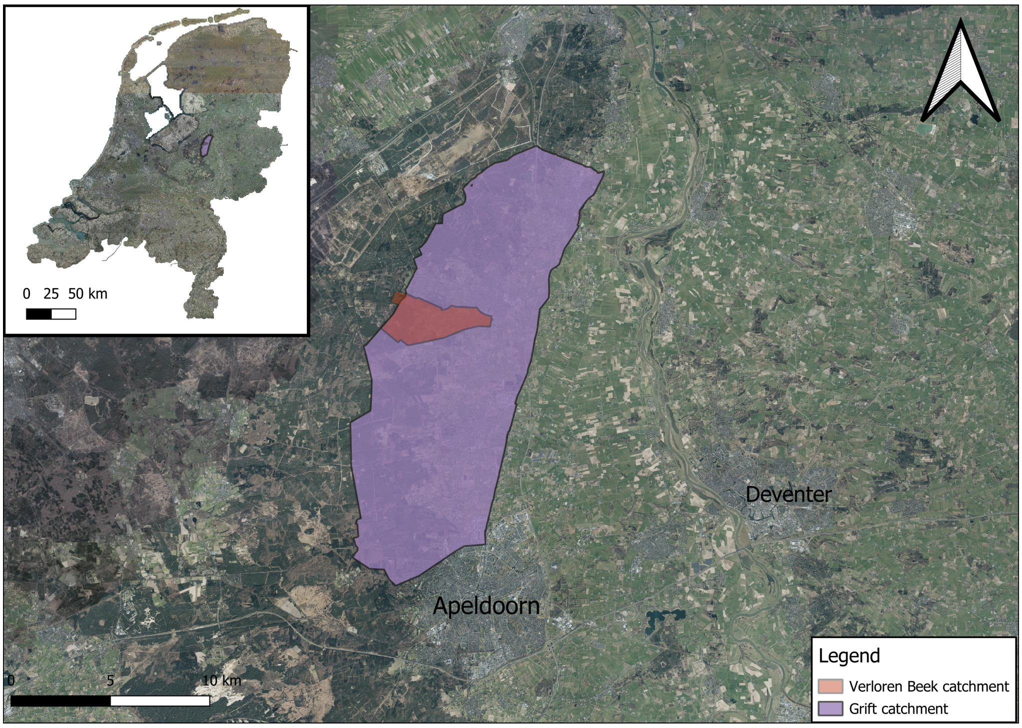

Figure 1: Location of the Verloren Beek within the Grift catchment in the Netherlands

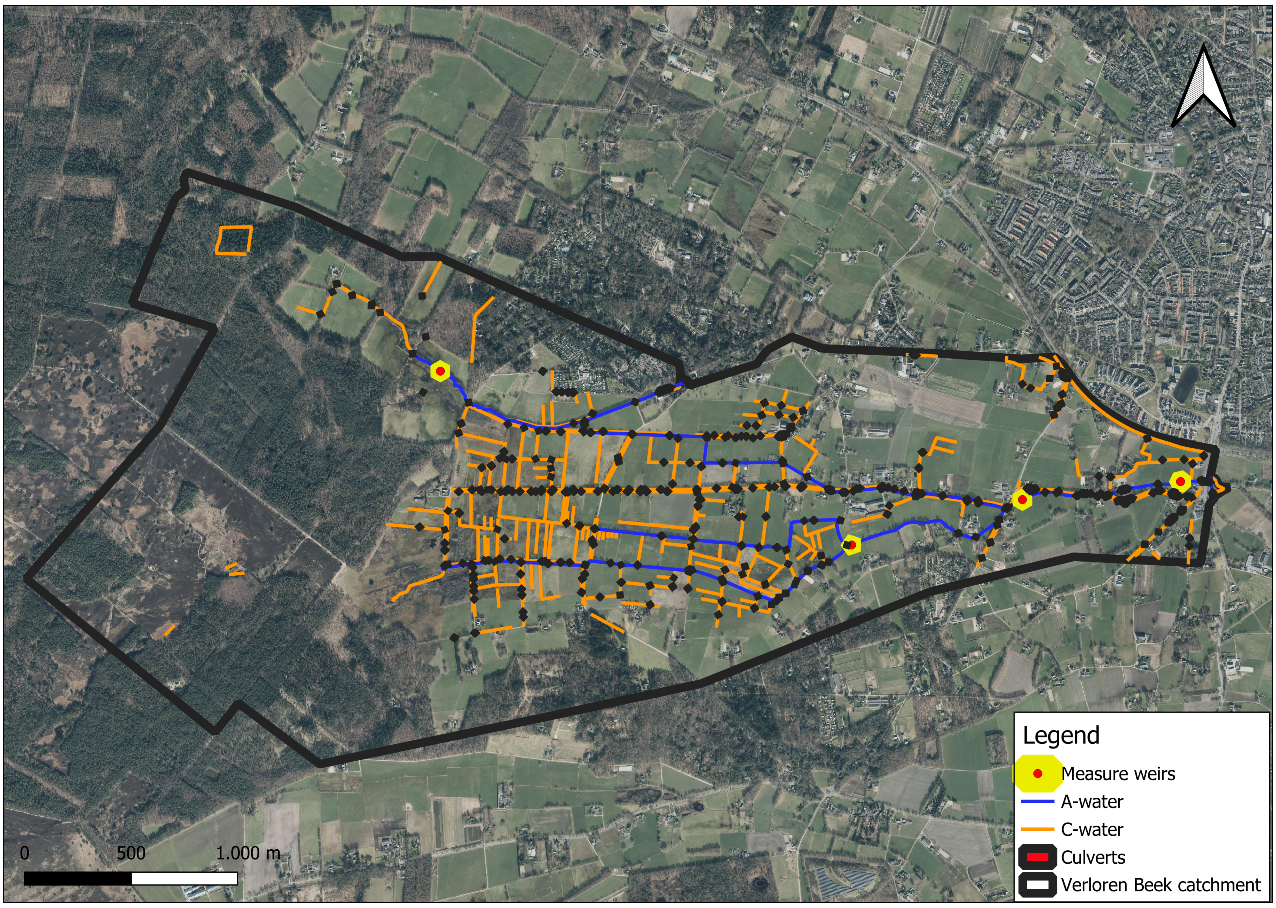

Figure 2: Catchment of the Verloren Beek distinguished by primary and tertiary waterways, including relevant waterworks.

The catchment of the Verloren Beek and her sub-branches start at the Wisselse Veen in the western part. The border of the Veluwe area is located at the western part as well. Three separate branches come together and end up in the Verloren Beek, which in turn flows in the Grift. The Wisselse Veen is a 'Natura-2000' area located near the Veluwe area. The blue lines indicate the A waterways, the yellow lines indicate the C waterways. The study area is bordered by the black polygon. The black dots illustrate the culverts. There are no B waterways present in the water system.

4.1.2 Relevant stakeholders

Within this study, there are a few notable parties and stakeholders. A relevant party in this study is waterboard Vallei & Veluwe. Their goal is to cope with droughts and intensive rain properly. Based on the concept proposed by Deltares and previous research by STOWA (Deltares, 2022; Kaandorp et al., 2021), they are looking into possible innovations. The waterboard has asked Aveco de Bondt to look into the feasibility of water retention within sandy areas located at (the border of) the Veluwe. Additionally, many farmlands are located around or close to the Veluwe. This makes water retention particularly interesting for farmers nearby as agriculture requires large volumes of water. Furthermore, water retention measures are of largely impact the local ecology and biodiversity (Kaandorp et al., 2021). Therefore the relevant nature organisations play an important role as well. This is partly covered by the waterboard, as they are responsible for water quality, but also by Staatsbosbeheer which is a governmental organisation responsible for larger nature areas in the Netherlands. 'Het Geldersch Landschap en Kasteelen' Is the organisation in charge of the Wisselse Veen.

Moreover, the entirety of the Veluwe is arguably the most important 'Natura-2000' area of the Netherlands (van Voorst tot Voorst, 2022). Therefore, with regards to nature conservation, the interest is both local and national.

4.2 Geo-design software Tygron

In this section, the basis of Tygron will explained. Furthermore, the reason why Tygron is used for this study is explained.
Tygron is a geodesign software package. It was originally designed to form a computer game. Since then, it has been adjusted with various overlays that enable water and heat stress calculations. Therefore, it can be considered as a serious gaming tool. Currently, the main goal of Tygron is to be an accurate digital twin. Part of the models abilities is providing overlays for water and heatstress calculations (Tygron, 2014).
The Tygron platform consists of two separate applications, Tygron Engine and Tygron Client. Tygron Engine is a central cloud, hosted in Utrecht. This cloud contains a supercomputer which performs the computationally heavy calculations for the Tygron Client application. This application is a 3D visualization program the user installs on their own computer. Using this application, the user is able to adjust models and request the calculations done by the Tygron Engine. Although the visualizations are 3D in the Tygron Client, the model calculations are done in 2D horizontally.
As mentioned in Chapter 3.1, the aim of this research is to investigate what the influence is of various measures with regards to different rainfall scenarios. Tygron offers a suitable approach to conduct such calculations as it combines ground water flow calculations with surface flow calculations. Moreover, it is able to process and combine large portions of data to create one structure that can be visualized using the Tygron Client. Additionally, Tygron has a function that is able to generate the location of culverts based on open source data. The combination of these functionalities, as well as it's ability to generate results in rapid fashion, makes it a suitable model to perform this research.
Many processes are integrated in the Tygron water overlay. These are also referred to as modules. A schematic overview of the water overlay is given in Figures 3 and 4. All these processes are dependent on each other and are therefore computed simultaneously per time-step. The combination of these different phenomena and processes together try to resemble the hydrological cycle as best as possible.

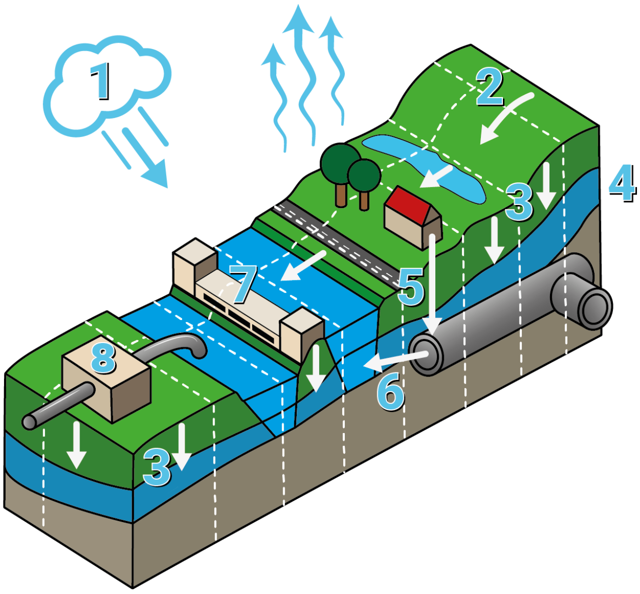

Figure 3: Illustration of water flows, phenomena and processes together forming the hydrological cycle in Tygron.

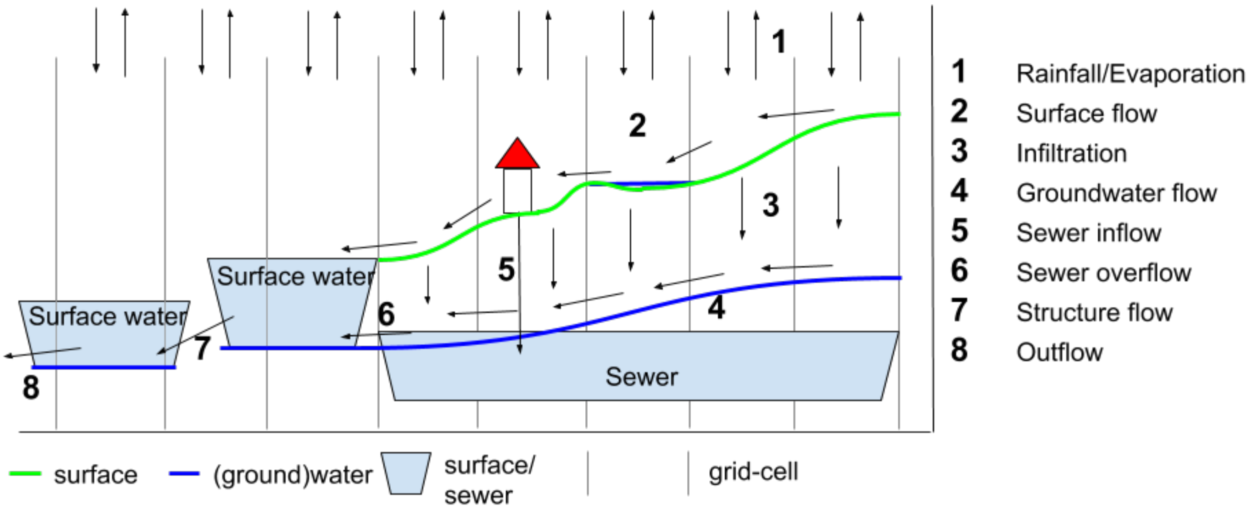

Figure 4: Schematization of water flowing top to bottom in various modelled systems in Tygron.

These processes are computed via many different theories applied in the Tygron software (Tygron, 2014). Tygron uses a grid based system, meaning that the area is split in a large amount of cells of 0.5 x 0.5 m at the smallest scale. Each cell has a respective elevation B, waterheight h and combined height w. Figure 5 illustrates this. Moreover, each cell has many parameters describing the processes happening in that specific cell. As the model is horizontally 2D, only flow from cell to cell is computed. Vertical flows are not taken into account. The model computes these phenomena using various equations, the 2-D Saint-Venant equations (Horváth et al., 2014), enhanced by Kurganov and Petrova (Alexander Kurganov, 2007), are an example of the computation of the surface flow process. This is just one example of the computation of a process described in Figure 3. Other processes modelled in Tygron that are relevant for this research are the Rainfall/Evaporation module, the Infiltration module and the Groundwater Flow module.

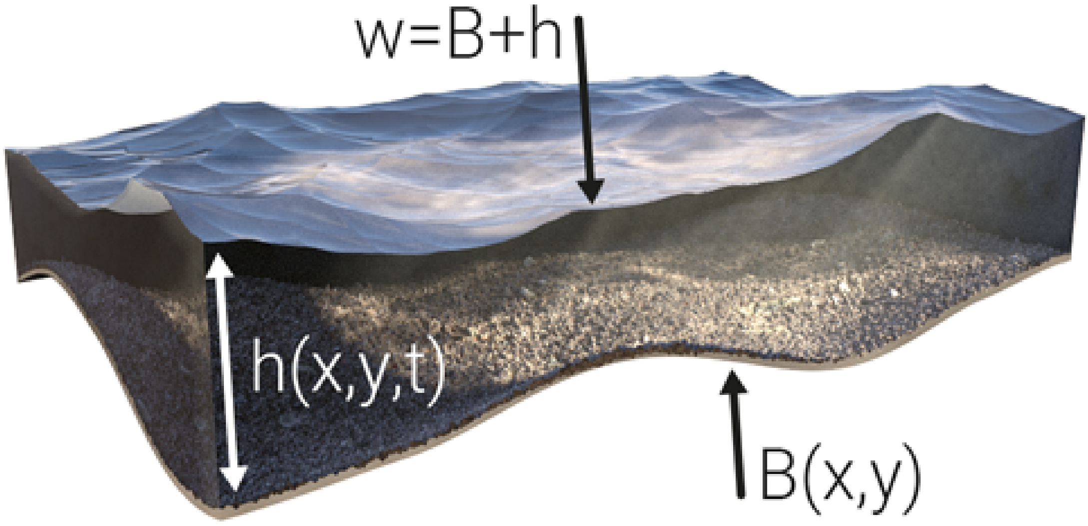

Figure 5: Illustration over water height computed in Tygron with bottom elevation accounted for.

4.3 Data

In this study, a base model provided by Aveco de Bondt is used. The model consists of general data based on the soil registration database of the Netherlands (BRO), elevation maps of the Netherlands (AHN3), basic registration adresses and buildings (BAG) and many more open source datasets (Tygron, 2023). Additionally, waterboard Vallei & Veluwe provided Aveco de Bondt with the precise locations of culverts in the study area. However, the precise location of every culvert is not always known as they are often located on land parcels. Therefore Tygron has a built-in AI generator which determines likely locations of culverts. This all together covers the basis of the model.

Additionally, data has been used to determine the average length of rain and drought periods in Epe. The data has been provided by Weerstation Epe ("Weather Station Epe", 2010). This data has been used to determine the rainfall scenarios. An elaboration about how this data is analysed can be found in Section 5.2.

5 Methodology

In this chapter the methodology is explained. The methodology can be separated in different sub-chapters. This consists of a sub-chapter explaining proposed measures and their respective method of implementation. The determination of rainfall scenarios has also been explained. Furthermore the comparison values are elaborated upon. Lastly, the step-wise approach that has been followed during this research is explained in detail.

5.1 Measures

In this section, the proposed NWRMs aiming to retain more water to store in the soil layers introduced. The same measures used in prior research (Visser, 2022; Vries, 2023) are assessed in this research. These are the implementation of embankments alongside all waterways and the closure of tertiary culverts.

5.1.1 Embankments

An embankment can be schematically visualised as a small dike next to a waterway. The traditional goal of a dike is to keep the water flowing in the waterway itself, withstanding it from inundating the nearby surface. In this case, the goal of the embankment is the opposite by avoiding water flow from the surface to the waterway. When precipitation occurs, ponds form on the land parcels when the intensity of the rain is larger than the infiltration rate of the soil and the water cannot flow to nearby waterways. This last boundary is created by embankments. Forming such ponds results in more time for water to filter through the vegetation layer in the soil instead of flowing into the waterway directly. This is illustrated in Figure 6. For this study, the embankments are assumed to have an elevation of 30 centimeters. When more water infiltrates into the soil layers, water is stored in the soil layers which can later on be used during periods of drought.

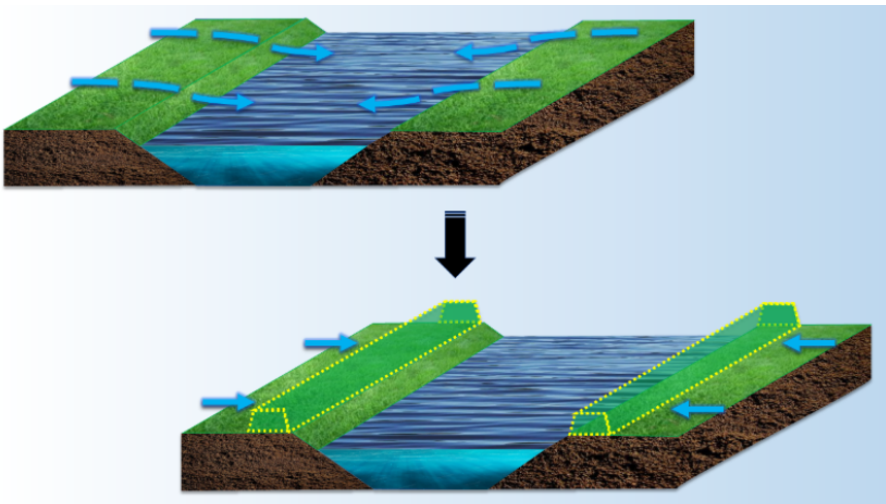

Figure 6: Illustration of implementing embankments alongside waterways to prevent water from flowing into the waterway. (Visser, 2022)

5.1.2 Closure of tertiary culverts

Surface water flows can be differentiated in primary, secondary and tertiary waterways, also known as A, B and C waterways. This classification is done based on the amount of discharge flowing through a waterway. See Figure 7 for an illustration of A,B and C waterways and their connection. These links are illustrated via the red dots and lines between them. Tertiary culverts are classified as the culverts linking a C waterway to another waterway.

Tertiary culverts can be described as small passages for brooks to connect each other. These brooks usually run alongside agricultural areas and next to roads. Culverts are implemented to connect different small waterways to each other, creating one large drainage system instead of several small systems. When such connections are closed or removed, the drainage system is divided in separate systems. This results in water being retained in each separate system, which in turn decreases run-off times by withstanding flow to primary waterways and therefore leaves more time for infiltration in soil layers. The research performed by Aveco de Bondt has shown that only closing culverts in tertiary waterways delays surface run-off times the least. Therefore this selection will also be used when choosing which culverts to close and which culverts to leave open. Figure 7 schematically visualizes this implementation in the water system.

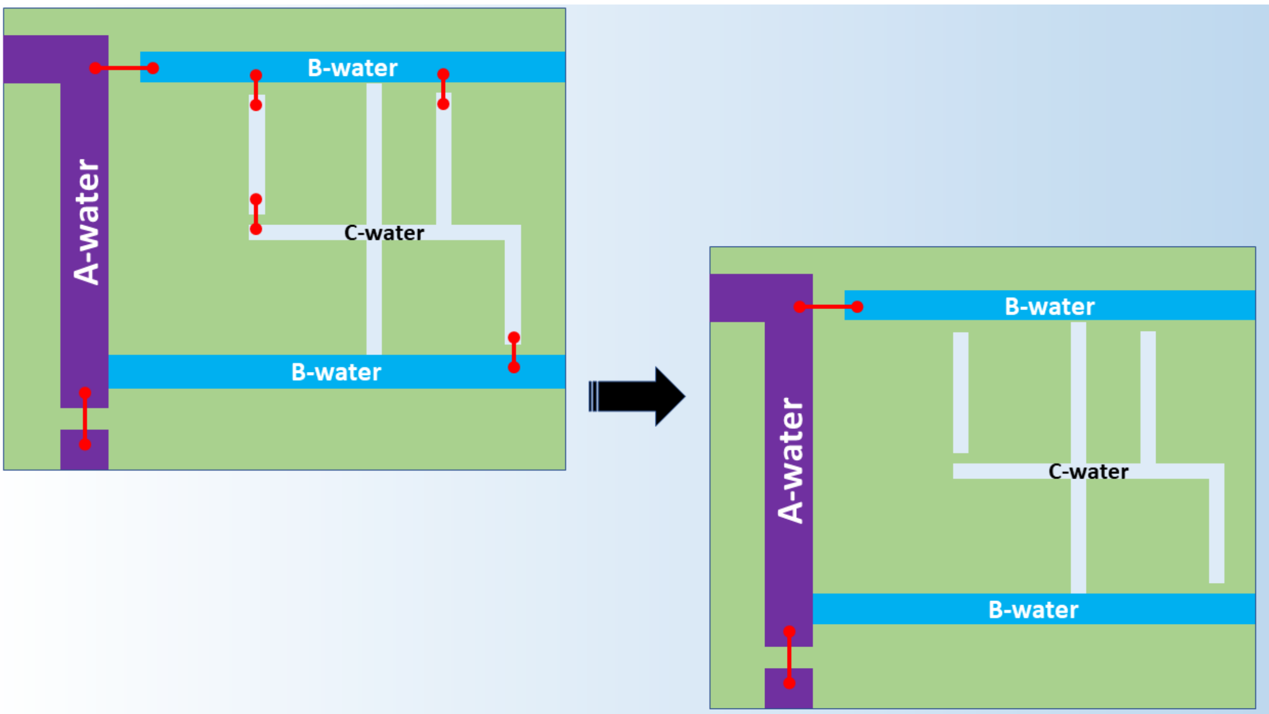

Figure 7: Schematization of closing culverts in the A, B and C water system. Red dots and lines show the locations of culverts before and after implementation of this NWRM.

5.2 Determination rainfall scenarios

To perform model runs, the rainfall scenarios used have to be determined. Such a rainfall scenario is formed by deciding on the total model run-time and combining this with a rainfall pattern. In the previous research, arbitrary rain intensities were chosen, after which the total model run time was based on expert knowledge. In this research, two common rainfall events are simulated. This has been based on statistical analysis of the precipitation around Epe during 2022 and 2023. The two rainfall scenarios run are Evenly Distributed Rainfall (EDR) and Spread Pattern Rainfall (SPR). To resemble an average rainfall scenario occurring in Epe, both of these rainfall scenarios are based on the average time span of a precipitation event as well as the average time span of a period of drought. To determine these periods, an analysis has been performed on rainfall data for a sequence of days as well as hours in the city Epe ("Weather Station Epe", 2010). The data used is measured during 2022 and 2023. An average time span of 2.6 hours (160 minutes) per rainfall event was found. The average period of drought is assumed to be 15.9 hours. A detailed determination of these values can be found in Appendix A.2. The similarities and differences between the Evenly Distributed Rainfall and Spread Pattern Rainfall are as follows:

- *Evenly Distributed Rainfall (EDR)*
  This rainfall scenario has been set-up to get an insight into the consequences of the two NWRMs using an average, everyday rainfall scenario with one period of rain followed by one period of drought. The values determined previously are used sequentially, meaning one period of rain is followed by a period of drought. If the total run-time is larger than twice the period of rain and period of drought combined, the period of rain as well as the period of drought is doubled. This is done to ensure that the ratio between rainfall time and drought time stays the same, while still being able to determine the run-time arbitrarily. Combining this with the average rain intensity in Epe, a rainfall scenario can be formed.

  In this report, such a rainfall scenario will be denoted by the structure (EDR or SPR) and the total volume afterwards. For example, EDR-10 resembles a precipitation event of 10 millimeters covering the entire area in an homogeneous sequel of one period of rain followed by one period of drought. If the total run-time is larger than 37 hours, the period of rain is 5.2 hours and sequential period of drought is 31.8 hours.

- *Spread Pattern Rainfall (SPR)*
  EDR aims to resemble a consecutive precipitation event. SPR aims to resemble the contrary, a non consecutive precipitation event. The same length of periods of rain and drought as determined previously are used. However, each sequel of rain and drought is followed by each other instead of one consecutive sequel, resulting in multiple small precipitation events with smaller, in between, periods of drought. This has been illustrated in Figure 8.

  This is denoted in the same way as EDR. For example, SPR-40 resembles a precipitation event consisting of multiple precipitation events, each having a time span of 2.6 hours of rain followed by 15.9 hours of drought with a total volume of 40 millimeters. The amount of individual precipitation events followed by periods of drought is fitted to the arbitrarily decided run-time.

For research questions one and two an everyday rainfall event is assumed. The average intensity of such a rainfall event near Epe is determined via statistical analysis. Regarding the EDR scenario used for research questions one and two, a daily statistical analysis has been performed due to prior unavailability of hourly data. The total intensity has been estimated at 10 mm total. The total run time is equal to 93 hours, consisting of 48 hours of rain and 45 hours of drought afterwards. This calculation can be found in Appendix A.1.

A SPR scenario has also been modelled to investigate whether an increase in intensity and difference in rainfall pattern yields different results. Figure 8 illustrates the difference between these two scenarios. For this scenario, the total run time as well as the periods of rain and drought are determined by the same statistical analysis as explained earlier and can be found in Appendix A.1. The intensity has been estimated based on expert knowledge.

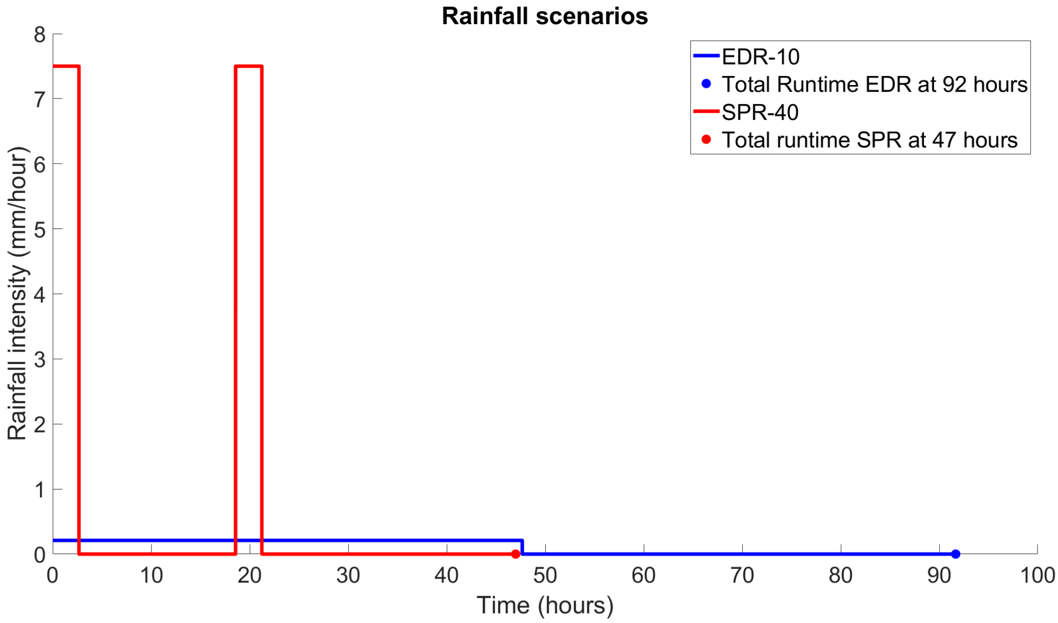

Figure 8: Rainfall scenarios EDR-10 and SPR-40 describing the intensity of the rainfall at different points in time.

5.3 Comparison method

To answer the research questions, three comparisons are performed. To compare different models and rainfall scenarios, a framework assessing the relevant elements of the water system is needed. This framework has been set-up by determining three assessment values. These values together form a picture of the behaviour of the water system. The following assessment values have been selected:

- *Water balance & water depth*
  The water balance can be measured at different points in time within the model, both locally and regionally. In this study, the water balance is generated to compare the total inflow with the total outflow of the system. Moreover, an insight in where the water is stored or leaves the system can be given by looking at the distribution between the land parcel storage, surface water storage, infiltration and evaporation. This distribution will be used to make a comparison between the different scenarios. Large amounts of outflow indicate that the relative amount of infiltration is low. To the contrary, low amounts of outflow indicate that a large portion of water is still in the system. As this does not leave the system, it is likely to be stored in the soil layers. However, there are exceptions to such a rule of thumb, especially in areas which have large elevation gradients. Therefore a map indicating the water depth of the inundation area can be used to confirm whether the indications made based on the water balance are likely to be realistic or not.

- *Discharge graphs*
  Discharge can be measured with relation to time at different points in the system. The points chosen can be seen in Figure 2. For this study only the most eastern measure weir, number four, is assessed. The generated discharge graphs can then be used to compare the flow volume at different points in the system between different rainfall scenarios. This gives a better understanding of the water system in comparison to the adapted systems. Large water volumes flowing through the system indicate that the global water system is particularly dependent on that waterway. This dependency is, when

compared between different scenarios, an indicative method to investigate whether local measures have an influence and what consequences might follow. Furthermore, discharge graphs are able to depict a delay and possible decrease of the outflow peak taking place after a precipitation event. The generated discharge graphs will not have a linear horizontal axis. Instead, their horizontal axis will be based on practical measure points for three different rainfall scenarios. This is done to minimize calculation times.

- *Maps indicating the run-off times*
  Aveco de Bondt has developed a tool in Tygron to generate maps displaying the run-off times from land-parcels to the primary waterways. This can be classified in various time intervals during the precipitation event. This assessment value is a method to check whether the embankments and closed culverts reach their initial goal, reducing run-off and increasing the ground water scale. Fast run-off indicates little infiltration, slow run-off indicates that land parcels inundate for a longer period of time, resulting in more infiltration and a higher ground water scale. Such surface run-off maps also give an insight into the local consequences in the area. This helps to locate where the consequences are likely to take place in the study area. These maps will only be used for the third research question.

All together, this assessment framework consisting of three separate assessment methods are able to give a complete insight in the relevant behaviour of the system and it's water retention capabilities.

5.4 Step-wise approach

In this section the previously explained principles are combined in a step-by-step scheme defining the several steps in the methodology. Starting off, the model resembling the current situation is run with an EDR-10 scenario. Afterwards the model and rainfall scenario are changed to fit the research questions multiple times. Lastly, the comparison is made between the results. Using these results, conclusions are drawn. The scheme indicating the exact steps is shown in Figure 9. Within this diagram, a red box indicates a model, a yellow circle indicates the adaption of an existing model to a new model. The green boxes refer to model runs with their respective result as output indicated in blue. The rainfall scenario that is used as input for the model run is described in the green box itself. These results are then grouped in which they are compared. Green arrows indicate steps that have already been performed in previous research. The purple circle indicates a selection that will be made. A couple of abbreviations have been used for lay-out purposes. These are explained in the list of abbreviations.

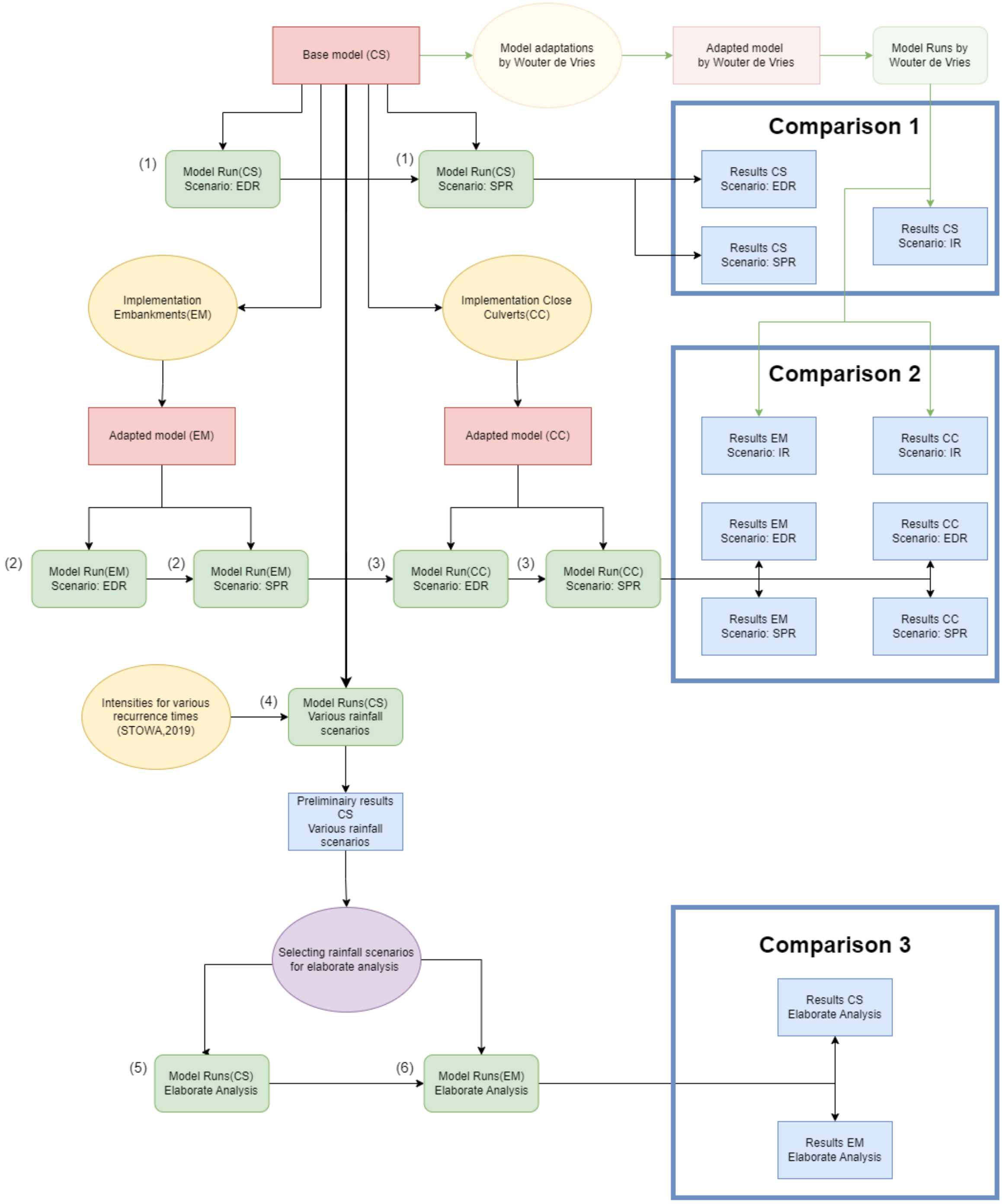

Figure 9: Methodology scheme illustrating the separate steps followed to reach the objective of this study.

The first comparison box serves as an initial comparison to verify the modelled situation acts as expected. When conclusions are drawn from the comparison described in the second blue comparison box, the first two research questions can be answered. When conclusions are drawn from the third blue comparison box, the third and last research question can be answered. This all together leads to the fulfillment of the research objective as stated in Section 3.2.

5.5 Model runs & selection

5.5.1 Model run current situation with EDR-10 and SPR-40 scenario

The first model run covers the current situation. That means that a representation of the actual water system is run in Tygron. The rainfall scenarios used are EDR-10 and SPR-40. The EDR-10 scenario is run to gain an insight into the current behaviour of the water system during everyday rainfall events. The SPR-40 scenario has a higher intensity and different distribution when compared to the everyday EDR-10 scenario. This combination should give a complete insight in the consequences of everyday rainfall in the Verloren Beek catchment due to the differences in intensity, volume and structure of the rainfall pattern.

5.5.2 Models run with implemented measures

The second and third model run cover the model runs for both embankments and closure of tertiary culverts, each in their separate model. The rainfall scenarios used are EDR-10 and SPR-40. Together with the first run and results from Wouter de Vries, a comparison is made. This comparison serves as the main basis to answer the first two research questions as described in Section 3.2.

5.5.3 Model run current situation with various rainfall scenarios

In the fourth model run, various rainfall scenarios are run to acquire an insight in the behaviour of the current system for different rainfall intensities, as determined by the rainfall statistic of 2019 by STOWA (Beersma et al., 2019). This model run generates a table indicating the land parcel storage for various model runs after the rain event. This table is then used as a selection tool for further analysis in the next step.

5.5.4 Choice for deeper analysis & fifth and sixth model run

By assessing the values from the generated table in step 4, a few rainfall scenarios are chosen for an elaborate analysis. This includes a comparison between the rainfall scenario with embankments alongside waterways and current scenario performed for these five rainfall scenarios.
Land parcel storage just after the rain event serves as the deciding factor for this selection, as this metric indicates the percentage of potential water that could be prevented from flowing into the waterways when implementing embankments. The five scenarios selected are chosen based on suitable comparisons with each other as well. Hence, rainfall scenarios show a similarity in their percentage land parcel storage are not selected twice.
The model run of the selected rainfall scenarios are run five and six in the methodology diagram. Afterwards these results are compared which ensures an answer to the last research question.

6 Results

This chapter covers the results obtained by following the steps taken in the methodology. It is divided in 3 separate sections, each covering the results of one comparison.

6.1 Comparison 1: Results current scenario for EDR-10, SPR-40 & IR scenarios

The first comparison evaluates how the current situation (base model) reacts to different rainfall scenarios. These are Intense Rainfall, EDR-10 and SPR-40 as indicated in Figure 8. The response of the model is monitored via the water balance at the end of the run as well as the discharge graphs measured at various points in time.

6.1.1 Water balance

Table 1: Water balance of base model for various rainfall scenarios

Base Model	Land parcel storage	Surface water storage	Infiltration	Evaporation	In/Outflow
IR	47,37%	12,47%	34,36%	0,64%	5,16%
EDR-10	1,34%	3,47%	24,28%	71,16%	-0,25%
SPR-40	1,13%	1,03%	90,72%	7,06%	0,06%

Based on Table 1 it can be noticed that different rainfall scenarios influence the distribution largely. The high intensity of the IR scenario causes large amounts of land parcel storage and relatively low amounts of evaporation. This is the opposite for an EDR scenario, which has low amounts of land parcel storage and a high percentage evaporation. The SPR scenario is an in-between in this case, as a lot of infiltration takes place with a relatively low amount of evaporation. This can be explained by taking into account the spread intensities of SPR in comparison to EDR, resulting in more time for water to infiltrate in a SPR scenario in between each separate precipitation event. Moreover, the larger volume of the SPR scenario influence this too, as it causes an increase in intensity. When the rain intensity exceeds the maximal infiltration rate, the most of the excess water infiltrates.

6.1.2 Discharge graphs

The discharge graph of the base model as shown in Figure 10 does not yield any unexpected results. Intense rainfall causes a peak in discharge at measure weir 4 after the precipitation event has taken place. The total volumes of EDR and SPR are relatively small when compared to IR, therefore being negligible to the IR scenario.

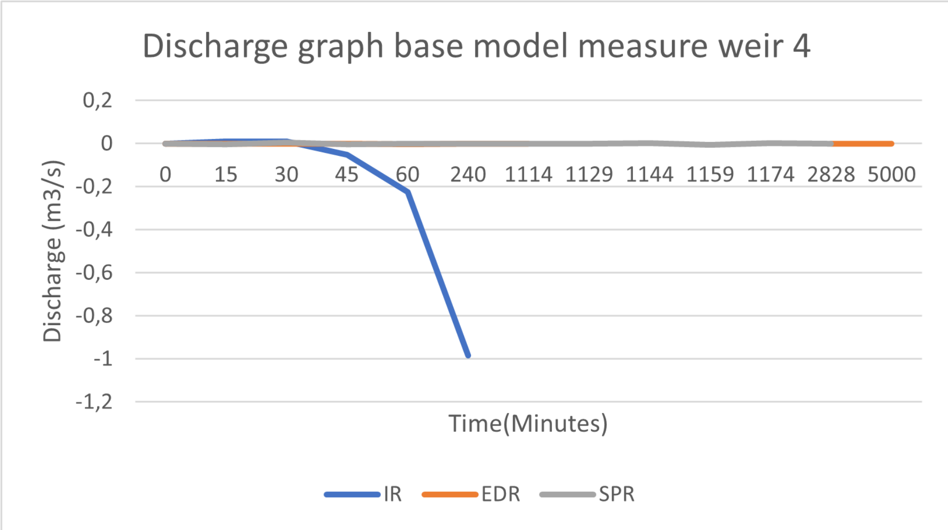

Figure 10: Discharge graph of three different rainfall scenarios run in the model of the current situation at various points in time. Measured at measure weir 4.as shown in Figure 2

These two metrics together show that the behaviour of the water system is largely dependent on the rainfall event. A clear distinction can be made between intense rainfall, uncommon and more common rainfall events.

6.2 Comparison 2: Results embankments alongside waterways and closure of tertiary culverts

The results shown in the next two sub-sections are comparisons between the current situation (base model) and implementation of embankments or closure of tertiary culverts. This comparison has been performed for three rainfall scenarios, EDR-10, SPR-40 and Intense Rainfall. In the following section , the water balance is depicted, showing what percentage of rainfall is stored where in the water system regarding the current situation, embankments alongside waterways and closure of tertiary culverts.

6.2.1 Comparison based on the water balance

The comparison between the base model and two proposed measures has been performed using three rainfall scenarios. To perform this calculation, the base scenario is used as reference. For example, modelling embankments results in a land parcel storage of 50.72 %. The base model has a percentage of 47.37 % land parcel storage as shown in Table 1. Together this leads to an increase of 3.35 % when embankments are implemented, as shown in Table 2.

Table 2: Comparison between base model and two proposed measures. Assessed for three different rainfall scenarios. In percent difference from base model.

IR	Land parcel storage	Surface water storage	Infiltration	Evaporation	In/Outflow
Embankments	3,35%	-0,76%	0,79%	0,01%	-3,39%
Closed culverts	-0,08%	0,21%	0,10%	0,00%	-0,23%

EDR-10	Land parcel storage	Surface water storage	Infiltration	Evaporation	In/Outflow
Embankments	0,17%	0,16%	-0,41%	0,06%	0,02%
Closed culverts	0,04%	0,02%	-0,07%	0,00%	0,00%

SPR-40	Land parcel storage	Surface water storage	Infiltration	Evaporation	In/Outflow
Embankments	0,10%	0,00%	-0,02%	-0,02%	-0,06%
Closed culverts	0,01%	0,01%	-0,01%	-0,01%	0,00%

Table 2 shows various observations. The Intense Rainfall (IR) scenario effects the water balance largely, as shown in prior research as well (Vries, 2023). A lot more water is stored on land parcels and In/Outflow is reduced, making sure that more water is stored in the area. However, the influence of closing the tertiary culverts is relatively small compared to the implementation of embankments.

Moreover, it can be noticed that differences between the base model and model with embankments are insignificant when more common rainfall scenarios are used. At most a change of 0.41 percent is found. Such low values make it impossible to draw meaningful conclusions based on such small differences.

All together the differences in the distribution between the base model and implemented embankments or closure of culverts are (nearly) negligible. Based on the water balance, the proposed measures seem to be non-influential during EDR-10 and SPR-40 scenarios.
Additionally, the discharge graphs have been generated at measure weir four for EDR-10 and SPR-40 scenarios. However, no significant influence can be observed, as the difference between the results is negligible compared to the total discharge. This is inline with the previously presented results in Table 2.

6.3 Selection for further analysis

This selection is based on the results provided in Appendix B. The following five rainfall events have been selected for further analysis:

1. EDR-30 for a total run-length of 24 hours.
2. EDR-39 for a total run-length of 48 hours.
3. EDR-66 for a total run-length of 48 hours.
4. SPR-39 for a total run-length of 48 hours.
5. SPR-66 for a total run-length of 48 hours.

This selection was made based on a few factors. First of all, the run-time of 24 and 48 hours gives room for a comparison to different rain lengths and intensities, as 30 millimeters of rainfall over 24 hours in an EDR scenario has a higher precipitation rate (in mm/hour) than 39 millimeters of rainfall distributed over 48 hours.

This has been illustrated in Figure 11 as well.
Secondly, the results as presented in Appendix B show a large difference in land parcel storage between these scenarios. This makes for a suitable comparison to investigate whether such a difference can be noticed in the surface run-off maps as well.
Additionally, the distinction between EDR and SPR has been made to gather additional knowledge to which degree the structure of the precipitation event, either consecutive or nonconsecutive, is of influence on the previously generated results.

For these five rainfall intensities, the rainfall pattern has been adjusted to fit the EDR and SPR structure. Hence, the three EDR scenarios all start with a period of rain, followed by a period of drought as described in Section 5.2.

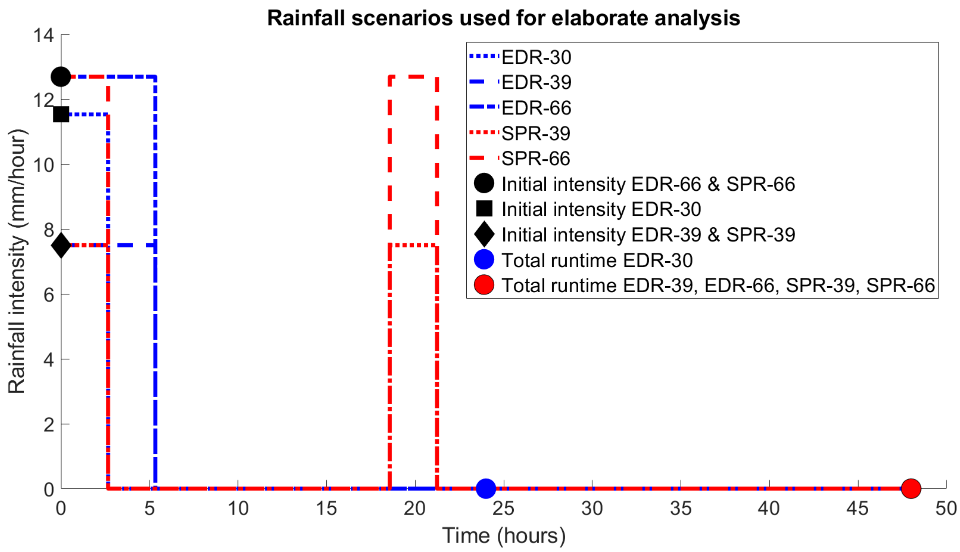

Figure 11: Rainfall scenarios selected for elaborate analysis, describing the intensity of the rainfall over time.

6.4 Comparison 3: Elaborate analysis for distinct selection

As presented in the previous section and Chapter 5, the third comparison consists of a elaborate analysis for five distinct precipitation events. This covers three EDR scenarios and two SPR scenarios. The following sections are divided accordingly.

6.4.1 EDR scenarios

The three EDR scenarios, EDR-30, EDR-39 and EDR-66 have been analysed more thoroughly to create the surface run-off maps. The maps shown in Figures 12, 13 and 14 display the comparison in surface run-off times between the current situation and the model with embankments implemented alongside the waterways.

It can be seen that there is little surface run-off in the majority of the Verloren Beek catchment. However, there are small ponds forming in both models, mainly nearby waterways. The water in these ponds wants to flow towards the tertiary and primary waterways, but are delayed by the embankments alongside these waterways indicated by the green areas in Figure 12.

Additionally, it is observed that embankments partially have a reverse effect where they are act as regular dikes and fasten the run-off to the waterways. This is indicated in Figure 12 in purple.

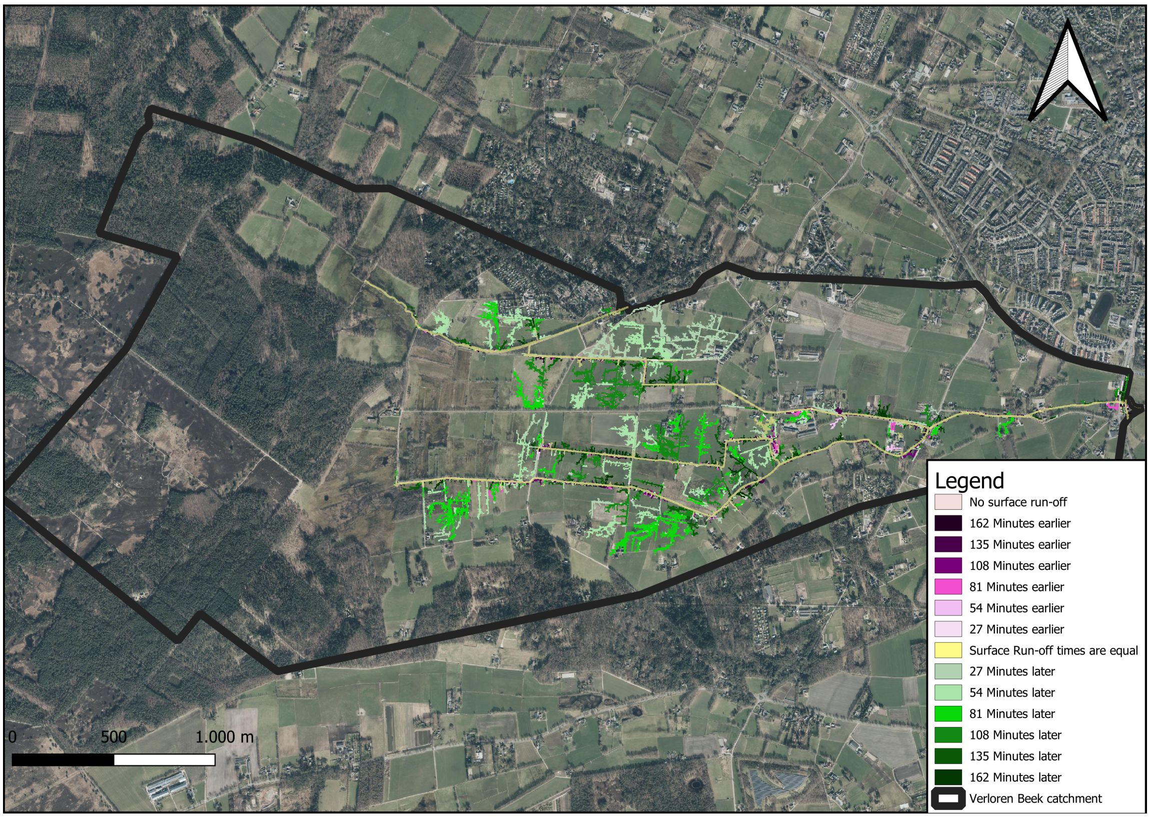

Figure 12: Comparison between current situation and implemented embankments alongside waterways during an EDR-30 scenario with a time span of 24 hours

Figure 13 shows the surface run-off map of a precipitation event spanning 2 days with 39 millimeters of rainfall in total. A small difference between the base model and implementation of embankments can be seen. However, this is negligible in comparison to the entire area. Such a result is to be expected due to the relatively lower intensity of this precipitation event in comparison to a rain event as shown in Figure 12.

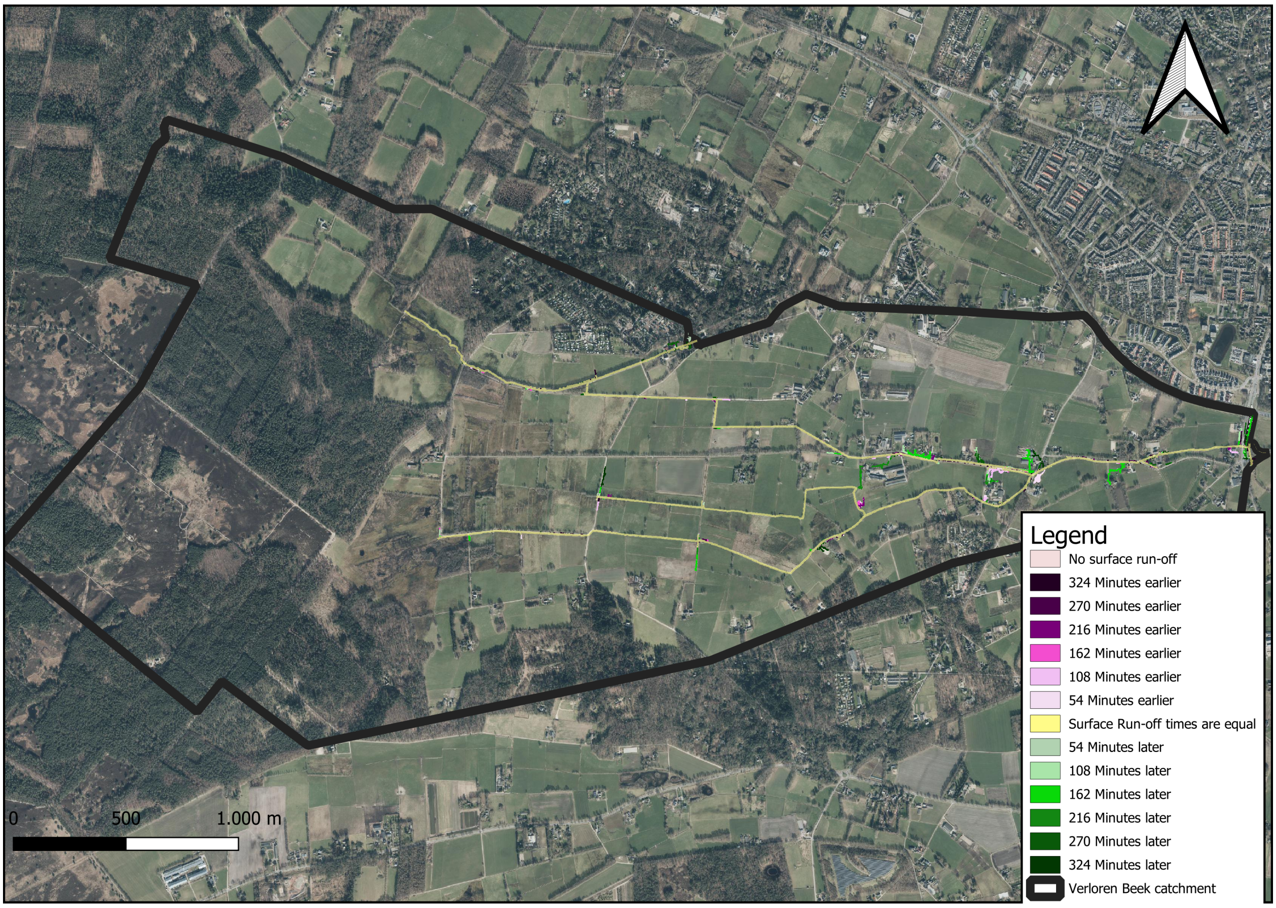

Figure 13: Comparison between current situation and implemented embankments alongside waterways during an EDR-39 scenario with a time span of 48 hours

In Figure 14 a significant difference is observed in the entire study area. The implementation of embankments delays the surface run-off, varying between one and six hours, which creates a longer time span for water to stay on land parcels and infiltrate in the soil layers.

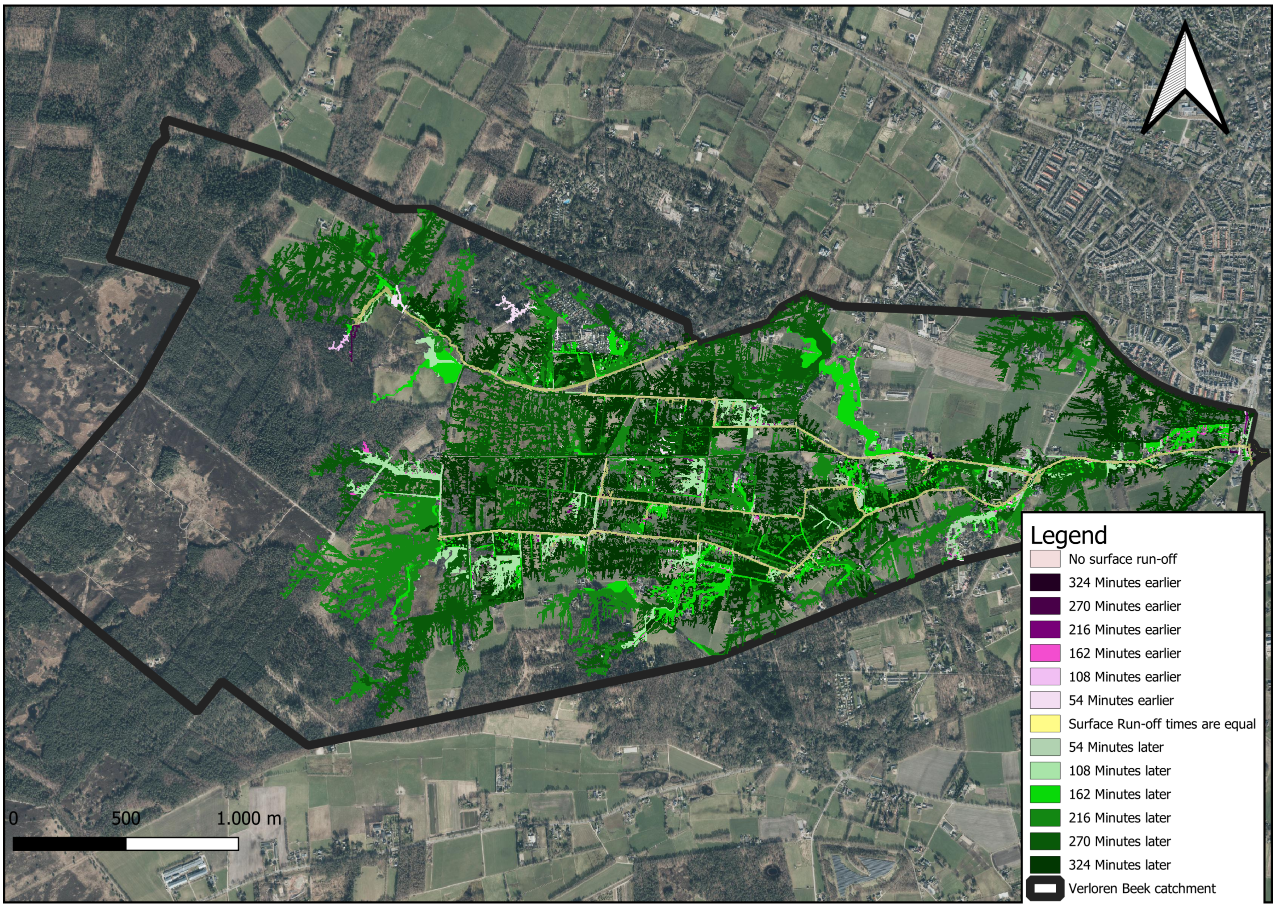

Figure 14: Comparison between current situation and implemented embankments alongside waterways during an EDR-66 scenario with a time span of 48 hours

Analysing these three maps together leads to the observation that most land parcel storage occurs near the primary waterways and the smaller waterways closely linked to them. Moreover, the rainfall intensities influence the land parcel storage and therefore the available time for infiltration largely.

6.4.2 SPR scenarios

The two SPR scenarios, SPR-39 and SPR-66 will be depicted and compared to the EDR-39 and EDR-66 scenarios.
The map illustrated in Figure 15 shows that the structure of a rainfall event can largely affect the influence embankments have on the surface run-off times. Whereas, in the EDR-66 scenario depicted in Figure 14, embankments have a large effect on the run-off times, this is not comparable to the SPR-66 scenario described in Figure 15. Even though their total volume is equal. Although the implementation of embankments significantly influences the run-off rates in this scenario as well, the total surface run-off nor time delay matches to the EDR-66 scenario and is rather comparable to the EDR-39 scenario as analysed prior.

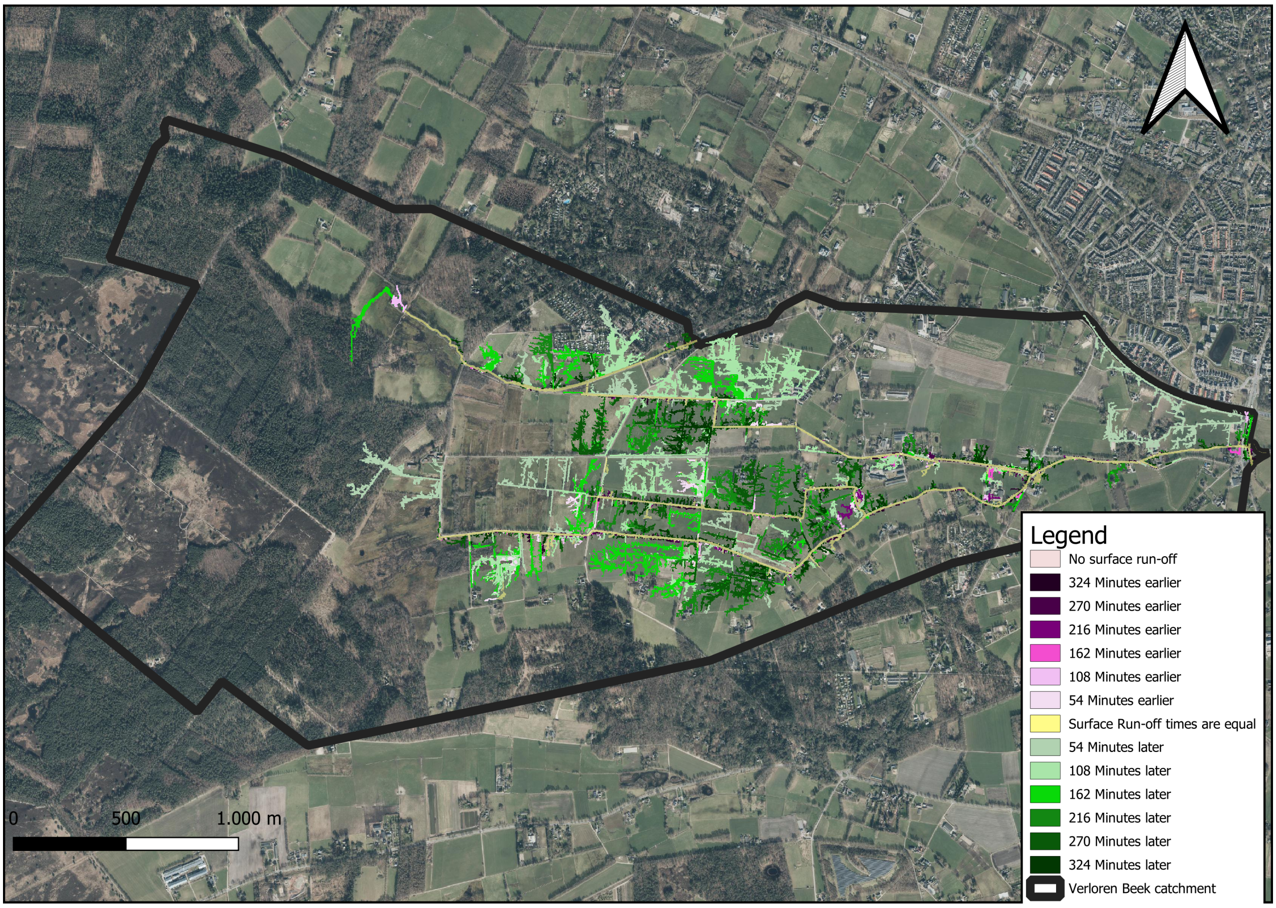

Figure 15: Comparison between current situation and implemented embankments alongside waterways during an SPR-66 scenario with a time span of 48 hours

A large difference cannot be observed when comparing an EDR-39, in Figure 13, and SPR-39, in Figure 16, rainfall scenario regarding the influence that embankments have on the water storage capabilities of the soil layers. As previously mentioned, the intensity is too low to result in surface water being built up at the low lying areas. Hence the implementation of embankments is not able to influence any surface flow, as the surface water on land parcels is non existent. Therefore comparing the influence of embankments in two different rainfall scenarios also does not yield any differences.

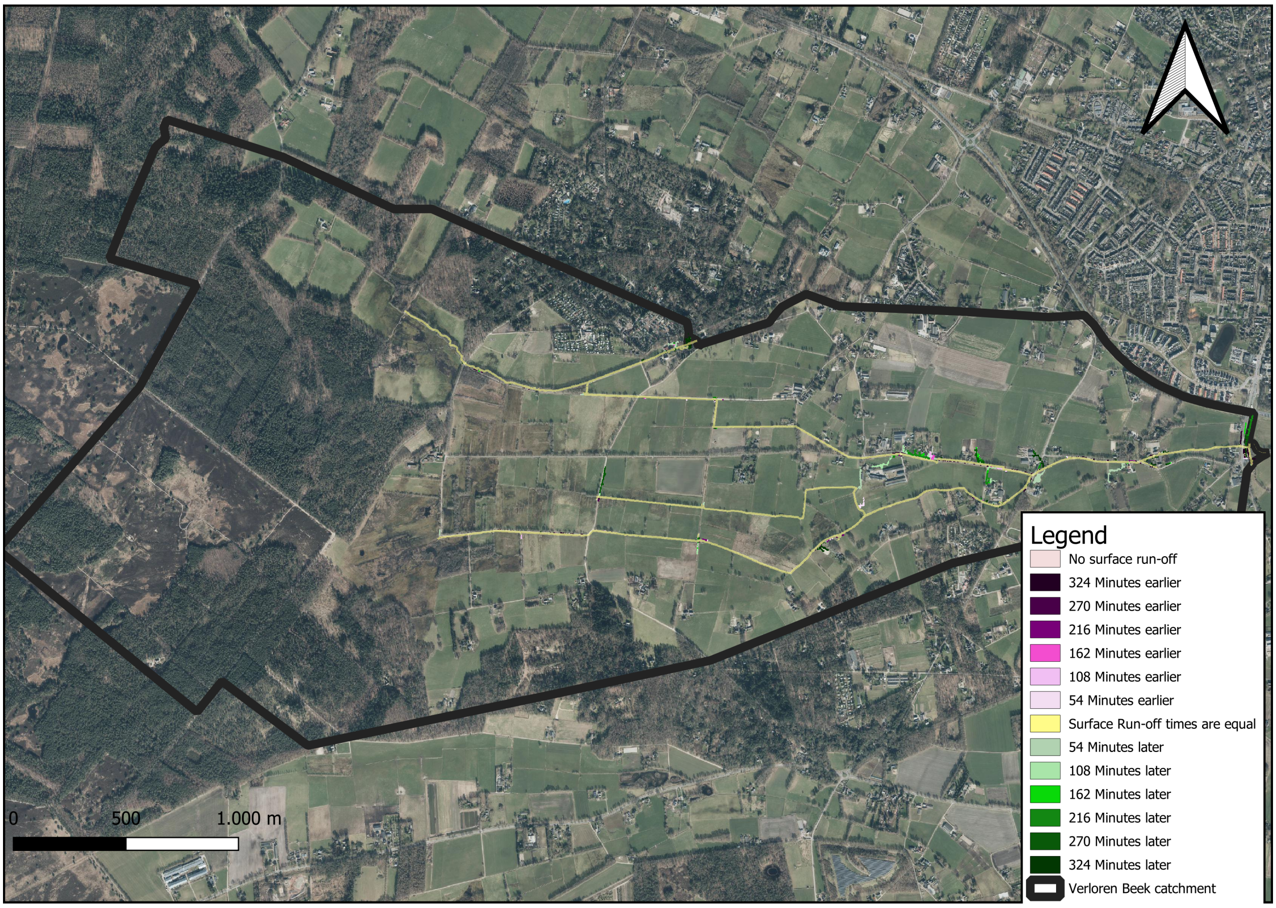

Figure 16: Comparison between current situation and implemented embankments alongside waterways during an SPR-39 scenario with a time span of 48 hours

All together the comparison between the EDR and SPR scenarios have shown that the structure of the rainfall event can largely influence the behaviour of the water system with and without implemented embankments.

7 Discussion

This research offers an insight into the consequences of implementing embankments alongside waterways and closing tertiary culverts during various rainfall scenarios with regards to the water storage capabilities of soil layers. By following the methodology described, the reproduction of this research should yield the same results. This section will elaborate on and interpret the results in comparison to the available literature. It also addresses a few uncertainties that need to be taken into account when interpreting these results in a broader context.

The first analysis as presented in Section 6.1 shows that the adaption of the behaviour of the water system to different rainfall scenarios is inline with the established theory. When intensities are low during the EDR-10 scenario, the majority of rain evaporates and the portion of water that is left infiltrates in the soil layers. In the SPR-40 scenario, the precipitation intensity exceeds the maximal evaporation rate. Hence, a large portion of the water is left, which infiltrates into the soil layers. However, the precipitation intensity does not exceed the maximal infiltration rate of the soil layers during this rainfall scenario. Therefore no land parcel storage forms. During the rainfall scenario where the intensity exceeds the normative scenarios, the maximal evaporation rate as well as the maximal infiltration rate is exceeded. Therefore the majority of the water ends up on the land parcels. This in turn causes run-off towards the water ways, which quickly discharge the excess water. This is inline with the outflow in the current situation during intense rainfall and confirms what prior research has shown. (Visser, 2022; Vries, 2023).

This also clarifies the results of the second comparison. No significant difference is observed between the current situation and implementation of NWRMs during the EDR-10 and SPR-40 scenarios. This can be explained by looking at the initial purpose of embankments alongside waterways and closure of culverts. Their aim is to retain water at land parcels. When retained at land parcels, more time is available for infiltration. However, the maximal infiltration rate is not exceeded during the EDR-10 and SPR-40 rainfall scenario. As a result, no excess water is stored on land parcels and the NWRMs are not needed, as they cannot retain water on land parcels if there is no water on land parcels to start with. Although this interpretation of the results is inline with the expectations based on the first analysis This additional analysis adds an insight into the behaviour of the water system and enhances the robustness of the presented results.

This consequential process of exceeding the evaporation and infiltration rate where after land parcel storage increases is relevant for the third comparison as well. It serves as the basis to select the rainfall scenarios for further analysis in the last comparison. The last comparison shows that the influence of embankments between various rainfall scenarios is partially dependent on the intensity of these rainfall scenarios. However, it also addresses the usefulness of these embankments. The results show a large delay of the run-off times during precipitation events with intensities of twelve millimeters per hour and above. The results also show little delay during rainfall intensities lower than seven millimeters per hour. This implies that the boundary where embankments start to have a significant effect lies somewhere in between the intensities of seven and twelve millimeters per hour. Moreover, the results show that the length of the precipitation event has a large influence on this comparison as well. This could be the consequence of the soil layers becoming partially saturated in local areas of the catchment. This in turn would increase the amount of surface run-off, as the infiltration speed likely decreases (RIONED, 2020). However, it should be taken into account that the surface run-off maps give an indication instead of a numerical assessment.

This research has been demarcated beforehand to clarify what is researched and what not. Therefore, limiting factors have to be taken into account when interpreting these results. One of them being the assumption that the rainfall scenarios are an accurate resemblance of common and uncommon rain events. As mentioned in Section 5.2, the rainfall scenarios for EDR and SPR are determined via a statistical analysis performed

on data available around the Epe area. For the determination of less common rainfall events, this has been combined with a statistical analysis of STOWA. This approximation of rain events can be improved by only using data from one source, ensuring data validity and preventing statistical errors.
To add to that, it is assumed in Section 6.4 that the rainfall scenarios as provided by STOWA can be divided in a sequence of rainfall followed up by drought. This renders the recurrence times unusable for this research. By coupling the rainfall scenarios used in this research to certain recurrence rates, a more complete overview could be given regarding the consequences of predefined rain events. Moreover, there is a difference between the rain/dry ratio of the hourly and daily results as presented in Section 5. This difference could be caused by measurement inaccuracies as well as the difference in time period for which the data sets have been obtained.
The calculation process also has limitations. Phenomena such as rain, infiltration and water flow in general vary largely over time. This makes a comparison between different rainfall scenarios quite complex. In this study, not all the assessment values take this time component into account. An evaluation of the water balance over time would make the model more robust and sequentially would enhance the trustworthiness of the results.
Moreover, the initial conditions of the model can largely influence the outcome of the results. In this case, the assumption has been made that the initial ground water level is equal to the average level during spring. Assumptions made based on the drawn conclusions are therefore only valid during spring periods. Therefore, determining the sensitivity of the initial conditions could affect the strength of the drawn conclusions largely.

Besides evaluating the assumptions made to acquire the results, it is important to also address the relevance of the found conclusions in a larger setting. Interpreting the results of this case study raises the question whether these findings are applicable in other areas and situations as well. When assessing whether these NWRMs can offer solutions to other areas, the aforementioned limitations and assumptions need to be taken into account. If a potential other area shows similarities based on the area characteristics to this case study, the findings of this thesis should, to a certain degree, be applicable in that area as well. This implies that areas with similar characteristics are likely to have a boundary somewhere between an intensity of seven and twelve millimeters per hour for a certain period of time. This boundary could indicate that the implementation of embankments would significantly influence the water storage capabilities of the soil layers for rainfall events with intensities higher than twelve millimeters per hour.
Additionally, part of this study offers an insight into the influence of 30 centimeter high embankments aiming to withstand water flow from land parcels to waterways. However, the same goal could potentially be reached via alternative methods as well. For example, by a reduction of the gradient or making small embankments out of clippings, grass cuttings or grind. This study contributes to this process in such a way that it shows that embankments can be effective for certain precipitation events, but also suggests that alternatives could show similar results. This raises the question what alternatives are suitable for this goal, but also practical to implement.
This practical view is of great importance prior in the implementation phase as well. Current legislation does not allow waterboards to enforce the two NWRMs proposed in this study as they are both implemented locally on the premises of farmers. Hence, they will need to convince farmers, perhaps monetarily, to implement these measures. However, such local measures also result in very local consequences which could enhance the usage of their land but also bring them at a disadvantage compared to their competitors. This should be taken into account when assessing whether such measures can be beneficial for a specific area. This study contributes to this process in particular by providing an insight into the influence of these measures during normative rainfall scenarios.

8 Conclusion

In this thesis I have researched the influence of two Natural Water Retention Measures during two common rainfall scenarios in comparison to less common rainfall as researched prior (Vries, 2023; Visser, 2022). The first and second research questions read as follows: 'What is the influence of embankments alongside the river basin on the water retention capabilities of the Verloren Beek catchment during everyday rainfall compared to extreme rainfall occurring once every 100 years?' and 'What is the influence of closing culverts within the C-water system on the water retention capabilities of the Verloren Beek catchment during everyday rainfall compared to extreme rainfall occurring once every 100 years?'.

Based on the water balance and discharge graphs, the presented results show no significant difference between the current situation and the implementation of embankments alongside waterways nor closure of culverts in digital twin Tygron. Hence, this has lead to the conclusion that the implementation of these NWRMs barely influences the water retention capabilities during such rain events in the Verloren Beek catchment.

Consecutive or nonconsecutive rainfall also does not play a large role in the influence of these measures on the water retention capabilities of the Verloren Beek catchment during everyday rain events, as shown in Section 6.2.

The third research question is aimed at gaining an insight for which precipitation events the impact of embankments becomes significant. This was summarized in the following research question: 'At what intensity and rainfall time-span does the implementation of embankments start to significantly influence the water system and water storage capacities?'.

This has been assessed by doing an overall analysis of the land parcel storage percentage, for which this analysis has then been expanded upon for a small selection of rainfall scenarios. The results depicted in Section 6.4.1 show that the implementation of embankments significantly influence the behaviour of the water system during rain events with intensities varying between 7 and 12 mm/hour. However, the length of such a rain event plays an important role as well, as it is simultaneously linked to the intensity of the precipitation. This is the main phenomena that contributes to the influence embankments can have on the behaviour of the water system and therefore water storage capabilities of the soil layers.

Moreover, the results presented in Section 6.4.2 show that the structure of the precipitation event has a large influence on the effect of the implemented embankments. The difference between consequential and non consequential rainfall is relatively large and should therefore be accounted for when considering the implementation of these Natural Water Retention Measures.

All of these conclusions have to be interpreted by taking into account the limitations and assumptions this study entails. Extrapolating the results of this case study indicate that a boundary is found when the implementation of embankments starts to become significant, taking into account the area characteristics. However, the assumptions made during this research are a key aspect of this generalization and should therefore always be taken into account.

9 Recommendations for further research

Based on the presented results, drawn conclusions and evaluated discussion points there are a couple recommendations for further research that that are elaborated upon in this chapter.

As mentioned in the discussion as well, the proposed measures are both implemented on the premises of farmers. Hence, research assessing the practical feasibility of these NWRMs would add value to the discussion whether to implement one of these concepts. Such research could take into account the stakeholders and involve practical experiences, possible incentives and an overall method of how to implement such measures in a multidisciplinary approach.

Moreover, potential research objectives could address the time component in the concept of storing water in soil layers. This would yield knowledge that is currently unknown, as especially the concept of embankments alongside waterways is relatively new. An examples of this would be how long it takes for soil layers to become saturated and what method achieves this in an optimal fashion.

To add to that, research into possible alternatives of embankments alongside waterways could be beneficial. These could be clippings, grass cuttings or a reduction of the gradient for example. In this research, it is important to also take the practical feasibility of these alternatives into account. Comparisons such as cost, time consumption and different consequences could be relevant as well.

Lastly, it would be valuable knowledge to have a clear picture of the expenses, advantages and disadvantages of these two NWRMs. Especially the monetary considerations when looking at this alternative would be helpful in forming the next step in the implementation process

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A Determination average period of rainfall & average period of drought

A.1 Daily

For this determination, data is provided by Weerstation Epe. The data contains the amount of rainfall for each day, accurate till 0.2 millimeters per day. The data covers the entirety of 2022. The following steps are taken to obtain the results:

1. Sequences of rainfall are determined by checking whether it has rained the day before for each day.
2. The cumulative rainfall per sequence is determined. The following examples illustrates this:

   If it has rained for five consecutive days, the cumulative rainfall on day three is equal to the rainfall of day one, two and three combined. The total rainfall for that sequence is equal to the cumulative rainfall on day five. At day six, no rain falls. Hence, the cumulative rainfall becomes zero and starts counting again once another sequence of rain occurs.
3. The length of every rainfall sequence is summed. This is then divided by the total amount of rainfall sequences. This results in the average time-span of a rainfall event, denoted by $T_{rain,davg}$ in days.
4. The total rainfall of each rainfall sequence is summed. This is then divided by the amount of rainfall sequences. This results in the average cumulative amount of rainfall per sequence, denoted by $I_{rain,davg}$ in mm.
5. Sequences of periods of drought are determined by checking whether the day before was dry for each day.
6. The length of every drought sequence is summed. This is then divided by the amount of dry sequences. This results in the average time-span of a rainfall event, denoted by $T_{dry,davg}$ in days

This results in the following values:

- $T_{rain,davg} = 1.99$ days.
- $I_{rain,davg} = 10$ mm.
- $T_{dry,davg} = 1.89$ days.

A.2 Hourly

This step by step process has been performed on an hourly basis as well. However, the intensity has not been determined for the hourly analysis. The hourly data is accurate till 0.2 millimeters per hour. The data provided covers January 2023 till May 2023. The following results are found:

- $T_{rain,havg} = 2.67$ hours.
- $T_{dry,havg} = 15.09$ hours.

B Results analysis for further selection

Table 3 shows the intensities and lengths of various rainfall events for precipitation events taking place twice a year (0.5) till once every 1000 years. The green cells indicate the rainfall events that have been run in the base model. The blue cells indicate rainfall events that have been run and chosen for elaborate analysis afterwards.

Table 3: Recurrence rates for various rainfall events (STOWA,2019)

Recurrence rates(years)	10 min	30 min	60 min	2 hours	4 hours	8 hours	12 hours	24 hours	2 days	4 days	8 days
0,5	8,1	10,4	12,6	15,3	18,6	22,2	24,6	30,4	38,6	50,4	68,3
1	10,2	13,5	16,2	19,5	23,4	27,7	30,5	36,8	46	59,3	79,4
2	12,2	16,6	20	24	28,4	33,4	36,5	43,8	54	68,6	90,5
5	15,1	21,2	25,8	30,7	35,9	41,7	45,2	54,2	65,5	81,4	105,1
10	17,5	25,3	31	36,8	42,8	49,1	52,9	63	74,9	91,6	116,1
20	20,3	30,2	37,2	44,2	51,1	58	61,9	72,6	85	102,1	127
25	21,3	32	39,5	46,9	54,1	61,2	65,2	75,9	88,5	105,6	130,5
50	24,7	38,2	47,7	56,5	64,8	72,5	76,6	86,9	99,5	116,6	141,5
100	28,7	45,8	57,7	68,4	78	86,2	90,2	98,9	111,4	128,1	152,3
200	33,4	55	70	81,3	88,7	95	98,1	112,1	124,2	140	163,2
250	35	58,4	74,5	86,5	93,9	100	102,9	116,7	128,5	143,9	166,7
500	40,8	70,4	90,7	105	112,2	117,5	119,6	131,7	142,5	156,4	177,5
1000	47,6	84,9	110,6	127,6	134,4	138,3	139,2	148,2	157,5	169,4	188,3

Table 4: Land parcel storage in Verloren Beek catchment in percentage of total rainfall for a: EDR and b: SPR. for various precipiation events based on length and recurrence rates

Recurrence rates(years)	60 min	24 hours	2 days	4 days
0,5		17,92	4,35	2,95
1		26,02	6,17	3,19
2		32,51	12,5	3,5
5		41,82	20,69	4,03
10		47,09	26,12	5,54
20				
25				
50				
100	47,37			
200				
250				
500				
1000				

Recurrence rates(years)	2 days	4 days
0,5	3,09	1,55
1	4,1	1,54
2	7,55	1,56
5	11,96	1,61
10	14,96	1,69
20		
25		
50		
100		
200		
250		
500		
1000		

By fitting the rainfall scenarios to the EDR and SPR structure, the assumption that these rainfall events take place between twice each year to once every five years is no longer valid. Therefore, the recurrence time is not referred to in this study.