Bachelor Thesis

THE EFFECTS OF PINCH CULVERTS ON THE GLANERBEEK WATER SYSTEM THROUGH THE USE OF A COMBINED SURFACE-GROUND WATER MODEL

Author Edison Bonilla s2031027

Institutes University of Twente

Waterboard Vechtstromen

Programme Bsc. Civil Engineering

Supervisors W. M. van der Sande

Ir. B. Worm

Ir. J. van der Scheer

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Summary

Dry periods and flooding have been exacerbated in recent years by rising temperatures and precipitation, which is predicted to continue. Droughts are particularly severe in Twente due to the soil's sand layers and the narrowness of aquifers, which means that only a little amount of water can be retained in the soil. Additionally, Twente's elevation relative to the rest of the Netherlands results in rapid evaporation of any extra water (Hasselerharm, M, 2020). Municipalities and other entities responsible for water management have investigated solutions. Vechtstromen serving as one of Twente's water management agencies conducted research on Twente's most effective and impactful water retention techniques. From this, it was determined that pinch culverts had the most potential for water retention improvement.

The purpose of this research is to ascertain the influence of pinch culverts on Glanerbeek discharge while also taking into account the dynamics of groundwater and surface water. Gabriëls' Sobek (2021) surface model was used to calculate the surface dynamics. For groundwater modelling, the MIPWA model, which is based on MODFLOW, was chosen. Both models were coupled together, and the results examined.

The results of this study demonstrated how merging a surface water and groundwater model can provide further insight into a water system's operation and responsiveness to interventions. For instance, it shows how pinch culverts contribute to groundwater recharge by increasing infiltration and consequently water retention. Over 10 years, the culverts with a 25% of its original diameter increase the volume of water entering the groundwater system by over 1 million cubic meters. Finally, a unified model provided a better understanding of the interplay between the surface and subsurface water systems, both in their current state and with the implementation of further measures.

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1 Preface

This article discusses the last assignment for my Bachelor Thesis, which was titled 'The effects of pinch culverts on the Glanerbeek water system through the use of combined surface-ground water model'. This project concludes the major element of my bachelor's degree in Civil Engineering at the University of Twente, which I completed in collaboration with the waterboard Vechtstromen.

Conducting this research and writing this report was not a simple task. Numerous technological and organizational challenges required time to fix, lowering the time available to address the remaining subjects on the agenda. As a result, everything that was supposed to be accomplished in the outset was unable to be accomplished. Regardless, I believe that this research has given me vital and exciting new insights into the consequences of structures such as pinch culverts on surface and groundwater systems. Additionally, the language barrier is a hindrance, not so much when interacting with my supervisors, who were always happy to assist, but also while performing research, as some crucial pieces of information were discovered in Dutch rather than English. The process was challenging at times but ultimately highly enlightening.

I am grateful to Vechtstromen for providing me with the opportunity to conduct this research and giving me as much assistance as possible throughout the duration of the research. Special thanks to my supervisors at the water board, Bas and Jeroen, who were always willing to assist me with any doubts or problems that I encountered, as well as checking in on me and ensuring that the research was conducted properly. Additionally, I would like to thank my student advisor, Ms. Judith Roos, for her constant assistance with any personal and administrative issues that I encountered not only while completing my report but throughout my studies. Finally, I want to thank my family and friends for their constant encouragement and guidance, which provided me with the motivation to continue my research.

Edison Bonilla

Enschede, November 24 , 2021

2 Introduction

This section will provide an overview and general notion of the project. The context of the problem will be introduced in Section 2.1, followed by a description of the problem in Section 2.2, which will lead to the justification for writing the report. Section 2.3 will then detail the research's objective and research questions. Finally, Section 2.4 will include an outline of the report.

2.1 Problem Context

Climate change has emerged as a critical issue in the global context in recent years. This unsurprising interest in global climate change stems from the alarming rise in temperatures. According to a study published in 2018 by the Intergovernmental Panel on Climate Change (IPCC), global temperatures increased by approximately 1°C in 2017 and are expected to continue increasing by approximately 0.2°C every decade (IPCC, 2018). Continuously rising temperatures, combined with increased precipitation, have caused a number of droughts and inundations around the world, with the effects expected to worsen.

Droughts are more severe in Twente than in other places because the majority of the soil is made up of higher sand layers. Furthermore, the water-permeable layers (aquifers) of the ground are very thin, implying that only a small amount of water can be retained in the soil. Further to that, due to Twente's elevation relative to the rest of the Netherlands, the soil quickly becomes saturated, and excess water is quickly released (Hasselerharm, M, 2020). This combination of characteristics found in the region of Twente, and in this case, the Glanerbeek region, causes water to drain quickly, resulting in dry water channels during dry periods.

The drought is affecting both the region's surface and groundwater systems. This has compelled municipalities and other entities in charge of the region's water supply to seek solutions to these problems. Vechtstromen is one of the aforementioned entities in charge of water management in the Twente region, which, as previously stated, is one of the more drought-prone regions. Vechstromen has conducted numerous studies ((Attema., M. J., 2020),(Gabriëls, S, 2021),(Hehenkamp, M. , 2019)) in the Twente region on various methods of water retention in order to determine the most effective alternative and the effects of these interventions. In terms of increasing a water system's water retention capacity, pinch culverts were the most promising approach.

2.2 Problem Description

The creation of models was required to assess the pinch culvert's influence on the system. Hehenkamp (2019) used the software SOBEK to create a one-dimensional representation of the surface water network in order to investigate these effects on the water system. He discovered that the beneficial effects of water retention due to pinch culverts on maximum discharges could be demonstrated with certainty in the model. Furthermore, the outcomes of the study strongly show that the actions will benefit the groundwater table.

While Hehenkamp's surface water model produced encouraging results in the Glanerbeek area, Gabriëls enhanced it by including Attema's (2020) Walrus runoff model (Gabriëls, S, 2021). Gabriëls used the properties of the Walrus model and blended them with those of Hehenkamp's model, resulting in a model that provides a more accurate representation and calculation of the water system's discharges. This new unified and improved surface model was used to anticipate the region's impact of pinch culverts under present and future climate conditions. As a result, it was established that these structures increased the region's water retention capacity by reducing

water system discharge (Gabriëls, S, 2021). This cannot be determined completely, however, because the groundwater system in the region has not been modelled and its behaviour examined. All of the studies cited above demonstrate that pinch culverts are an effective measure for drought prevention; however, these studies also demonstrate how these impacts could be seen on the groundwater system, although this cannot be said with certainty because none of the experiments modeled this system.
One could argue that there are legitimate reasons to believe that pinch culvert installation will have an impact on the groundwater system. However, no data to support this hypothesis has been presented, implying that there is a research gap in the interaction of the surface and ground water systems.

2.3 Research Aim and questions

The purpose of this study is to ascertain the influence of pinch culverts on Glanerbeek discharge while also taking into account groundwater and surface water dynamics. Finally, it is intended to assess whether incorporating the groundwater system affects the evaluation of the water retention effect of pinch culverts. This would be accomplished by integrating a previously developed surface-water model with a groundwater model. As previously stated, this analysis will concentrate on the groundwater model and its coupling with the surface-water model, as the surface-water model's calibration and features will be derived from past research. While this study will focus on pinch culverts, it is expected that the required tools, most notably a new integrated model, will be developed for assessing future field measures.This will be accomplished by responding to three research questions.

1. How can a surface-water model be coupled to a groundwater model?
2. What is the influence of pinch culvert on the retention capacity, when groundwater dynamics are considered?
3. What advantages and novel insights does the combined model offer in terms of analysing the influence of pinch culverts in a water system?

2.4 Report Outline

This section has introduced the research by explaining a problem and giving background information on previously performed studies into the subject. The next section will provide more general information on the models, data and study area used throughout the study. In the section 4 the methods used to answer the research questions are described as well as more detailed explanation of the process to couple the models. The results of this are presented in section 5. A discussion of the results and the research is given in section 7. Finally, the report concludes with conclusions and recommendations in section 6.

3 Study area and models

This section will explain and elaborate on the models and pinch culverts in order to aid in the comprehension of the rest of the report. To begin, a synopsis of the study region and a description of pinch culverts will be provided; following that, a brief description of the two distinct models that will be combined will be provided.

3.1 Glanerbeek area

The research area is the Glanerbeek water system, which consists of a small river in the eastern Netherlands. Figure 1 depicts the research region and its water bodies. It's worth noting that this location was initially identified by prior research because its characteristics may be considered representative of the Twente region.

Agriculture occupies over half of the area's 800 hectares. The remaining half of the region is dense forest with a few small lakes (Hehenkamp, M. , 2019). A critical quality that influenced the research region's selection was the area's hydro logical system's separation from its surroundings; this simplifies the study procedure by reducing the amount of external issues that must be addressed. In other words, the research region's surrounds can be ignored because external influences on the area's water system are quite minor.

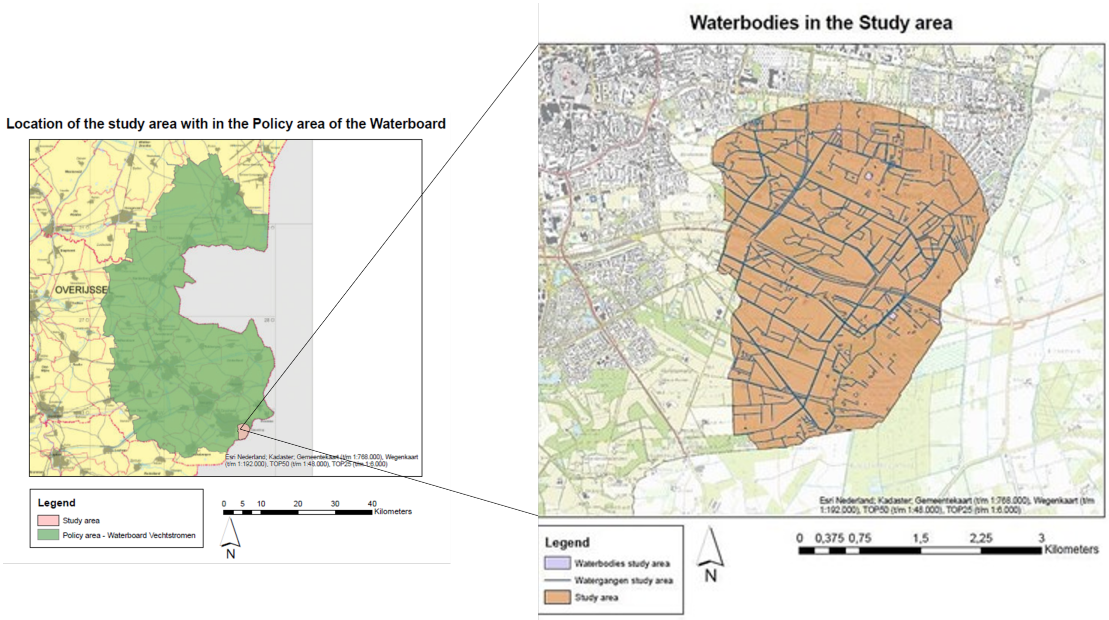

Figure 1: Study Area location (Hehenkamp, M. , 2019)

3.2 Pinch culverts

A culvert is a tube that connects multiple bodies of water as it can be seen on figure 2. Culverts are primarily underground structures that allow water to flow freely between two points without being obstructed by a dam or a road. By constructing a culvert, water can flow freely across an area, hence increasing discharge. A pinch culvert is similar to a culvert, except that it is not designed to drain entirely during severely wet conditions. This is accomplished by limiting the quantity of water that can run through it. As a result, more water is retained behind the culvert. It is worth noting that the effectiveness of these structures is dependent on how they are constructed; for example, how much smaller the area where the water passes through is, the more water it can retain; additionally, the location of the flow-throw gap is important, as its placement in relation to the stream's soil height can affect the pinch culvert's effectiveness. Figure 2 illustrates a pinch culvert.

Figure 2: An example of a culvert (left) and a pinch culvert (right) (Hehenkamp, M. , 2019)

3.3 Models

In order to meet the objectives of this assignment, the surface and ground water models Sobek-Walrus and MIPWA were coupled. This section will provide a description of each of these models, as well as the reasons why those models were chosen to be integrated and analyzed in this study.

3.3.1 Surface water Model

Sobek is a Deltares-developed integrated software package for river, urban, and rural management. Its integrated framework enables Sobek to connect river, canal, and sewer systems for a total water management solution, making it ideal for the purpose of this proposal.
This model enables engineers to create precise and straightforward models of water systems, allowing them to assess the behavior of diverse systems and use the generated data to make water management decisions. The Sobek model is based on high-performance technology, which enables it to operate on any type of network, whether large and complex or small and simple. This is one of the software's primary advantages, and one of the reasons it was chosen, as it can be used to model not only a small area like Glanerbeek, but also a much larger one (DELTARES, 2019). The model is structured, which means that input data and simulation settings must be entered first, and the simulation cannot begin until the model is completed. To create a representation of a particular area, nodes must be added to an existing or new system and connected via linkages. These nodes can be classified as weirs, channel cross-sections, or inflow locations, which enables the creation of a very detailed model as it can be seen on figure 3.

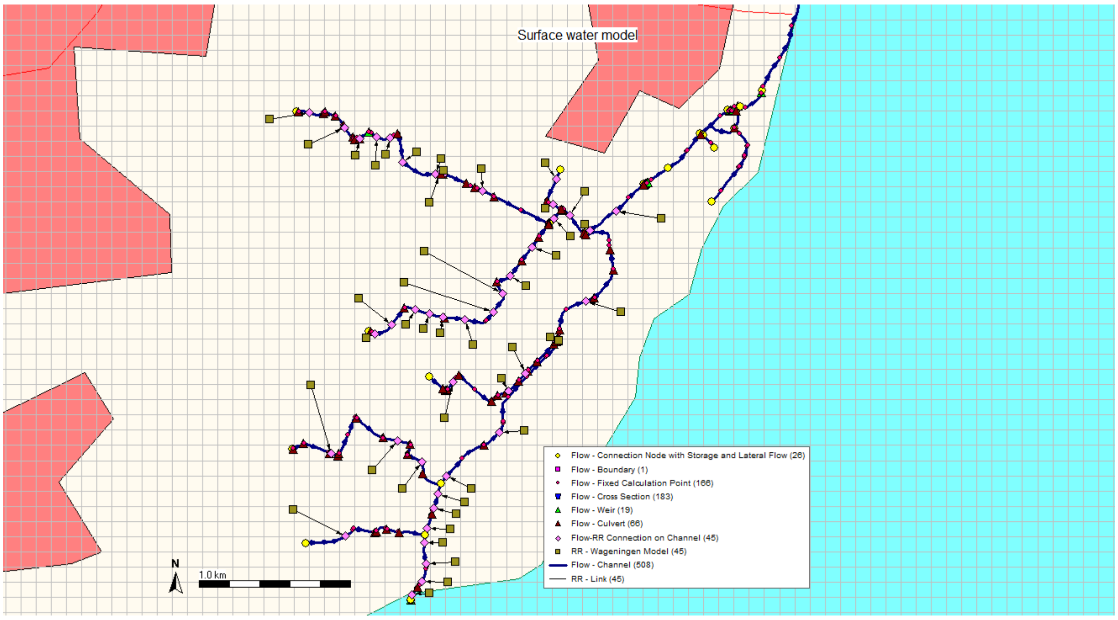

Figure 3: Surface water model network and nodes

In the figure 3 it can be seen a particular type of node call RR-node. The hydraulic model is given rainfall and runoff data via an integrated rainfall/runoff model (RR-nodes).In this instance, the Walrus is the RR kind. In the original Sobek model, each zone receives an equal amount of rain. While some of this rain evaporates, the overwhelming majority is collected and stored by the water distribution system. Each segment of the area is represented by an RR-node, and each of these nodes is associated with the Walrus parameters calibrated by Attema (2020), allowing Walrus to automate this technique. When a time series of precipitation and evaporation is detected, the nodes use the Walrus model (shown at Appendix A) to determine the amount of water flowing from the land into the water channels.

3.3.2 Ground water Model

Many water partners in the northern Netherlands have worked together to create the MIPWA. The MIPWA model has a high level of detail, since it can model large number of surface water bodies ranging from the smallest ditches to the largest lakes (Berendrecht, W.L, nda). All basic information from the MIPWA groundwater model has been compiled in a groundwater model reference database. The reference database has a high resolution (25×25 m) and covers a region of approx 145×167 km. The model covers the area of interest plus a buffer area to decrease the impact of the model boundaries. The database is made accessible via the interactive user environment iMOD. As iMOD, model input and output may be displayed and studied, both in map pictures and in time series or profiles. In addition, the MIPWA model can be calculated straight from iMOD (Berendrecht, W.L, ndb).
The most recent version of the model was intended to be utilized as the starting point for this project. However, this version faced issues whenever attempts were made to modify the research region's coordinates. As a result, a previous version of the model was given and chosen. A test run was conducted, and there were no issues detected.

4 Methodology and coupling of the models

This chapter describes the procedures followed in order to address the research questions specified in Section 2.3. These techniques are applied to all study topics in order to ensure that the answers are visually comparable. The procedure for integrating the two distinct models, as well as any modifications to these models, is first discussed. Following that, a summary of the various model scenarios is provided. Finally, the procedure for calculating infiltration is discussed, as well as the various groundwater levels.

4.1 Data used

The ground water model uses spatially distributed data to represent precipitation values. On the other hand, the Gabriëls (2021) surface model is based on precipitation data collected near the research region at a measurement station. The distinction between these two types of data is in how they were obtained; geographically dispersed data, as the name implies, is gathered from multiple places on a map, whilst the other form of data is gathered from a single spot. This on-site data collection technique may result in over- or under-estimation of some peaks located far from the location where the data was collected; however, the difference in values between the two sets of data was quite modest. As a result, it was decided to use earlier Gabriëls (2021) precipitation and evaporation data. This means that both models will be calculated using data from the period 1 January 2000 to 31 December 2010.

4.2 Coupling of the models

To create a cohesive model, it was critical for the models to communicate with one another. As a result of the differences between the two models and the assembly's rigorous time constraints, an interactive technique was judged unworkable. The models do not communicate with one another during operation; rather, each model communicates with the other independently. This means that to combine the MIPWA and Sobek models, the Sobek model's computations and findings were supplied as input to the MIPWA model as is shown on the diagram of figure 4.

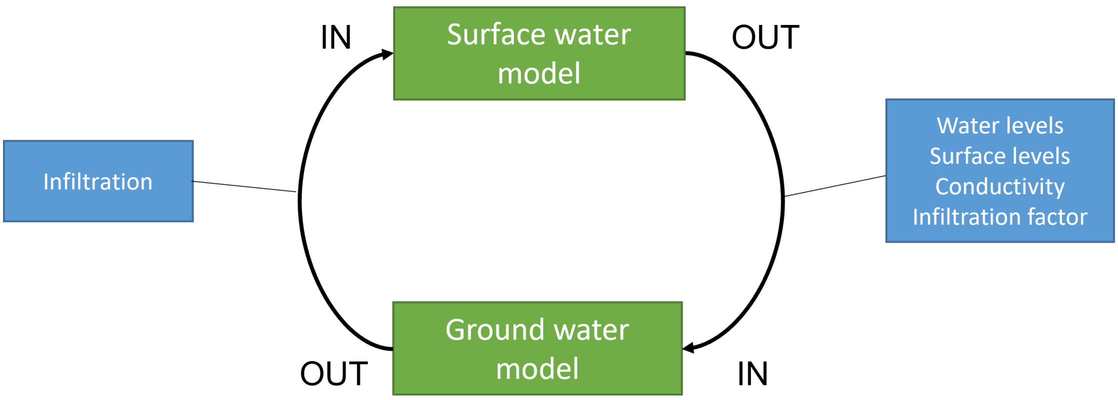

Figure 4: Diagram representing the interaction between the models

When using the Sobek model, it is not possible to obtain water levels of zero meters, which means that a proper draught cannot be represented. Using a surface water model, this does not pose any difficulties, because a straightforward solution is to use a minimum water height as a new zero and subtract this value from the model's height results, thereby providing an answer to the problem. When the groundwater component of the system is included, however, the availability of water on the surface becomes critical, because the ground water model requires accurate dry watercourses, as otherwise unavailable water infiltrates, resulting in exaggerated estimations.

To address this issue, a strategy was devised that involved extracting water from the surface model in order to reduce any excess water that in real life is not available. This extraction was modelled in the surface water model using negative later flow discharges to approximate the extraction. However, in order to acquire the correct extraction values, a feedback loop between the two distinct models was required. The surface model will be completed first, so that the relevant files and variables may be generated for the next stage. To be more precise, the values for the surface water level, the surface level, the conductivity, and the infiltration factor.

The groundwater model is then run, using the values obtained from the surface-water model to calculate infiltration and drainage. The infiltration values obtained from the groundwater model are presented in raster form, which means that each point in the study area has an infiltration value. Because these infiltration values are the same to those that will be extracted from the surface model, it was necessary to calculate the total infiltration across the catchment areas. Figure 5 illustrates these catchment areas. The total infiltration over the points that defined these catchment areas was calculated by adding them together, yielding a value that corresponded to the catchment area's total infiltration.

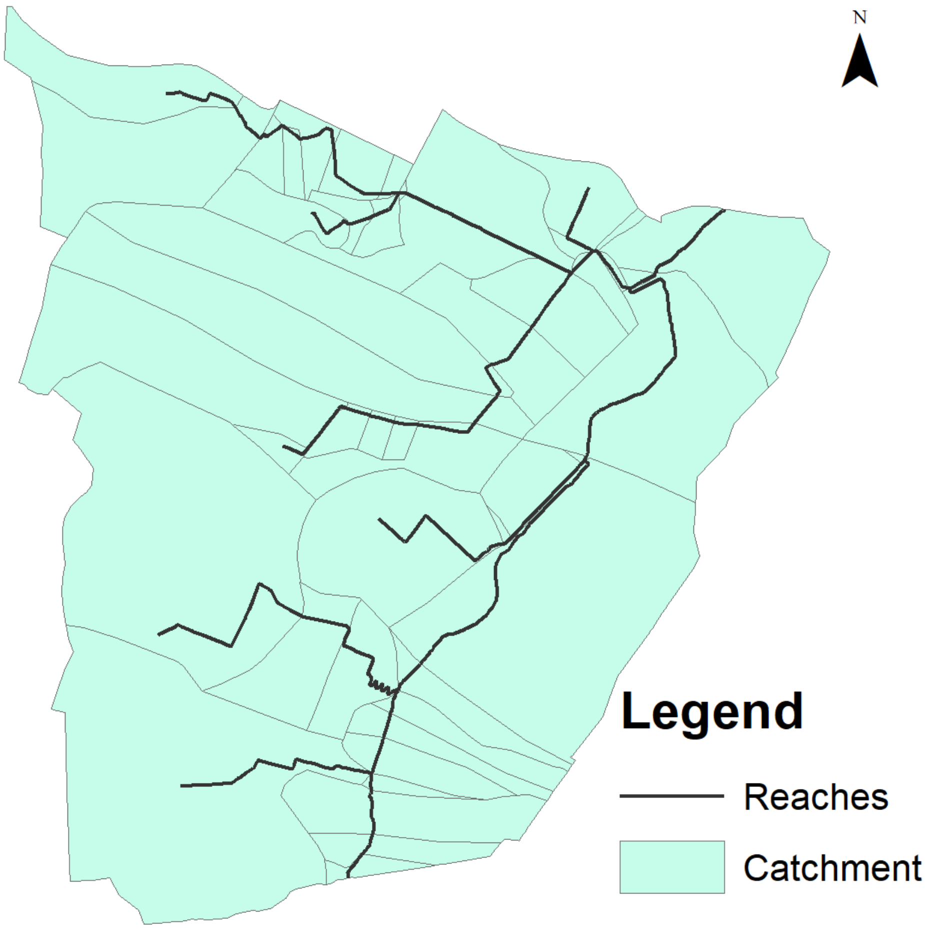

Figure 5: Catchment areas over the study area

Following the path of the loop shown in figure 4 the infiltration values are input on the surface-water model, but as extraction. This is accomplished through the use of a tool called lateral flow that is included in the surface-water model. This lateral flow is a discharge that can be used to supplement or deplete a water course's water supply. The lateral flow tool can be a node, which means that the discharge occurs at a specific point, or a reach, which means that the discharge occurs along a water course. Both of these types of lateral flow were used; the following section explains why each was used and in which scenario. After implementing this lateral flow in the surface-water model, the model is run and the refinement result is used as input to the groundwater model. The groundwater model is rerun and its output is evaluated. This completes one iteration of the loop depicted in Figure 4, ensuring that the models are coupled since both models communicate via their respective inputs and outputs.

4.3 Scenarios

As mentioned in the section 4.2, the lateral flow tool have different types node and reaches. The explanation of which type and any other modification made to the mode in each scenario is explained in the following sections.

4.3.1 Base Scenario

Apart from the incorporation of lateral flows, the surface model remained unchanged. On the upstream side of all of the systems' weirs, these lateral flows were implemented. Because this is the most likely location for water to accumulate, it is the best location for water extraction from the system. Due to the fact that water is only intended to be extracted at particular spots on the map, a node lateral flow was utilized to avoid pulling an excessive amount of water from the network. Given the fact that the bulk of weirs were located in four distinct catchment zones, only their infiltration values were employed. In figure 6, a yellow diamond indicates the location of the node lateral flows. Except for the modifications described in Section 3.3.2, no changes to the groundwater model were made.

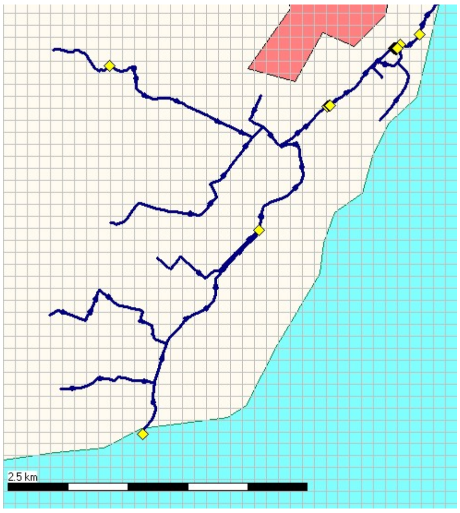

Figure 6: Base scenario network with lateral discharge

4.3.2 Pinch culvert Scenario

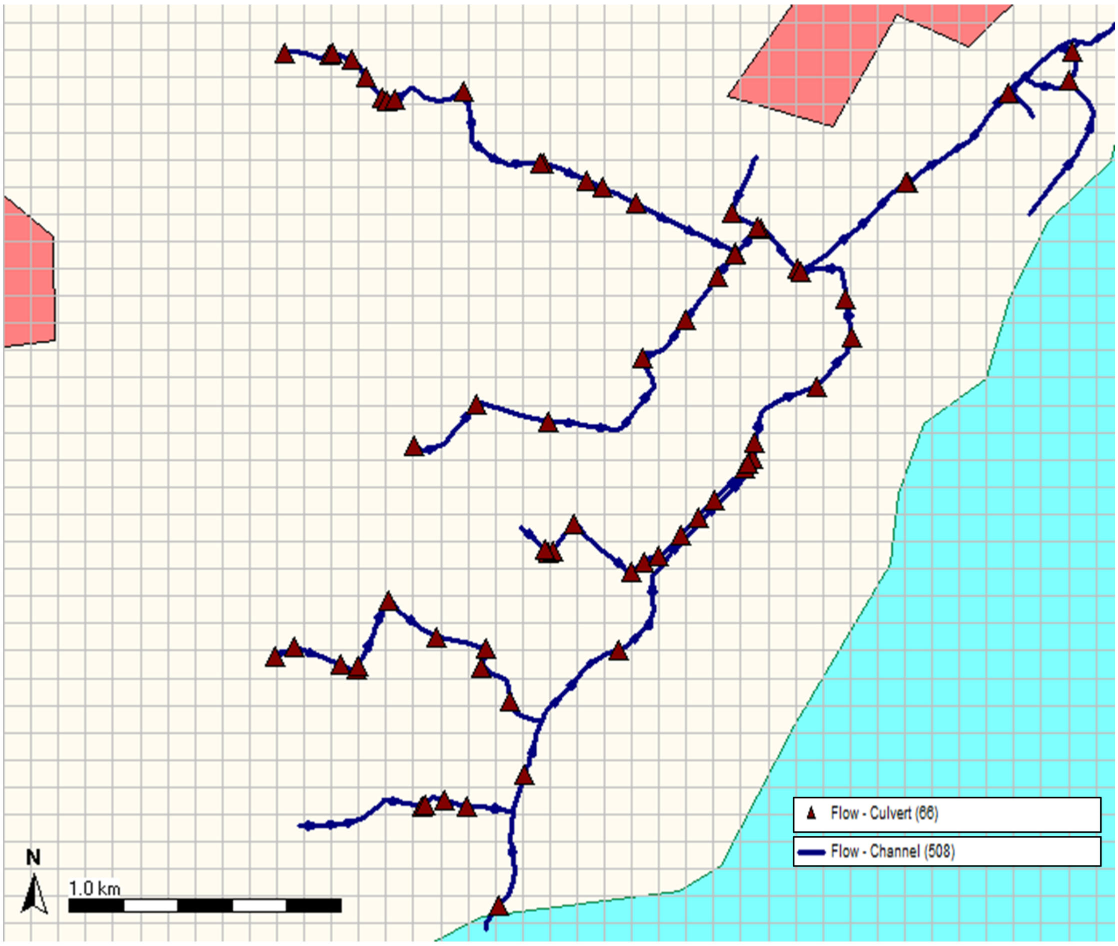

Figure 7: Pinch culvert locations on the model

The modelling of the pinch culverts were done in the surface water model, were the diameter of the culverts were reduced to a 25 % of its original size. This approach is similar to the approaches performed by Gabriëls (2021). In this case, the best spots for locating extraction points will be upstream of the pinch culverts (see figure 7), because their function is to retain water, and thus the points with water accumulated will be upstream of this structure. Similarly to the base scenario, it is critical to avoid extracting too much water, as this will cause the model to crash. As a result, a reach lateral flow was used to model the extraction process, as it is more efficient. Because the lateral discharge's reach option extracts water alongside the water course, the extraction values for each of the 13 water courses that constitute the model had to be calculated. To begin, catchment areas were reclassified based on which water course they are in contact with. As a result, 13 new combine catchments were discovered (see figure 8). The infiltration value relevant to these catchment areas was taken from the groundwater model results and divided by the length of the water course to which they belong; the result was used to calculate the amount of water extracted along each water course over a ten-year period.

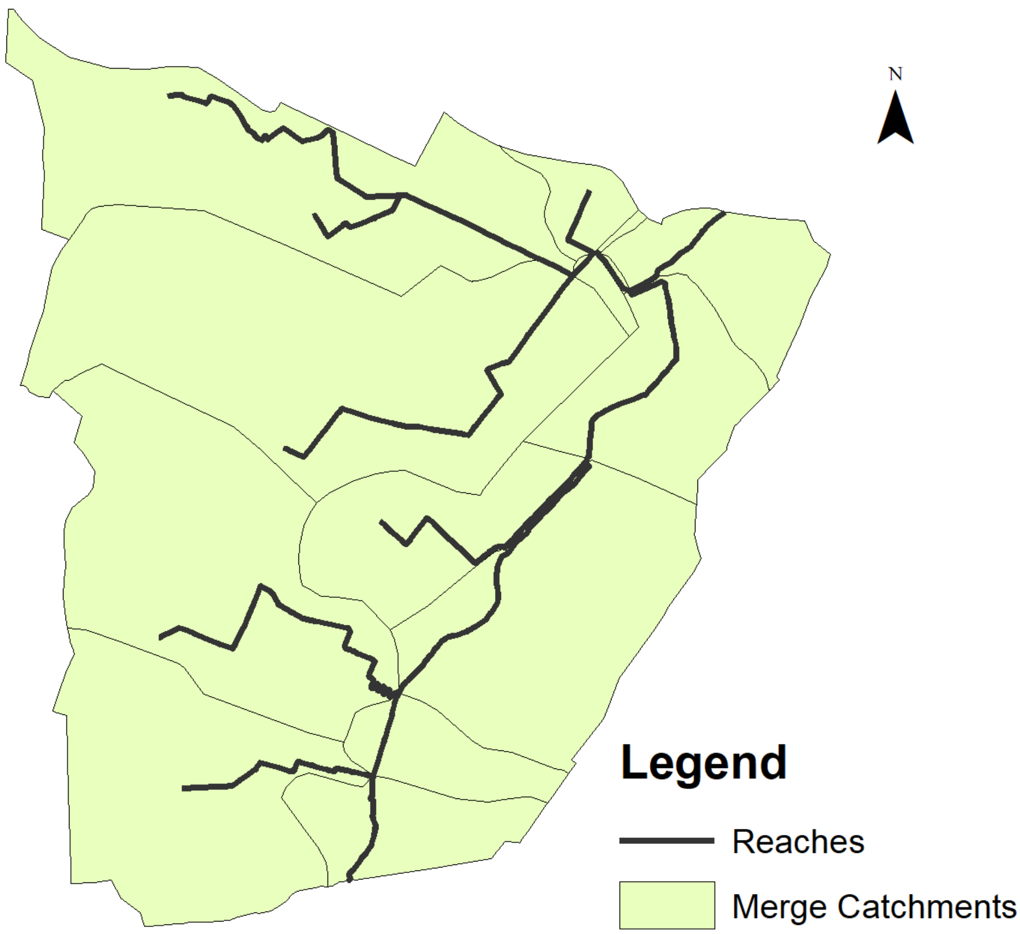

Figure 8: Base scenario network with lateral discharge

4.4 Calculating Infiltration

The locations from where the results were extracted are illustrated in figure 9; from these locations, the infiltration among the nine layers for each day was analysed. These points are located near agricultural areas and in reaches with culverts. This is why these points were chosen, as Vechtstromen intends to locate pinch culverts in agricultural zones above all else, due mainly to the critical nature of water retention in these areas.

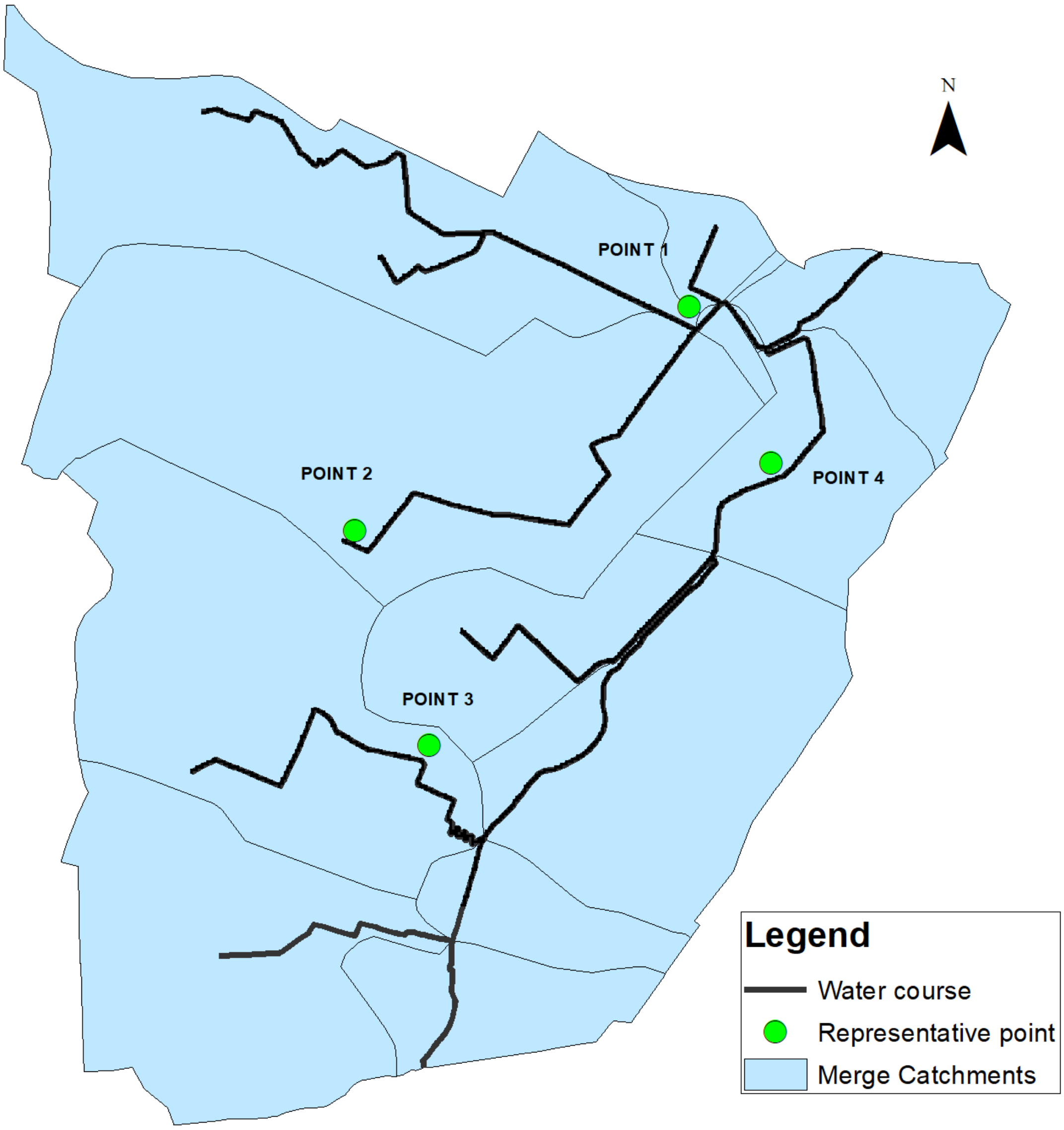

Figure 9: Representative points along the study area

4.5 Calculating GxG

GxG is the name that is given to the set of different measurements such as GHG and GLG; these measurements are an efficient way to analyze the output of a groundwater model, since is consistent and easy to understand. The term "GHG" denotes the average maximum groundwater level, whereas "GLG" denotes the average minimum groundwater level. Annually, between April 1 and March 31 (hydrological year), the three highest groundwater levels are averaged, and the ten-year average of these annual values is used (Knotters, M., nd).

These values were calculated for both the base and pinch culvert scenarios. The difference between the pinch culvert scenario and the base scenario was calculated based on this. These values were derived from the same points shown in figure 9.

5 Results

The results of the experiments are visualized and illustrated in this section. The infiltration and GxG values are shown. Finally, an overall comparison of these findings to previous research findings is performed.

5.1 Infiltration

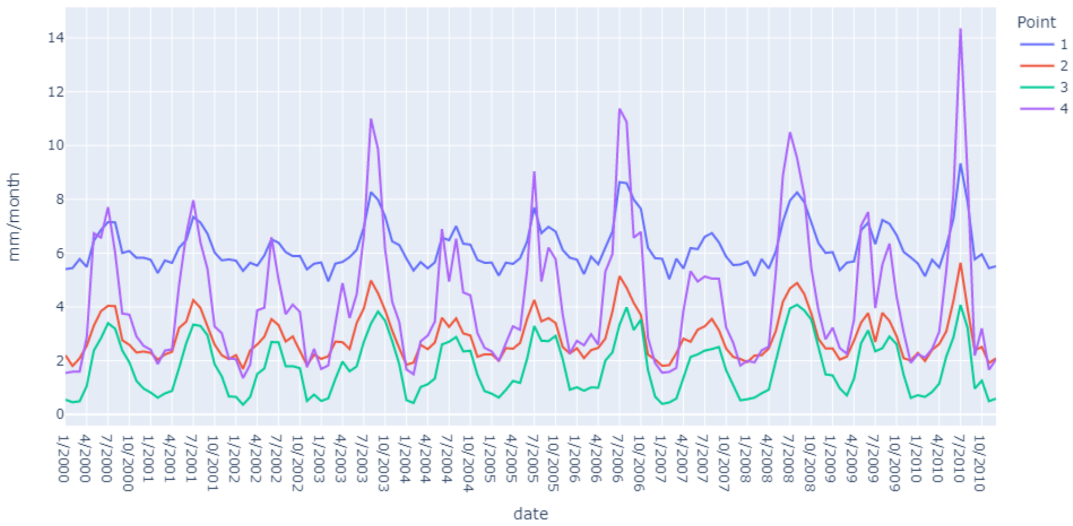

Figure 10: Infiltration results of the Base Scenario over the years

The figure 10 depicts the infiltration values for the base scenario derived from the four distinct areas of the places specified in Figure 9. These numbers represent the total amount of infiltration measured in millimeters per month during a ten-year period. As seen in the figure, point 4's infiltration has the greatest values of the other locations, which is consistent with its location in the system's downstream portion. It's also worth noting how a consistent pattern emerges across all four data points, with the lowest values occurring around January and February and the largest values occurring around July and August.

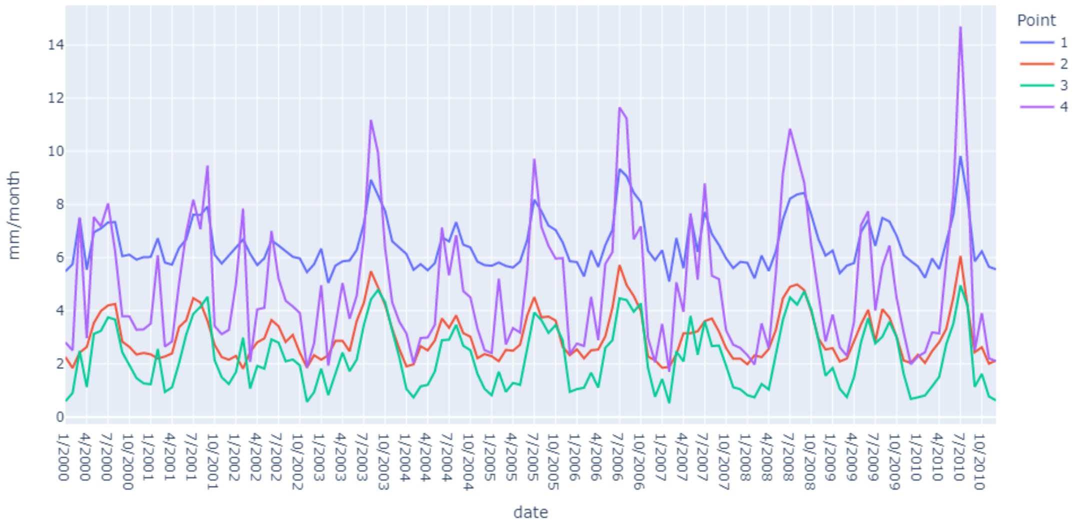

Figure 11: Infiltration results of the Pinch culvert Scenario over the years

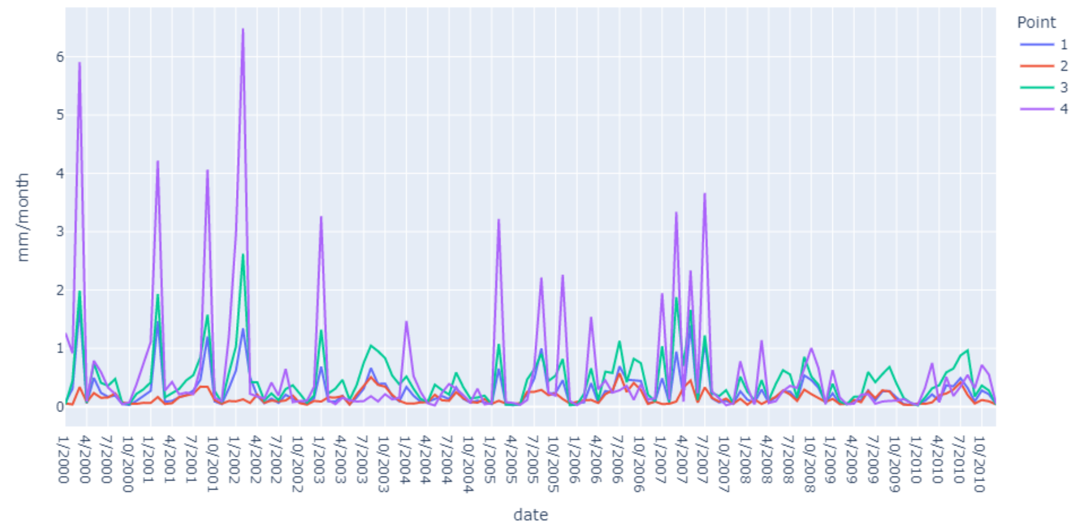

Figure 12: Infiltration results of the Different among the Base and Pinch culvert Scenario over the years

The results for the pinch culvert scenario are depicted in Figure 11. The same pattern of peak values is observed in this picture as in the base scenario (Figure 10). However, there is a significant difference between the months of January and March, when the pinch culvert scenario values are higher than the base scenario values. This is illustrated more clearly in Figure 12, where the biggest peaks occur during the initial months of the first years. This suggests that pinch culverts increase infiltration levels throughout all four separate sites, more so in the months when the infiltration is low than during peaks .

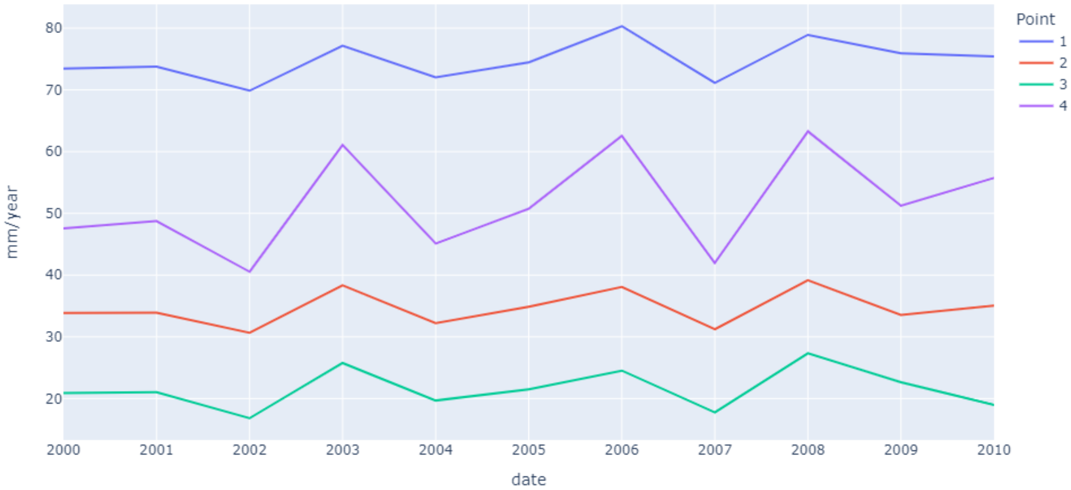

Figure 13: Infiltration results of the base scenario over the ten years

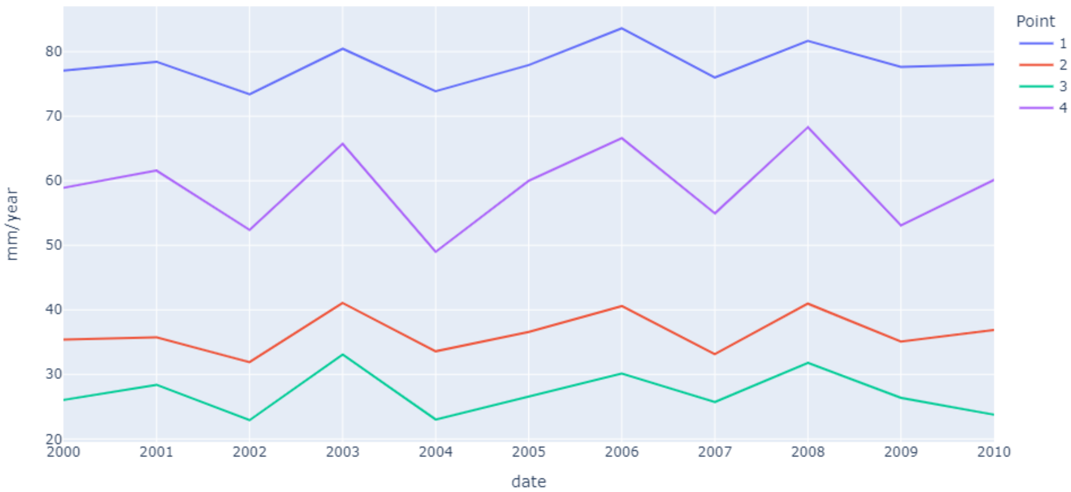

Figure 14: Infiltration results of the pinch culvert scenario over the ten years

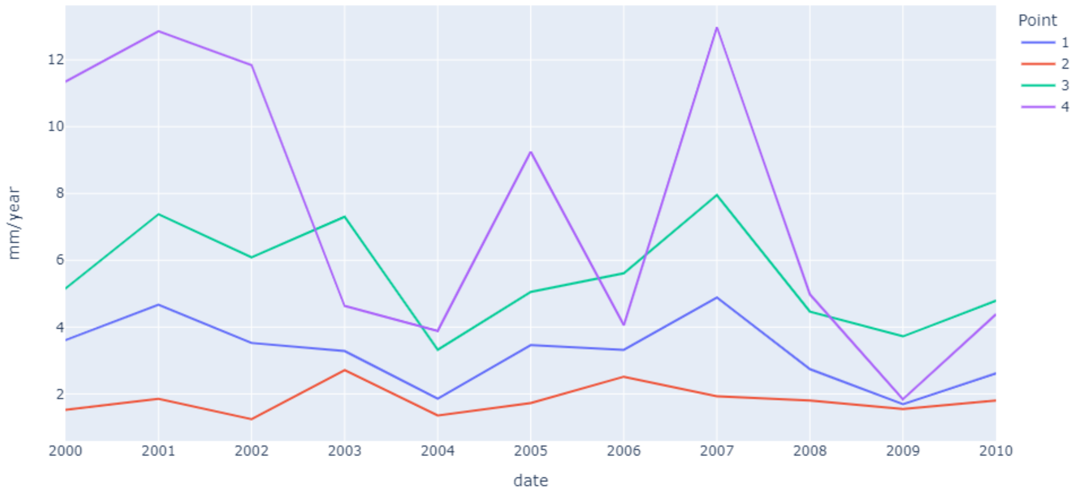

Figure 15: Infiltration results of the difference between the pinch culvert scenario and the base scenario over the ten years

In order to have a better understanding of the results, a more general display of the infiltration values is shown in figures 13 and 14 which illustrate the infiltration values throughout a ten-year period. As observed in these charts, the 2003, 2006, and 2008 peaks are nearly identical for both situations. However, similar to the preceding paragraph, the lower values are significantly greater in the pinch culvert scenario than in the base scenario. Additionally, the difference between the Pinch culvert and Base scenarios can be seen in Figure 15 where the largest peaks in this figure occur in the first three years (2000, 2001, 2002) and in 2007, which correspond to the base scenario's lowest values.

It is obvious from this graph that the installation of pinch culverts increases the amount of water that infiltrates into the groundwater distribution system. It can be seen in the figure 15 that for some points, the difference is as little as 2 mm each year, yet for other points, the difference can reach even 14 mm.

In summary, as demonstrated by comparing the combined findings of the two models, pinch culvert construction has an effect on the groundwater system. This is also evident when we look at the total overall difference (Pinch culvert - Base) over ten years, which is nearly 200 mm, indicating that the amount of water that is fluxing from the surface to the groundwater system increases by approximately 20 mm each year after implementing the pinch culverts. Considering the area of the representative points , 20 mm of additional water per year is not a sizable amount.

5.2 GXG values

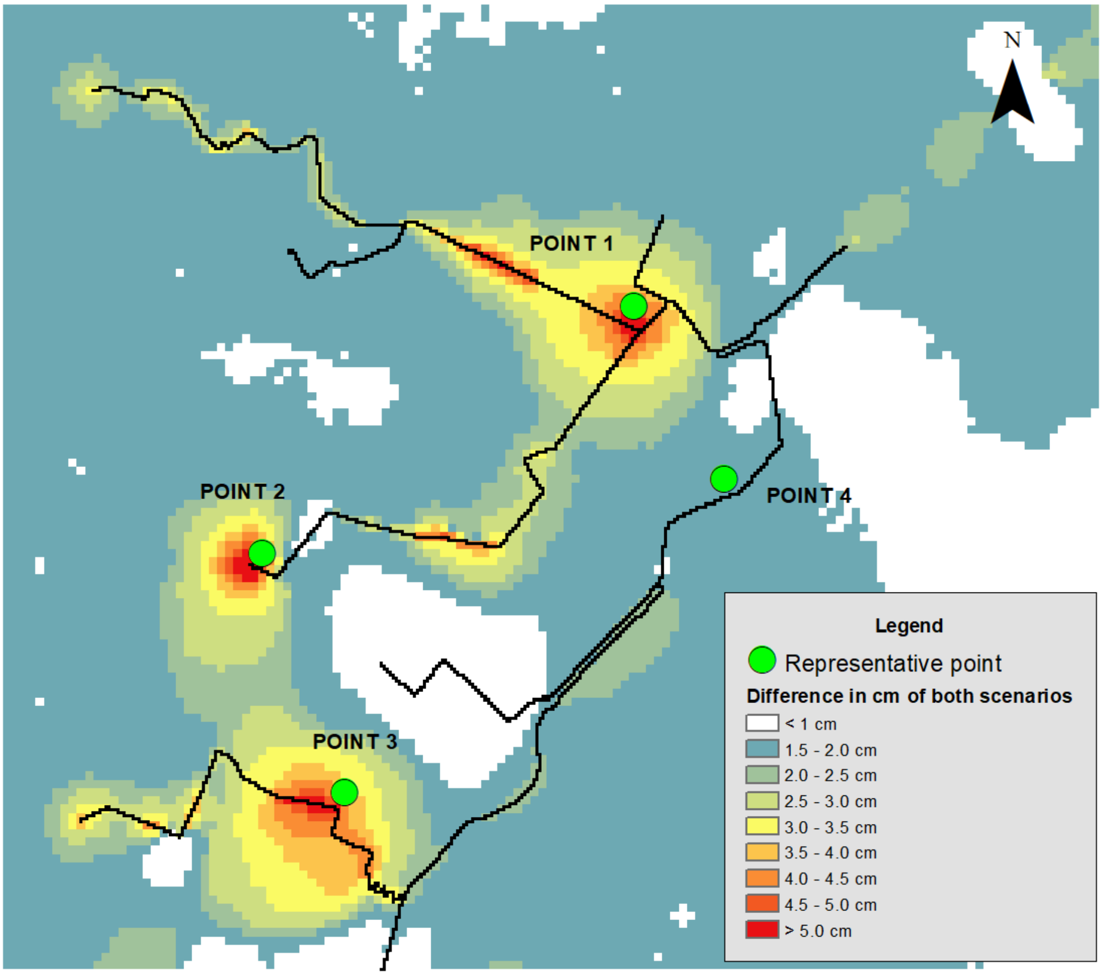

Figure 16: GHG map representing the effects of pinch culverts

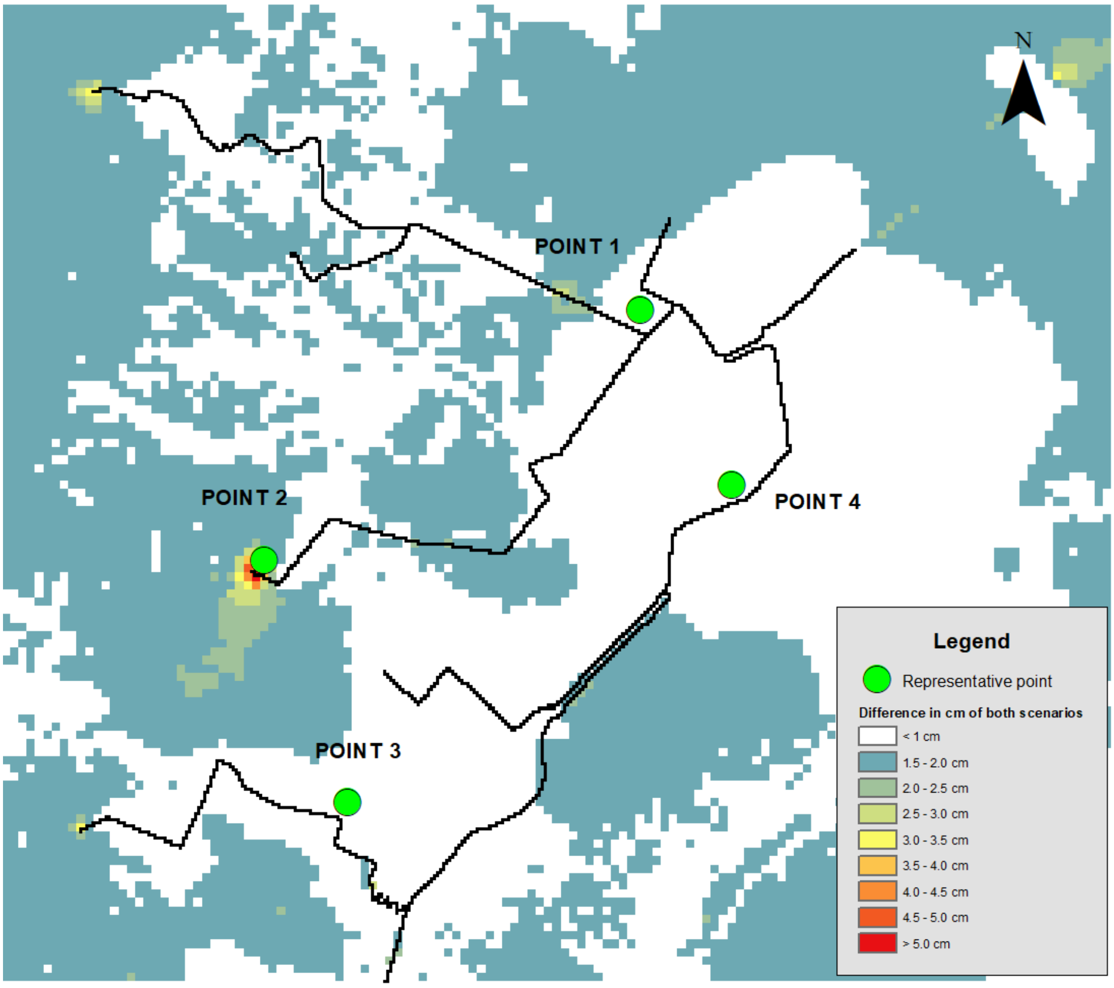

Figure 17: GLG map representing the effects of pinch culverts

The figure 16 depicts the difference in GHG values between the pinch culvert and basic scenario, whereas the figure 17 illustrates the difference in GLG values between the scenarios.
According to the legend, the overall difference throughout the entire map is positive, indicating that the pinch culvert scenario's groundwater system has higher groundwater levels than the base scenario. As illustrated in figure 16, the greatest difference (greater than 5cm) occurs at points 1, 2, and 3, whereas the difference in GHG values between these two scenarios is almost negligible at point 4. This pattern can be attributed to a variety of factors; for example, point 1 is located at the confluence of three distinct water courses; additionally, it is located near the downstream portion of these water courses, which means that the majority of the water will accumulate on these zones; the more water available, the more water will infiltrate, increasing the groundwater level of these points. On the other hand, point 4 is located in the most forested area of the map, which means that the majority of the water is retained by trees and other plants, reducing the amount of water available to the groundwater system and thus lowering groundwater levels.
Additionally, Figure 17 illustrates the difference in average low groundwater levels between the two scenarios. As illustrated in the figure, the majority of the sites on the map differ by less than

1 cm, meaning that the difference in groundwater levels between the two scenarios is minimal when considering the minimum groundwater levels at the majority of the representative spots (1,3,4). The representative point number 2 has the highest values on the map (more than 5 cm), showing that pinch culverts have the greatest effect on low groundwater levels in this location. This confirms what the infiltration values indicated, namely that the deployment of pinch culverts increases the volume of water diverted toward the groundwater table. However, this difference is not significant, which may indicate that the pinch culvert's schematization was not completed effectively or that it requires refinement. In other words, by enhancing the modelling and representation of pinch culverts on both models, the amount of effect demonstrated might be increased. Maps of the different GXG results can be found on the Appendix C.

	Base		**Pinch Culvert**		**Difference**	
Point	*GLG*	*GHG*	*GLG*	*GHG*	*GLG*	*GHG*
1	72.90	125.34	74.48	131.60	1.58	6.26
2	81.60	140.37	83.05	148.80	1.45	8.43
3	85.26	165.30	86.02	169.03	0.76	3.73
4	84.55	133.27	87.05	133.36	2.50	0.09

Table 1: GxG values (in centimeters) of the interest points.

As illustrated in Table 1, the different GXG values obtained for the various interest points can be compared, demonstrating that the points where the reaches experienced a high infiltration rate also have the highest values.
It should be noticed that the map's bottom section in figures 16 and 17 is not represented, in comparison with other figures of the study area. This part of the map was discovered to be troublesome, because of the way certain components of the Glaneerbeek water system are portrayed. This will be discussed in further detail in the subsequent section.

5.3 Comparing results with previous studies

Gabriëls, S (2021) developed and validated the Sobek + Walrus Model utilized in this investigation. Additionally, both experiments employed the identical precipitation, evapotranspiration, and pinch culverts information. Gabriëls, S (2021) described how pinch culverts lowered peak discharges, hence increasing the amount of water retained; however, it was observed over the course of this research that the additional stored water penetrated rapidly into the groundwater once the pinch culverts were constructed. This means that during a drought, a properly built pinch culvert may be able to retain sufficient water to compensate for water loss due to rapid floods. According to Gabriëls, S (2021), a pinch culvert has a substantial effect on the output of a water system. This is consistent with the report's findings, which indicate that pinch culverts can increase the amount of water accessible for infiltration, hence reducing the amount of water discharged at the system's downstream part.

6 Conclusions and Recommendations

6.1 Conclusion

This study demonstrated how a surface water model and a groundwater model can be combined to acquire additional information about a water system and the effect of applied interventions. The study demonstrates how pinch culverts increase groundwater levels by increasing infiltration and thus water retention in the surface-ground water system. Over the 10 year period, the pinch culverts with a diameter of 25% of their original size will increase the amount of water entering the system by nearly 1 million cubic meters. This value was calculated by multiplying the total amount of water infiltrating (200 mm), as illustrated in Section 5, by the total area of the four representative points (4.6 square kilometers). Given the area's size, the total amount of infiltration is minimal. However, this study discovered that pinch culverts have a negligible effect in some areas of the Glanerbeek area and a significant effect in others, as illustrated in figures 16 and 17, demonstrating how the implementation of a groundwater model allows for a more detailed understanding of this measure's influence. It is also understandable that, given that exist an effect of pinch culverts on the groundwater system it means that the way these structures are schematized is ineffective for analyzing their full potential, and a more detailed and comprehensive study should be conducted. The combined model has demonstrated to be a sophisticated and critical tool for analyzing the influence of pinch culverts and their effect on the water system.

Furthermore, it can be argued that a combined model enables a better understanding of the interaction between the surface and water system, both in the existing state and following the implementation of new measures. Additionally, it elucidates whether the pinch culverts would hold water in the catchment zone by retaining it in the reaches or in the ground. Moreover, when the two models were coupled, it was discovered that additional criteria such as handling of dry water courses, over flooding and dimensions of the pinch culverts were required, information that could not be gathered by the models running independently.

6.2 Recommendation

When considering whether or not to follow up on this study, it is recommended that researchers take into account two factors. First the loop in which the model was coupled might potentially be repeated multiple times to fine-tune the interaction between the two models and produce a more accurate outcome. This was not done in this report because only the groundwater model runs for about two to three days and the surface model runs for at least eight hours. This means that increasing the number of times the models run through the loop will likewise increase the time required to run the model without regard for any error or other unplanned event.

In particular, future research should focus on improving the accuracy of modeling pinch culverts, both in terms of their dimensions and the way they behave in a computer model, as well as how they interact with extreme situations. The proper placement on the appropriate reaches and catchment areas could also make a significant difference in terms of the analysis of this subject matter.

It is possible to conduct additional research on the behavior of the coupled model under different climate scenarios in the future. When the results of a coupled model are analyzed under extreme conditions, it may be possible to gain new insight into the impact of pinch culverts on the water systems.

It's worth noting that the time required to develop a well-coupled model was underestimated by both the supervisors and the researcher. This was due to the fact that the groundwater model was unavailable at the start of the research; this, combined with the difficulty of working from home rather than the office and the great amount of time that the models needed to run, increased the time required for this section beyond what was anticipated.

7 Discussion

This section discusses the findings and decisions taken during the course of this study's execution as well as the limitations of the approach chosen.

7.1 Limitations

7.1.1 Models

As previously stated in the preceding chapters, the two models encountered a number of issues. To emphasize the point, the absurd infiltration levels discovered in specific areas of the water system were the most concerning. The most noticeable infiltration was observed in the system's southern section, where infiltration rates of more than 1 to 2 mm per day were observed. This occurred as a result of the attempt to model a specific lake near the German border. Two reaches were built to replicate this lake, one with a significant height and the other with a width of more than a kilometre. Because it was modelled as a ravine, in other words, the prior and posterior reaches were higher than the stated lake, giving the appearance of a large open space with a lot of water.The elevation difference between these two locations results in significant drainage in the area, and the groundwater model predicts that this drainage results in large infiltration in the adjacent areas. This section was excluded to ensure the report's functionality. However, improvements in the cross-sectional areas of the reaches, as well as their representation in the model, may result in a significant rise in the results' accuracy.

Furthermore, as a result of the model's handling of over flooding, high infiltration values were generated. The way the Sobek surface model handles dry watercourses causes issues with model implementation, even though a viable solution was found. Improving this part of the model could significantly improve the quality of the outcomes of interventions such as pinch culverts or any other type of intervention.

It's worth emphasizing that the results illustrated and detailed in the section 5 indicate the maximum effect that a pinch culvert might have, as the effect is almost certainly underestimated. In actuality, when the water level in the reach behind a pinch culvert reaches a predetermined level, the water is allowed to flow through. This does not occur in the Sobek model, and the water level upstream of the pinch culvert increases, indicating that more water is available to seep into the ground water system. After analyzing the cross sections of the reaches where this phenomenon occurs, it was discovered that the top part of the reach is wider than the bottom, which means that when the water level rises, there will be a larger wet perimeter or area with a water level in contact with the ground water system, allowing for the infiltration of large amounts of water, depending on the system's over flooding and the shape of the cross sections. This does not happen in practice because, as previously indicated, once the water reaches a certain level, the pinch culverts will only let it to pass through, preventing over flooding.

7.1.2 Climate scenario

Due to time constraints, it was not possible to conduct and analyze a future climate scenario during the report's execution. Both the groundwater and surface models are capable of implementing climate scenarios, which suggests that a climate scenario for the coupled model could be implemented in a reasonable amount of time.

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Appendices

A Walrus Model

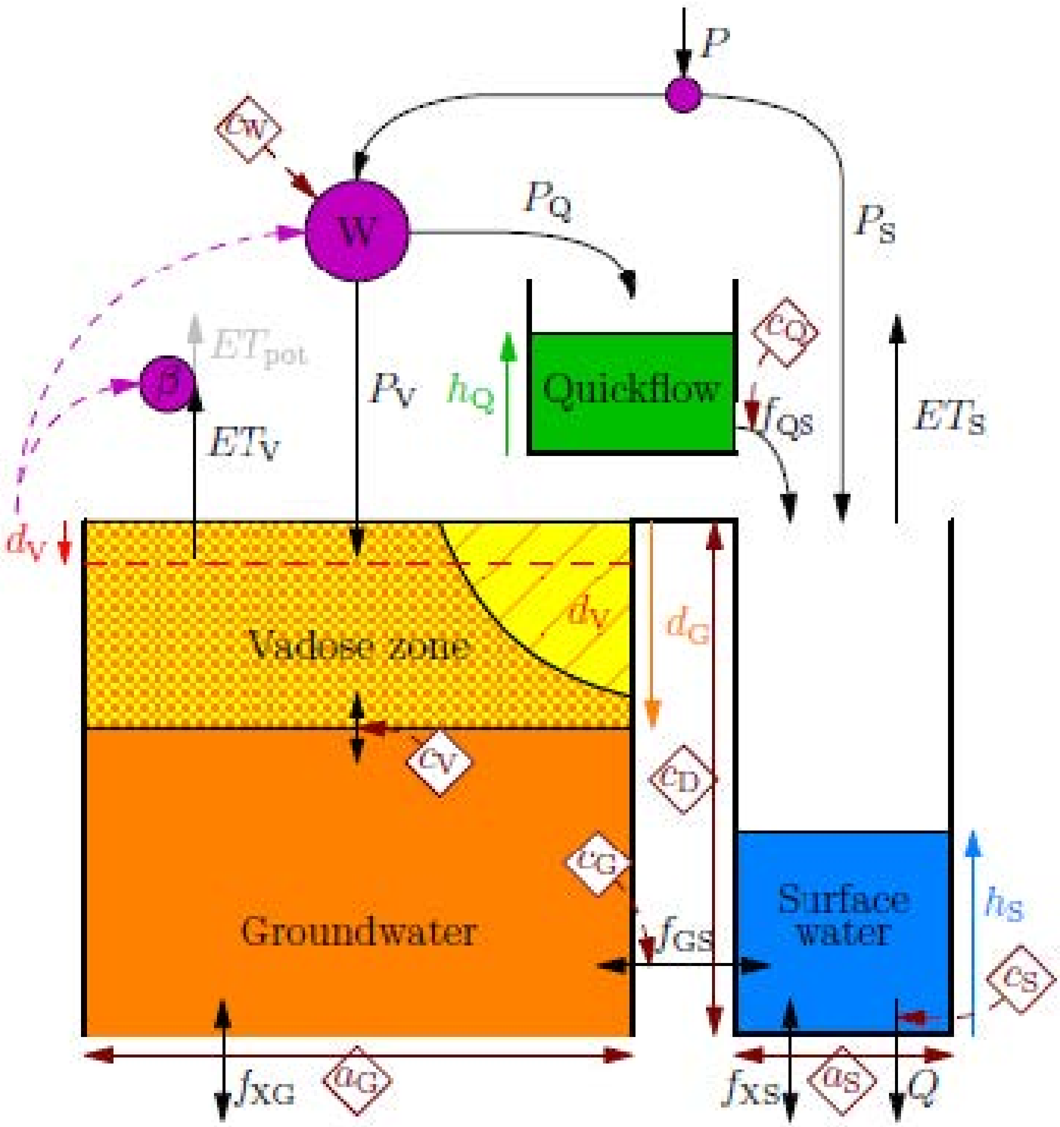

Figure 18: Stigmatisation of the Walrus model (Brauer, C., 2017)

B Infiltration Results

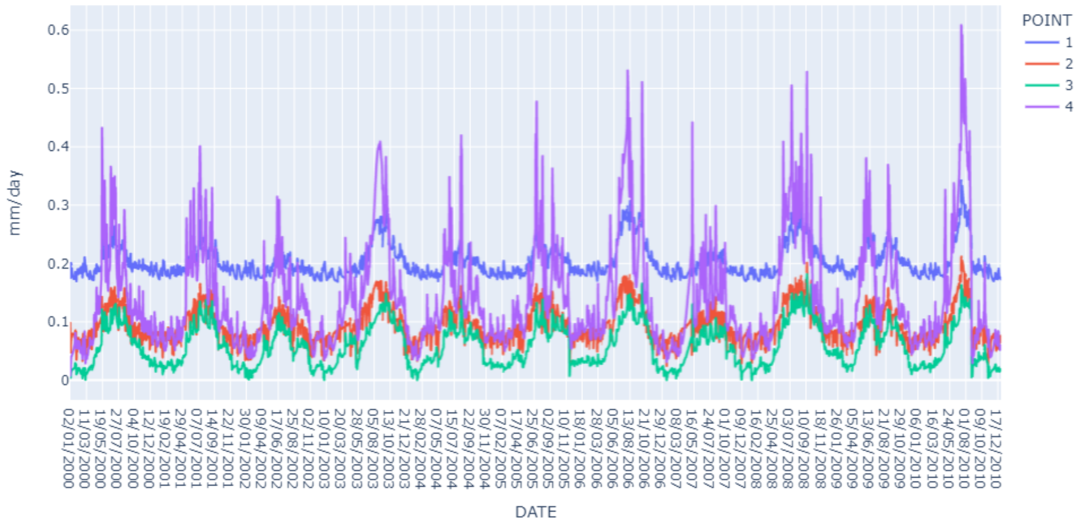

Figure 19: Infiltration values of the base scenario over a 10 year period

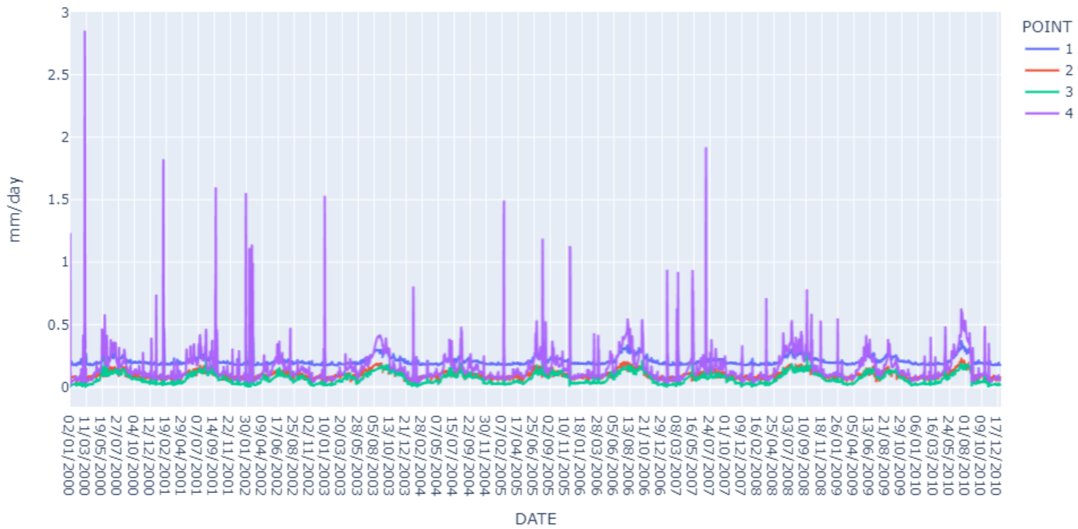

Figure 20: Infiltration values of the Pinch culvert scenario over a 10 year period

C GXG Results

In this section the GHG and GLG values for the base scenario as well as the pinch culvert scenario are shown. A more detailed view of the average low (figure 22 and 24) and high (figure 21 and 23) groundwater levels over the ten year period over the study area.

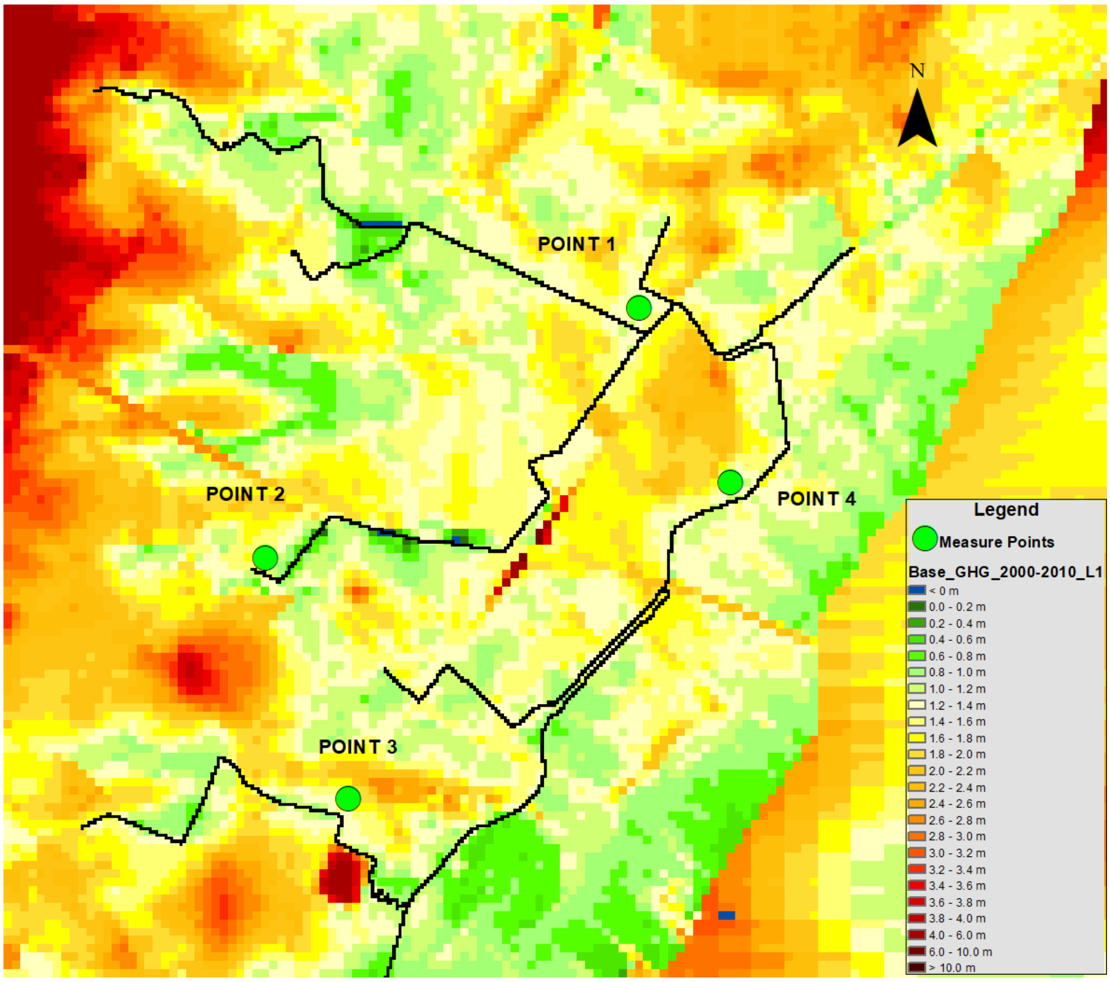

Figure 21: GHG results for the base scenario

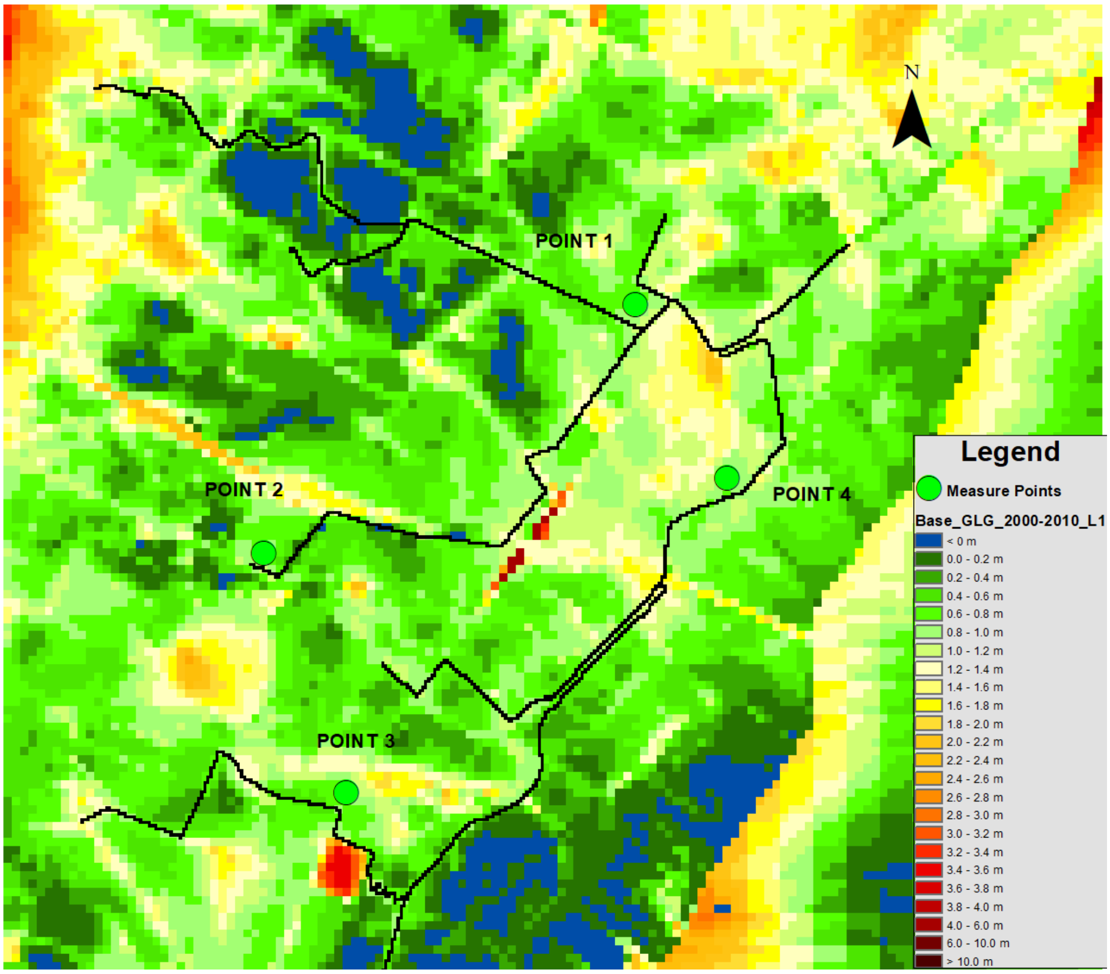

Figure 22: GLG results for the base scenario

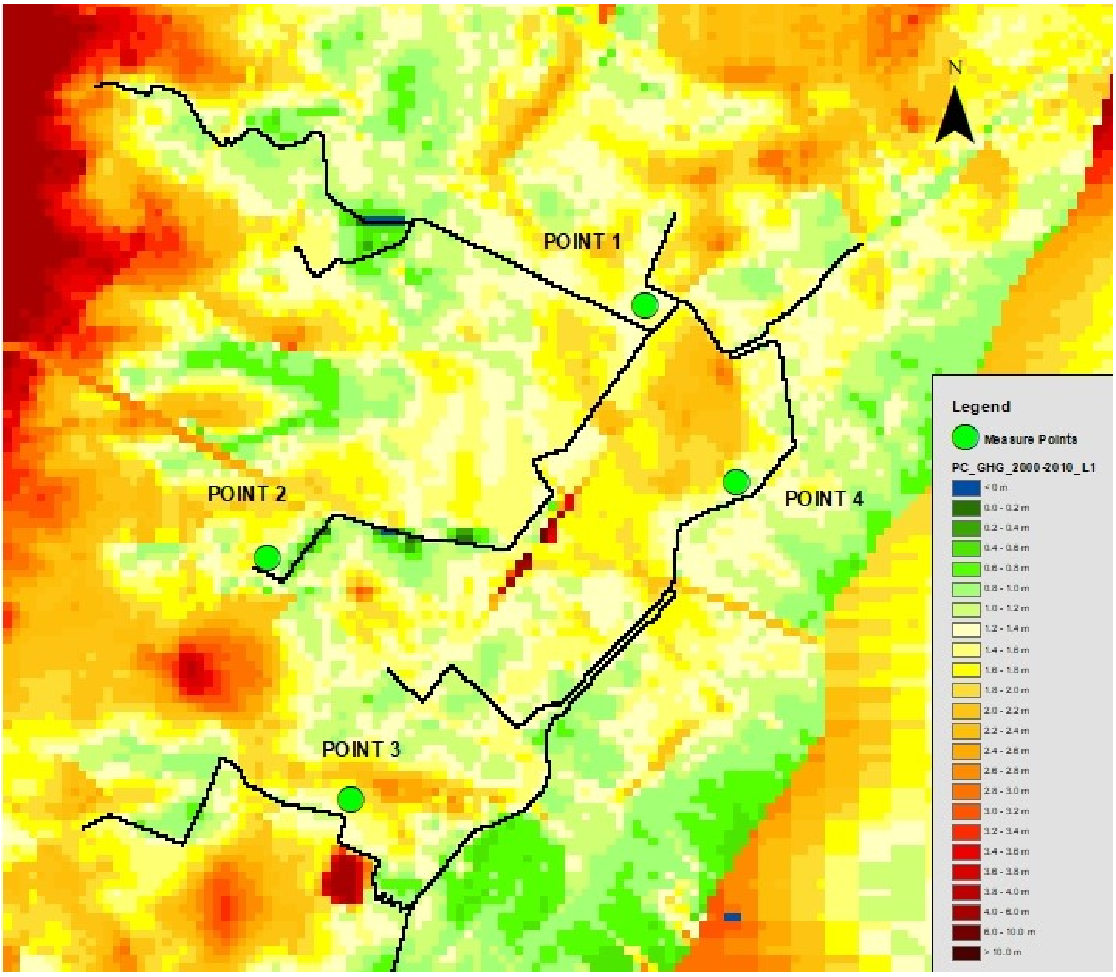

Figure 23: GHG results for the pinch culvert scenario

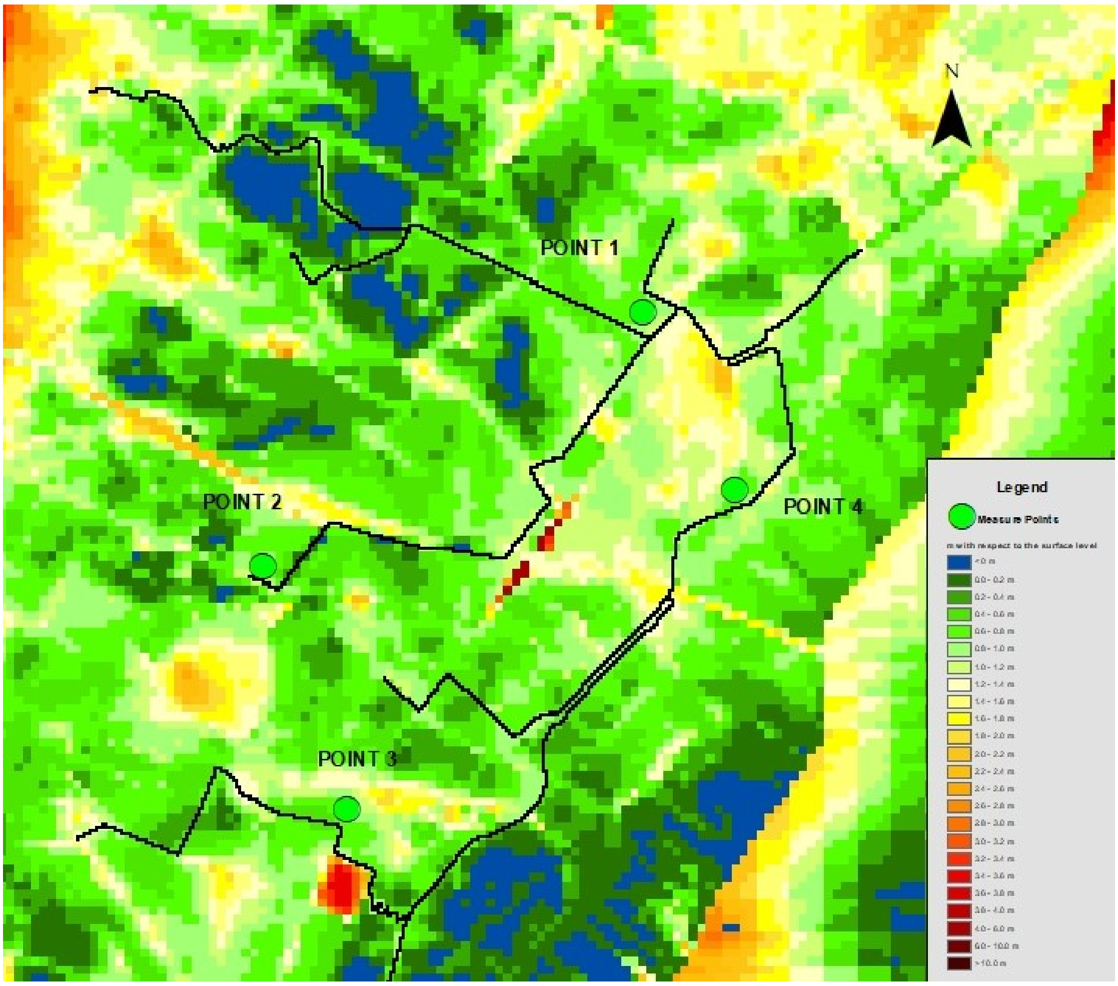

Figure 24: GLG results for the pinch culvert scenario