Exploring a 2D Hydrological Model in Tygron for Water System Modeling

Evaluating parameters and settings in Tygron and Case Study Implementation for Stream Restoration Initiatives in the Raamvallei

Master Thesis

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Evaluating parameters and settings in Tygron and Case Study Implementation for Stream Restoration Initiatives in the Raamvallei

by

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Preface

The thesis before you is the result of a long graduation trajectory during which I learned a great deal about 2D modeling with Tygron, stream restoration, and data accumulation. I took an unusual route for my graduation thesis and chose to conduct my research primarily externally at TAUW. Unfortunately, not everything went according to my original plan. However, I can say that I am proud of the work I did both at the office and behind my laptop. A large part of this thesis would not have been possible without the help and support of the following people.

First of all, I would like to thank my graduation committee. I know my communication and planning skills have not always been my strong points during this process and fluctuated significantly over the past months. This has caused some problems along the way, and I want to thank you all for your patience and feedback on my reports during meetings. Thom, thank you for your support, which allowed me to do this project outside of TU Delft. I am grateful for the opportunity to undertake this project in my own time and to experience a more practical side of conducting such a project independently. Olivier, thank you for the insights you provided during our meetings. With your questions, brainstorming sessions, and directions, the thesis evolved considerably in the latter half of the trajectory. Xander, thank you for guiding me at TAUW during weekly meetings and introducing me to the team. You provided me with valuable perspectives when I was stuck on certain problems. Lastly, Len, thank you for the excellent weekly/daily feedback and counseling sessions. Although they were frequent and time-consuming at times, I enjoyed our discussions about the project's findings, debating results, and searching for better solutions.

In addition to my committee, I want to thank the others at TAUW for welcoming me into their team. I enjoyed the table tennis sessions and the tea breaks, especially when I was deep into coding, reading or working with Tygron.

I also want to thank WSAM and especially Johnny for their assistance in navigating through the WSAM data they provided and for their feedback on whether the model was fit-for-purpose for use in the Lage Raam. Without your generosity in providing data, this project could not have succeeded.

Lastly, I want to thank Tygron for their support when I had questions, especially thank you to Maxim and Florian. During our meetings, I was able to ask many questions about Tygron, which helped clear up numerous errors in the model setup. I hope to see Tygron on the market for many more years to come.

R.T.S. Sutarto Hardjosusono
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Abstract

The increasing demand for stream restoration projects in the Netherlands, driven by legislation, prompted interest in more integrated approaches. TAUW (Technische Adviesbureau van Unie Waterschappen) and WSAM (Waterboard Aa and Maas) collaborated on stream restoration measures for the Lage Raam stream in the Raamvallei, initially using a 1-dimensional model. However, questions arose regarding the suitability of a 2D model for this project.

This research explored the applicability and potential of a 2D hydrological model made in Tygron to provide new insights and outputs for this stream restoration project, including inundation maps, water level fluctuations, and evaluating designed restoration measures. Simultaneously, the study assessed Tygron's applicability for large water systems in the Netherlands by evaluating its underlying settings and parameters.

In the first part of this research, the study demarcated stream restoration measures for the Lage Raam, focusing on redesigning the stream to enhance nature-friendly banks. The Tygron water module was introduced, emphasizing critical simulation setup adjustments such as the rainfall overlay and simulation settings investigated in the initial testcase study. The settings investigated in the testcase were: *'Water level to shorelines', 'Waterline reconstruction', 'Angle stabilizers for partly flooded cells', 'Manning value', 'Grid cell size', and 'Grid/stream placement'.*

Results from part 1 indicated that among the six settings tested, only three significantly influenced water level simulations in channels. Variations in *Manning values* demonstrated a pronounced effect on water height accuracy, with lower values correlating with better simulation outcomes in the testcase. The influence of Manning values was more pronounced in narrower streams, where shallower water depth worsened inaccuracies in the model's backwater effect. Notably, *Grid cell size* and *Grid/stream placement* were crucial for achieving accurate outcomes. The optimal grid cell size was found to be 1 by 1 meter or of higher resolution. Additionally, aligning streams parallel to grid cells generally improved results, although the influence of grid placement diminished with increased grid cell count per channel.

The second part introduced the study area, the 'Raamvallei', for case studies 2 and 3, outlining designs for cross sections with swamp areas as restoration measures. Case study 2 validated the Tygron model using measured data from the Raamvallei obtained from WSAM and rain events, testing its suitability and model setup for water systems. Case study 3 implemented TAUW's restoration design to evaluate Tygron's effectiveness of these measures.

The results in part 2 showed that evaluation in a larger watershed scenario (Raamvallei) underscored the model's robustness when configured for extensive water systems. Grid cell size sensitivity analysis highlighted the optimal range (1m x 1m or smaller), lower resolutions causing water loss in the Lage Raam water system, underscoring the resolution's impact on modeling outcomes. Achieving accurate connectivity between primary, secondary, and tertiary waterways was crucial, requiring iterative adjustments including culvert generation and hydraulic structure calibration. The third case study highlighted challenges in data retrieval and storage due to Tygron's limitations in exporting detailed simulation data over time. However, it also demonstrated Tygron's capability in simulating level fluctuations and flow rates, despite challenges in data analysis.

In conclusion, Tygron was capable of using the explicit Saint-Venant scheme to calculate 2D shallow water equations where it accurately simulated a complex large water system in the Netherlands. Additionally, it could be used for projects such as the Lage Raam to provide insights into stream restoration designs. However, for a model to be successfully used and have results that could be easily understood, some settings were important to look at and some changes in data collection were needed. Future research should encompass diverse test cases to validate Tygron's performance across various scenarios and compare it with other 2D hydrological models for broader applicability insights.

Based on the study's findings, several recommendations were proposed to enhance Tygron's utility

in hydrological modeling. These included exploring new data storage approaches to handle extensive datasets more efficiently, optimizing the use of limit areas to simplify model complexity without compromising simulation accuracy, and improving connectivity tools like the culvert generator for seamless integration with external data sources.

Contents

1 Introduction

1.1. Background information

Development on and creating of stream restoration is, nowadays, an inevitable aspect of water management in the Netherlands. Streams and their surroundings are important ecosystems on local and regional scale. Providing not only biodiversity, but they also play a factor in flood control, water quality and groundwater recharge. Among environmentalists, engineers, and governmental bodies such as water boards, there is a growing interest in restoring streams to their natural state (Smit and Tiehatten (2019) & Henckens and Engel (2018)). This is driven by policies to promote biodiversity, enhance ecosystem services, and improve the overall quality and resilience of our freshwater ecosystems. (Smit & Tiehatten, 2019). According to Dos Reis Oliveira et al. (2020) in the last 40 years the amount of stream restoration project have increased a lot due to the influence of policy goals. Important policies such as; the National Ecological Network (EHS), the Water Framework Directive (WFD/KRW), Birds and Habitats directive (Natura2000), focus on achieving a better ecological habitat and improving water quality for stream ecosystems in the Netherlands. Dos Reis Oliveira et al. (2020) observed however that the success rate of these projects have been rather low due to a mismatch between restoration goals and restoration measures.

In order to increase the success rate of restoration projects, restoration efforts must be integrated within broader catchments at the appropriate scale (Bernhardt & Palmer, 2011), such that restoration is not reversed by the prevailing disturbance regime (Lake et al., 2007). Pander and Geist (2013) mentions that stepwise evaluation of the primary factors of stream degradation may be most suitable when considering all major drivers of successful restoration. Overall it is advised to better determine and establish criteria for stream restoration design.
A key challenge is to determine when a stream restoration measure presents a viable solution for improving the ecological condition of an ecosystem (Bernhardt & Palmer, 2011). Successfully restoring streams is an combination between choosing the appropriate scale and selecting appropriate key factors on given sites (De Goede, 2020). Possibilities are however not endless, because the in theory perfect solution almost always conflicts with the practical availability of space, hence lowering the possibilities (Nijboer et al., 2004). Success is more likely with large-scale projects, but they will often be infeasible in terms of the available resources and conflicts of interest.

In the Netherlands water boards are responsible for water resources management on regional level. One of the objectives is to prevent future calamities, such as the inundations of agricultural lands next to streams (Besselink, 2016). Early stream restoration measures focused on reforestation and water quality improvements with waste water treatment plants (WWTP). Verschoren et al. (2016) mentions that from the nineties restoring the morphological features of the streams' length profile became more and more important.
Different measures can be taken to prevent calamities, for instance the use of water storage, decreasing peak waterflow, weir management or vegetation maintenance are examples to prevent them. However,

due to the densely populated and heavily land-used areas in the Netherlands, restoration in streams is both more expensive and more difficult than restoration in less densely populated catchments. Divided land (e.g. agricultural, urban, natural, and dense human infrastructure: roads, sewer lines) limit the spatial extent of stream restoration options.

The success of stream restoration projects partly depends on (the accuracy of) the hydrological models used to design and implement measures for these projects (Dos Reis Oliveira et al., 2020). 1-dimensional hydrodynamic models made in software like Sobek have been used for many years to support stream restoration projects in the Netherlands. However, streams have complex interactions between water flow, flow rate, water heights, sediment transport, and ecological processes (Crowder & Diplas, 2000). As there are limitations to 1D modeling approaches that may limit their effectiveness for stream restoration projects, there is also a growing interest in using 2D models for such projects. By using a 2D model, water managers can simulate the behavior of streams and surrounding areas in more detail (De Goede, 2020). With each software and hydrological model it is possible to design re-meandering streams or new profile streams in different ways and thus also brings differences in efficieny (Crowder & Diplas, 2006).

1.2. Problem definition

In the past 1-dimensional models were widely used for water related projects within the Netherlands (Dhondia & Stelling, 2004). While a 1D model is useful for predicting water levels and flow rates along channels, it may not accurately capture the behavior of a meandering stream or the hydrology within adjacent swamp areas (De Goede, 2020). A 1-dimensional model is limited in its ability to capture the spatial variability of (horizontal) water flow, which could have important implications for the success of restoration efforts.

2-dimensional hydrodynamic models simulate water movement in two dimensions, allowing for a more detailed and accurate representation of water flow and inundation in complex environments such as urban areas or areas prone to inundations. There are several 2D models available for simulating stream hydrodynamics, including D-hydro, Delft3D, Hecras, 3Di and Tygron (Afshari et al. (2018) & De Goede (2020)). All of them have been proven good enough as for inundation models to be used on the dutch market (Henckens & Engel, 2018). But these models all have their different capabilities, limitations, and requirements in terms of data input and computational resources.

TAUW, Technisch Adviesbureau voor Unie Waterschappen, is currently working on the stream restoration project the 'Raamvallei' for the Waterboard Aa en Maas and uses a 1D model made in Sobek for project plans. However, the limitations to 1D modeling approach has limits to the effectiveness for certain types of stream systems in the Raamvallei and restoration designs, such as differences in water flow rates in a cross section of a channel. Due to the absence of 2D models in the Raamvallei project for stream restoration, there is growing interest in assessing the potential benefits of employing a 2D hydrological model developed in Tygron for such restoration projects.
Tygron is a 2D modeling software that allows for the simulation of complex urban and environmental scenarios, such as flood risks, water management, and urban planning. However, Tygron is a fairly new software for hydrological purposes which makes it more interesting to see what the possibilities are for the program. The water module of Tygron could be a potential powerful tool for modeling and simulating scenarios in a 2D environment.

1.3. Research Question

The aim of this research project can be divided into 2 parts. The first interest lies in the part to test the 2D hydrological model Tygron in a case study to see what the benefits and complications are for using Tygron for a stream restoration project. The other interest was to explore the underlying settings/parameters for the hydrological model to see if Tygron could even be used in low-lying areas such as the Netherlands.

This lead to the following research question:

"Can Tygron be used to create a 2-dimensional hydrological model to effectively be employed in stream restoration projects within a low-lying area, and what are the underlying settings that influence the applicability of Tygron for a water system"

1.4. Objectives

In order to answer the research question some main and sub-objectives have been formulated for the research process. One of the main goals of this research was to investigate Tygron model for stream restoration projects. For this research it was chosen to use a case study area in Netherlands. The case study area for stream restoration focused on the 'Lage Raam' stream, which is part of a larger project in the 'Raamvallei' which is under management by the Waterboard Aa en Maas (WSAM). Together with TAUW, WSAM aims at reducing the risk of inundations while also restoring the ecological functions of the streams in the Raamvallei such as the Lage Raam. By building a 2D model in Tygron and simulating different scenarios, a better understanding of the factors that contribute to successful modelling a watersystem in Tygron has been created. The following objectives have been formulated for the research:

Part 1

1. Identify what stream restoration is and to what extent stream restoration can be used for the Raamvallei project
   (a) Explore what stream restoration means
   (b) Identify objectives for and demarcate stream restoration for the Lage Raam
   (c) Identify what the important criteria are for a stream restoration project
   (d) Explore possible mitigation measures for the Lage Raam
2. Assess the performance of water module setup in Tygron using a test case scenario
   (a) Identify what the most important settings are in Tygron
   (b) Create a test case to investigate these settings
   (c) Provide more insights in the use of the 2D model in Tygron
   (d) Determine the most influential parameters for a water system model in Tygron

Part 2

3. Assess the performance of the Tygron model considering water height data from the Waterboard Aa en Maas
   (a) Create and analyse the water system of the Raamvallei in Tygron
   (b) Assess the usage of Tygron for large scale watersystems
   (c) Identify benefits/shortcomings in the use of Tygron for a large water system
4. Assess the "swamp areas inundation profile" restoration measure in Tygron
   (a) Create a stream restoration case for the Lage Raam
   (b) Explore the possibilities in Tygron for swamp area inundation profiles
   (c) Identify the shortcomings and advantages in Tygron

1.5. Approach & Reading Guide

To address the objectives outlined in section 1.4 and ultimately answer the research question, this report is structured as follows:

In Chapter 2, we explore stream restoration within the context of the Raamvallei. This includes defining stream restoration and delineating its scope for this research. The chapter discusses the objectives behind the restoration efforts in the Raamvallei streams, establishes the boundaries of restoration measures within the Lage Raam, and focuses on aspects of stream restoration relevant to this study.

In Chapter 3, we present information on Tygron, a 2D hydrological modeling software, to provide a comprehensive background. The chapter begins with an analysis of Tygron, including a brief summary of the literature review and benchmarks. It then introduces the water module of Tygron and concludes with the determination of settings to be tested.

In Chapter 4, the first case study is presented. A test case is conducted in Tygron to assess its simulation settings, offering insights into the various options available for generating a simulation. This chapter provides a deeper understanding of the settings and the use of the 2D model in Tygron. Chapter 5 and Chapter 6 will show the results of the first case study and discuss them.

Chapter 7 introduces the study area, outlines its objectives, and presents proposed mitigation measures for the Lage Raam. The chapter concludes with an overview of the initialization of the 2D model in Tygron. The 'Lage Raam' stream in the Raamvallei is selected as the study area, strategically aligned with the broader 'Raamvallei' project, a collaborative effort between TAUW and WSAM.

Chapters 8 and 9 present the second and third case studies, respectively. The second case study examines the entire Raamvallei region, focusing on the applicability of Tygron for an integrated water system from a holistic perspective. The third case study focuses on a smaller segment of the Lage Raam, implementing stream restoration, and explores the potential of using Tygron for stream restoration projects.

In Chapter 10, the results of the second and third case studies are presented. Chapter 11 discusses these results, assessing the applicability of Tygron for a large water system and exploring the possibilities of a stream restoration scenario in Tygron.

Chapter 12 presents the conclusions of this research, answering the main research question: *"Can Tygron be used to create a 2-dimensional hydrological model to effectively be employed in stream restoration projects within a low-lying area, and what are the underlying settings that influence the applicability of Tygron for a water system?"*. This chapter draws conclusions based on the results, objectives, and discussions presented throughout the research.

Chapter 13 provides recommendations derived from the conclusions and discussions of the preceding chapters. These recommendations encompass future research possibilities with the Tygron model and aim to contribute to the continuous improvement of the model's effectiveness and applicability for future studies.

Part I

Introduction to Tygron and investigating simulation settings

2

Stream Restoration

In this chapter the term Stream Restoration will be explored to demarcate the term for this study. This chapter also shortly introduces part of the study area, the 'Lage Raam', used for the case studies in this research. In this chapter the objectives for the Raamvallei are presented together with hydrological characteristical goals for the Lage Raam. Possibilities for mitigation measures and a broad introduction to the study area are presented in chapter 7, as this is related to case studies 2 and 3. At the end the chapter provides the focused aspects of stream restoration related to this study.

2.1. General term of Stream Restoration

In the Netherlands, natural streams are a rarity, with 96% of lowland streams in the Netherlands severely impacted by human influences (Nienhuis et al. (2002) & Nijboer et al. (2004)). Originally, these streams resembled swampy or marshy areas, characterized by meandering waterways and trees altering the course periodically (Eekhout (2014) & Higler (1993)). And riparian areas surrounding the streams contained highly diverse vegetation and fauna.
However, human activities significantly contributed to the loss of these natural streams for various purposes. Population growth demanded more space, intensifying agriculture with increased fertilizer use necessitated more irrigation, and streams were diverted for agricultural needs (Eekhout et al., 2015). Channelization and the creation of new channels were common strategies to prevent erosion. Riparian forests disappeared due to logging or the need for space, swamp valleys were drained for agricultural purposes, and hydraulic structures were introduced for flood control and water level maintenance. This extensive alteration of natural streams resulted in a reduction in stream lengths and, consequently, a transformation in the hydrology and morphology of the streams, leading to ecosystem degradation (Baaijens et al., 2011).

Many streams no longer exist in their natural state, initially this was not a problem due to the desired positive outcomes resulting from these changes. However, the consequences of the lack of natural streams are becoming increasingly apparent, with a rise in flow dynamics (e.g. more frequent and prolonged periods of droughts and extreme floods) being just one indication of the negative impacts resulting from the disappearance of natural streams (Eekhout et al., 2015). Over the last 20 years the ecological importance of streams became more obvious (Verdonschot & Verdonschot, 2022). Legislative measures have played a big role in the increase of stream restoration efforts in the Netherlands, such as the Water Framework Directives (WFD), the National Ecological Network (EHS), and the Birds and Habitats directive (Natura2000). In these legal frameworks it was stated that designated water bodies should achieve a good qualitative status by 2015, but has been extended to 2027 (Lepper, 2000).

Stream restoration, also referred in many other synonyms such as river reclamation or ecological reconstruction, encompasses a range of measures aimed at enhancing the overall condition of water bodies. According to Balensiefer et al. (2004), it can be defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.". Building upon this, Wohl et al. (2015)

provides a more comprehensive perspective, describing stream restoration as the deliberate effort to support hydrologic, geomorphic, and ecological processes within degraded water systems. The ambition is to replace lost, damaged, or compromised elements of the natural system Wohl et al. (2015). Both definitions emphasize the integral role of systems, whether they are natural, stream-based, or ecological. The scale of stream restoration initiatives varies widely, ranging from implementing singular elements such as dead wood in a stream reforestation of entire catchments.

2.2. Demarcation of stream restoration for this research

Since the early 1990s, there has been a growing emphasis on restoring the morphological features of stream length profiles. Many restoration projects have involved some form of re-meandering, accomplished through digging and creating asymmetric transversal profiles (Verdonschot & Verdonschot, 2022) & replanting vegetation to create more biodiversity for swamp areas (Verschoren et al. (2016) & Eekhout et al. (2015)).

However, the term ”Stream Restoration” remains overly broad for the scope of this research. To achieve a more nuanced understanding stream restoration can be divided into two categories. The first category is form-based restoration, where physical interventions aim to enhance stream conditions immediately. This is for example bank stabilization, re-meandering, channel realignment and using hydraulic structures. The second category is process-based restoration, focusing on improving hydrological and morphological processes over time, facilitating a more natural recovery, e.g. promoting sediment transport, floodplain re-connectivity, and creating a stream corridor width (Bernhardt & Palmer, 2011). In form-based restoration the effects are direct and process-based restoration exhibits effects only after a longer period.

The chosen case study area is the Lage Raam stream in the Raamvallei (see chapter 7) on information of the study area). TAUW has designed a stream restoration project for the Water Board Aa en Maas (WSAM) in this region with the of a 1D model made in Sobek for calculating hydrological details. The WSAM has provided a report outlining the project’s specifications and directives.

”Plan van Aanpak Lage Raam” & Water Framework Directive

The ”Plan van Aanpak Lage Raam” outlines the WSAM’s objectives for the Lage Raam. According to the plan, the primary focus is on enhancing the development potential of the area by optimizing water management for its various functions. The overarching goal is to achieve improved water quality, both ecologically and chemically, aligning with the standards set by the Water Framework Directive (WFD). Concrete the rapport states the main objective as; to create ”Better quality of water and nature that complies with the WFD” (Besselink, 2016).

In the context of the WFD, achieving a good ecological quality involves several elements. The WFD defines this as ”The values of the biological quality elements for the surface water body type show a low degree of disturbance due to human activities, but deviate only slightly from what is normal for the surface water body type in undisturbed conditions” (Lepper, 2000). Here, a critical concept is the ”undisturbed state” of the surface water body.

Essentially, the WFD emphasizes maintaining surface water bodies in conditions that show minimal disturbance from human activities. Furthermore, the definition suggests that any deviations from the norm should be slight and align with what is typical for the undisturbed state of the specific surface water body type. This approach underscores the importance of preserving the natural conditions of surface water bodies and preventing significant alterations to their type-specific characteristics (Lepper, 2000).

Demarcation of Stream Restoration by WSAM for the Raamvallei

Stichting Toegepast Onderzoek Waterbeheer, commonly referred to as STOWA, created a document outlining references and benchmarks for natural water types aligned with the Water Framework Directive (WFD). This rapport establishes numerical values, or targets, for various natural water types. The unique hydrological conditions in the Netherlands pose a challenge, as truly natural water bodies are scarce.

Consequently, achieving undisturbed conditions, as outlined in the benchmarks are not entirely realistic within the Dutch context. Instead, the focus shifts to meeting the standard of the Good Ecological Status (GET), representing the lower limit of the quality class. This parameter is derived from the most similar natural water type, adapting the objectives to suit the distinctive characteristics of Dutch water systems.

The water system description of Waterboard Aa en Maas provides a foundational understanding for characterizing the Lage Raam water system (Groot & vd J., 2023). Despite certain sections being wider than 20 meters the WSAM classifies the Lage Raam as a swamp stream, denoted as a R20 stream.

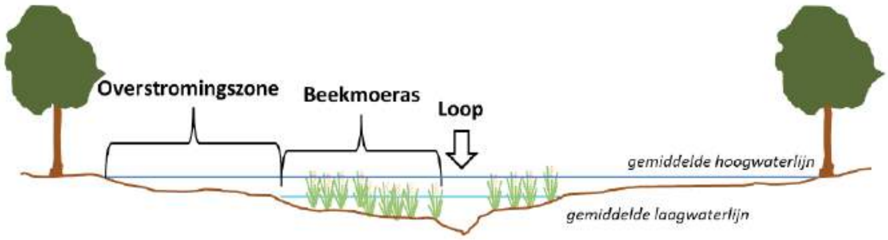


Figure 2.1: Swamp streams cross section example by STOWA

From STOWA and the WSAM the following restorationmeasures are named to be of importance for a R20 type stream ranked from least suitable to most suitable (Reeze & Winden, 2021).

- Sand supplementation
- Inserting gravel
- Creating shade (reforestation)
- Inserting dead wood
- Adapted mowing management of vegetation
- Creating mild riverbanks
- Remeandering of streams
- Waterlevel management
- Creating swamp area cross-sections (see figure 2.1)

The stream restoration measures mentioned above are all singular measures that if correctly incorporated in a large scale could eventually lead to restoring the stream. It can be seen that most of the stream restoration measures will be form-based. The WSAM has said that their primary focus lies on enhancing the Lage Raam stream aligning with the standards set by WFD (Keulen, 2023a). For the WFD stream restoration is to make a stream go back to the natural state with low influences of human interactions.

However, the goal of WSAM is not to make the stream go back to its original natural state, but to improve the streams. The current streams in the Raamvallei each have their necessary functions and are altered such that going back to its most natural state is seemingly impossible. The stream restoration for the Raamvallei has as goal to be as close as possible to the WFD by redesigning the current streams without impairing the current functions (Keulen, 2023a).

2.3. Output of importance

In the 'Ecologische streefbeelden watersysteem,' the WSAM provides additional insights into the ideal state of the R20 stream. This ecological target is derived from the target image presented by Buskens and de Wilde (2002) and is influenced by the Water Framework Directive (WFD), Natura 2000, Natuurnetwerk Brabant (NBB), and the Vision 'water in transitie'.

The R20 "swamp stream" or "marsh creek" naturally occurs on high sandy soils with a very small gradient (<0.5 m/km) and/or a low discharge. Despite the low gradient, there is sufficient discharge at the middle or lower course to maintain a clear channel in the marshy lowland within the stream valley. However, insufficient discharges or low flow velocities could lead to channel closure. During high water events, there is lateral exchange of surface water between the stream channel, the stream marsh, and the floodplain zone (figure 2.1). This lateral water exchange distinguishes swamp zones from flow-through marshes, where water movement mainly occurs downstream.

	Stroomsnelheid range	5-50 cm/s
	Gemiddelde stroomsnelheid zomer	≥ 14 cm/s (stromende delen)
	Peilbeheer	Half natuurlijk. Deels gestuwd, dan streefpeil met marge (natuurlijk toegepast) of vast streefpeil (winterpeil ≥ zomerpeil)
	Peilfluctuaties	< 0,5 m
	Aantal dagen dat beek buiten zijn oevers treedt	< 1 d/jr
	Mate van opstuwing (% onder invloed van verstuwing)	≤ 50%
	Stagnatie (# dagen)	≤ 22 (stromende delen)
	Droogval (% van de loop)	≤ 10%
	Passeerbaarheid voor vissen	Geen barrières of barrières met vispassage Zie het afwegingskader vismigratie (Riemersma en Arntz, 2021)
	Sinuositeit (mate van slingering) (lengte loop/ lengte beekdal)	≥ 1,06
	Waterbreedte (bij gemiddeld peil)	1-8 m
	Waterdiepte (bij gemiddeld peil)	0,1-0,7 m
	Talud bedding	Flauw (delen met weinig verhang), steil (delen met meer verhang)
	Dood hout (% substraat in de waterloop)	≥ 1%
	Oeverzone	Brede beek- begeleidende zone
	Beschaduwing	Het beekmoeras bevat bomen of struweel (50%)
	Maaibeheer (% gemaaid profiel)	≤ 75%

Figure 2.2: Hydrological charateristics based on WFD and adapted by STOWA

The swamp zones remain permanently wet due to incoming groundwater or appropriate water level management (fixed/target level). The vegetation in these areas ensures the presence of a substantial amount of organic material. Recommended hydrological characteristics for the R20 are made by STOWA, based on Elbersen et al. (2003), with adaptations for marsh streams by STOWA (Backx & Beers, 2018). WSAM further modified the characteristics for specific water bodies in ”Ecologische streefbeelden watersysteem” to strike a balance between ecological development and practical considerations such as agricultural and urban land use, which are shown figure 2.2 (Reeze & Winden, 2021).

Achieving the objectives of these characteristics in figure 2.2, involves the implementation mitigation measures such as the form based measures mentioned in section 2.2. To see if an objective is reached for different measures, hydrological models are used to perform hydrological tests for significant outputs of the models. Based on requirements of the client (WSAM) the following output has been chosen to be of the most importance as output of an hydrological model involving physical based run-off models (Ghonchepour et al., 2021):

- Flow rate
- Level fluctuations / Waterlevel management
- Stagnation
- River Dryfall
- Inundations

Flow Rate
Flow rate is a critical output for hydrological models, providing valuable insights into the distribution of low and high flows and identifying potential issues in water systems. Accurate modeling of flow rates holds particular significance for designing cross-sections, especially in swamp areas, as emphasized by STOWA (Reeze & Winden, 2021). This is crucial for achieving the desired outcomes in the Lage Raam project, which places importance on maintaining flow rates within specific values to guide the design of effective mitigation measures.

Level Fluctuations waterlevel managment
Another aspect is the management of water levels and monitoring level fluctuations. The hydrological specifications indicate that the water level must remain relatively stable without significant fluctuations.

This is essential for stream design factors ranging from 10 to 100%, representing the spectrum between minimal discharge in the stream and a rainfall event with a repetition time of 1 year (T>1x10 years).

Tracking level fluctuations offers valuable insights into the dynamic nature of the water surface. Understanding variations in water levels is important for predicting potential flood risks, assessing impacts on adjacent habitats, and optimizing restoration strategies to ensure stable water levels. As per the 'omgevingsveroderning', it is stipulated that the surrounding areas of streams can only inundate during a rain event with a recurrence time of T>1x10 years, while agricultural lands are subject to inundation only with a recurrence time of T>1x25 years rain events (Provincie Brabant, 2022).

Stagnation
Stagnation points in a stream are of vital importance for stream ecology. Identifying and addressing these points is crucial, as stagnant areas can contribute to decreased water quality, reduced oxygen levels, and the accumulation of sediment. These concerns are particularly prominent in the initialization phase of projects to find problem areas.

River Dryfall
When parts of the riverbed are left without flowing water, known as river dryfall, it messes with aquatic ecosystems and water quality. By simulating river dryfall, we can figure out how it stresses aquatic life, find out location with early droughts and with that come up with ways to prevent droughts.

Inundations
Inundations pose significant consequences for both natural ecosystems and human environments. Accurate modeling of inundation scenarios is crucial for identifying flood-prone zones, assessing potential damage, and implementing effective stream restoration strategies to minimize risks. Considering the planned mitigation measures for the Lage Raam, such as re-meandering and the creation of swamp areas, it becomes relevant to accurately map and visualize inundations in a model. This approach is vital for providing water managers with crucial insights into the initiation points of inundations and valuable information for informed decision-making and effective management.

In summary, these characteristics serve as key indicators for evaluating the hydraulic and ecological dynamics of a stream. Considering the objective of evaluating Tygron's applicability for watersystems, the study primarily concentrates on flow rate, level fluctuation/water level management, and inundations. Because the emphasis will be on wetter conditions, dry scenarios will be explored to evaluate Tygron's responsiveness to various weather scenarios. Stagnation and river dryfall may be subjects of future research, considering longer model runs.

3 Tygron

In this chapter information about the application of Tygron, a 2D hydrological modeling software, will be presented to provide a better understanding of the background of Tygron. In the first section, Tygron will be analyzed, starting with a brief summary of the literature study and benchmarks made on Tygron. Subsequently, the water module of Tygron will be introduced. For those interested in the underlying theory of the water module, a detailed explanation can be found in A.

3.1. Summary of Literature Background

The use of 2D models for hydrological purposes existed for a long time, however few authors assesses a model's ability to predict the hydraulic variables directly linked to the areas of interest (e.g. depth and velocity for ecological goals such as swamp areas or goals for fish rearing habitats) (Wright et al., 2017). From the relatively new software Tygron there is limited knowledge on its capabilities and limitations for e.g. water surface elevation calculations or its use for stream restoration projects. However, some research has been conducted on the Tygron software, and from these studies and benchmarks, certain insights can already be collected about its abilities.

These findings can be divided into two parts: features and technical possibilities. Features are aspects that may not significantly impact a 2D simulation but are often considered when choosing or using software. Some features that Tygron offers include interactive 3D visualization, real-time collaboration, an open API, use of open data, and a multi-disciplinary approach. Tygron also benefits from an advanced graphical user interface with the ability to generate instant calculation results.

For the technical possibilities the following can be said:

- A 2D model made in Tygron exhibited lower accuracy, than some models some other hydrological software, in simulating water levels. Especially in low-lying areas with complex topography (Henckens & Engel, 2018).
- Tygron can perform calculations with over a billion grid cells in a single project using high-resolution grid cell sizes (0.1 by 0.1 meter).
- Tygron has the capability to utilize both GPU and CPU for extensive computational power, resulting in significantly reduced computational times. The focus lies on GPU calculations.
- A study by Buwalda et al. (2023) comparing explicit and semi-implicit time integration methods for depth-averaged shallow water equations on GPUs demonstrated that simulations on GPUs are notably faster, ranging from 25 to 75 times faster compared to CPUs. Tygron uses this method efficiently and shows high computational power.
- High-resolution simulations, such as a model of the Netherlands with a resolution of 5 by 5 meters, 2 by 2 meters or even 1 by 1 meter, can be achieved in a reasonable time using GPUs (Klingen and Hoes" ("2016") & Buwalda et al. (2023)).

- According to STOWA , Tygron performed well overall in simulating a flood event, particularly in terms of accurately predicting flood extents and the timing of flood peaks (Henckens & Engel, 2018).
- Tygron lacks functionalities for 1D open water, 1D closed pipes, water quality (Henckens & Engel, 2018).

Benchmarks

To validate the workings of 2D models in Tygron, Tygron (company) has provided some benchmarks which have been conducted for validation of the software. These benchmarks are mostly related to (shallow) water related tasks of Tygrons water module. With each update, Tygron (company) ensures rigorous testing of the water module against these hydrological benchmarks to ensure the quality of the software. These benchmarks are:

- STOWA-2017 benchmark - testing various model instruments available on the Dutch market on shallow water tasks on various scenarios: overland flow, ponding, slopes and pipe-flow
- UK Benchmark - UK comparison of available 2D modelling software, which tested: sloping, floodplain filling, momentum conservation, flood propagation and dambreaks.
- Groundwater benchmarks - testing Tygrons capabilities for groundwater task, as: sudden waterway level change, freatic groundwater, seepage and radial wells.

In comparison to other 2D models, D-hydro, Sobek, Hecras, 3Di, Infoworks and MIKE, Tygron seems to do this as good as the established softwares (Henckens & Engel, 2018). While these models boast different specific features or capabilities , Henckens and Engel (2018) also identified some limitations of Tygron when compared to its competitors. For instance, Tygron exhibited lower accuracy than some other models in simulating water levels in specific areas of the test region, particularly in low-lying regions with complex topography. In summary, the studies suggests that the water module of Tygron could be a potent tool for modeling and simulating scenarios in a 2D environment. Tygron had some small inaccuracies with the 2D sheetflow calculations, but Tygron's arithmetic heart is functioning properly (Henckens & Engel, 2018). After 2018 Tygron however received multiple updates where the computing core has been updated as well using the Saint-Venant equations, but no new benchmarks have been published by STOWA with the same tests.

3.2. Water Module

To gain a deeper understanding of Tygron, this section provides a brief overview of the hydrological background of Tygron (refer to Appendix A for a more comprehensive explanation). Tygron refers to its 2D hydrological modeling as the 'Water Module'. Within the Tygron software, the Water Module serves as a tool for simulating the movement of liquid water and assessing its impact on a project area.

3.2.1. Basis of the Watermodule

The Water Module in Tygron employs a grid-based model using the 2D Saint Venant scheme to calculate the shallow water equations (SWE) (see appendix A.3.2). These equations describe the conservation of mass and momentum for shallow water flow in two dimensions. Because Tygron has chosen to calculate the SWE explicitly the solution at each time step is directly computed based on known values from the previous time step. It is computationally efficient for single time-steps, but causes stability limitations and for larger models/areas can cause computational heavy models.

To counter stability issues Tygron uses a second-order well-balanced scheme. When you have a second-order well-balanced positivity property for a numerical scheme applied to the Saint-Venant equations, it means that the scheme is accurate (second-order), capable of handling flow discontinuities between cells (well-balanced), and ensures that key physical quantities like water depth and velocity remain non-negative (positivity) as it computes solutions to these equations (Kurganov & Petrova, 2007). Further details on this can be found in Appendix A.3.3.

Next to the well-balanced scheme, Tygron also uses piece-wise linear discretization of the bottom topography for reconstruction of the water level at wet/dry fronts for the shallow water equations. Piecewise linearization is a method for approximating a function by breaking it into multiple linear sections. In other words it means that they approximated the bottom topography using a series of linear segments (Bollermann et al., 2014) (see also appendix A.3.1.

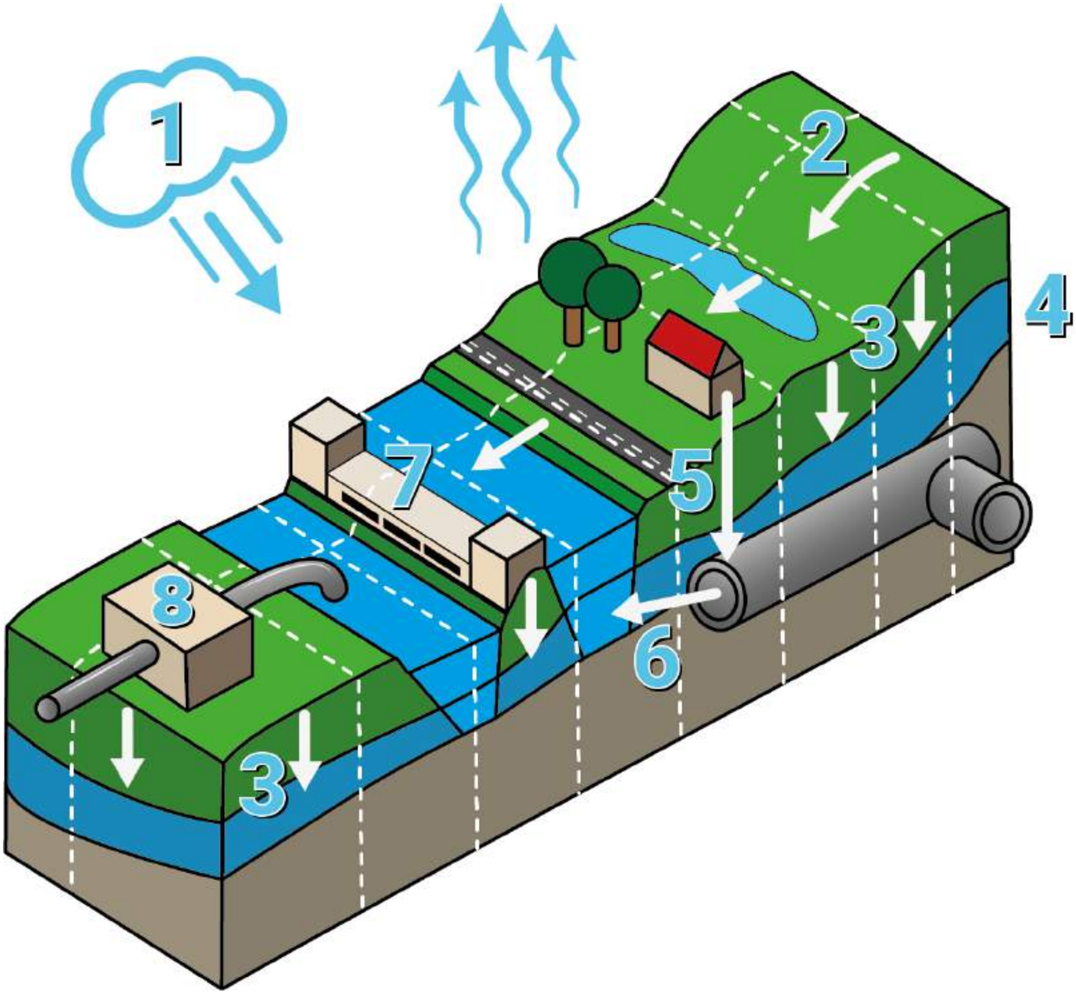


Figure 3.1: Water module - order of calculation

Furthermore, the water module of Tygron incorporates rainfall, infiltration, evaporation, groundwater flow, structure flow and water storage. Each cell exchanges water flow (and other information) with adjacent cells during a simulation in a 'overlay', with these calculations per grid cell following a defined "Order of calculations" (figure 3.1).

3.2.2. Rainfall Overlay

The Water Module has multiple "overlay models" that are used to create a water simulation. Notably, the Rainfall overlay is utilized to simulate a rainfall/storm event. In the rainfall overlay a couple of things can be set up.

Hydraulic Structures

Most hydraulic structures have been implemented in the model using open data, like using a legger from a waterboard (see chapter 7. In the rainfall overlay each separate structure can be addressed separately to change some settings. E.g. for a weir certain target levels can be adjusted in its PID controller, for a culvert shape and diameter can be adjusted, for pumps different discharge capacities can be changed if needed, in-/outlets can be created to make boundary conditions if necessary.

Culvert Generator

Sometimes open data does not contain sufficient information on hydraulic structures or there is no available data from hydraulic structures. This is especially true for culverts in private management. These culverts can be generated with a culvert generator, generating culvert between secondary and tertiary waterways for larger connectivity of a watersystem.

Rainfall event

In the rainfall overlay a rainfall event can be added, to simulate a rainfall event or storm event. It can be chosen to have uniform rain event on the whole model, or a location can be selected for a rainfall event.

Timeframes

For each rainfall event simulation it can be chosen to choose an amount of timeframes. These timeframes will be the results/data obtained after a simulation in the 2D model. For example if 100 timeframes are chosen, 100 timeframes evenly seperated over time of the simulation will be the output data given by Tygron.

Grid Cell Size & timesteps

For each simulation a grid cell size has to be given. For a 2-dimensional model, it is common practice to employ a grid, dividing the study area into a specified number of grid cells. A grid, essentially a pattern of intersecting lines or squares, serves as a foundational element in both 2D and 3D models. In Tygron, a structured Cartesian 2D grid is used to divide the model area into a number of rectangular grid cells. The landscape in the model can be discretized as a fully spatially distributed hydrological model, allowing rainwater to "fall" onto grid cells that interact with each other for surface water flow.

The grid cell size chosen will give all cells in the model the same size. This influences the amount of timesteps in the model (see 3.2.3. It is common that a simualtion has over 300.000 timesteps when chosen smaller grid cell sizes. All these time steps are calculated by Tygron on servers. However this uses a lot of data, so the only timesteps that are saved after calculations are the chosen timeframes mentioned in the previous section.

Limit Area

If a project area in the model is to big a limit area can be used to focus on certain parts in the model. This option can be used when the model is to computational heavy or only a certain area of interest is wanted to be calculated.

Measurement points

In the overlay also measurement points can be added to the model. For instance when interested in a certain output value these point can be implemented to export this data separately. E.g. along a stream measurement points can be added to export water level data, this data can be exported separately to create a longitudinal profile of the stream.

3.2.3. Grids, calculation cells and timesteps

As previously mentioned, Tygron exclusively employs 2D calculations, benefiting from a powerful calculation core within its engine. This capability allows for the SWE of numerous grid cells in 2D. A notable distinction lies in the flexibility of Tygron's grid cell sizes, ranging from very low cells of 0.1 by 0.1 meters to up to 10 by 10 meters. However, it's essential to note that while users can choose the size of the grid cells, the placement of these cells is predetermined and the recommended grid cell sizes remain unspecified.

Importantly, water does not flow diagonally between cells. These calculations are executed in discrete time steps, and the simulation can consist of a variable number of time steps, contingent on the Courant value.

To guarantee numerical stability, an adaptive timestep, as defined by formula A.6, is implemented using Kurganov and Petrova's method (Kurganov & Petrova, 2007).

$$\Delta t = min(\frac{\delta x}{4a}, \frac{\delta y}{4b}) \tag{3.1}$$

Where:

$x = y$: Cell size
a : max of one-sided speeds in y-directionn
b : max of one-sided speeds in y-direction

The selection of an appropriate timestep is crucial, especially in the context of shallow depths, to avoid numerical instability. Therefore, the timestep is carefully chosen to ensure that all computational cells adhere to one of the following criteria:

- The timestep is chosen so that each computation cell meets one of the following criteria:
  1. If a cell's water depth is below 5×10^{-3} m (the flooding threshold), there is no flow assumed between that cell and its neighboring cell.
  2. If a cell's water depth is above the flooding threshold, the maximum timestep is 100 times the water depth at the cell.
  3. If the water depth increases, the timestep is not larger than the formula above.
- If the numerical flux decreases, larger timesteps may be allowed than those set by Kurganov and Petrova, depending on the configured calculation.

In general, to meet this requirement, the Courant-Friedrichs-Lewy (CFL) condition is employed. The timestep formula for the scheme proposed in Bollermann et al. (2014) is given by the CFL condition. It is defined in formula 3.2 where t is the time step, x is the cell size, and a±j+1/2 are the maximum wave speeds at the cell interfaces.

This means that, following Tygron's decision to limit the Courant number to below 0.25, the Courant number in any given computation cell is either exactly 0.25 or smaller, determined by the cell with the highest flow velocity. This CFL condition ensures that each wave can travel at most one quarter of a grid cell per timestep, thereby limiting information propagation by restricting the timestep (Horváth et al., 2015). Consequently, due to this condition, water located in the middle of a grid cell cannot suddenly move to a neighboring cell.

$$CFL := \frac{\Delta t}{\Delta x} * max_j |a^{\pm}_{j+1/2}| \leq \frac{1}{2} \tag{3.2}$$

3.3. Simulation Settings

Because Tygron uses a finite volume method to discretize the saint-venant equations and solve them numerically, this also causes for numerical instabilities especially in dry/wetting cells. That is why next to the common settings Tygron also has some advanced simulation settings. The most important settings to change for a simulation in the water module are:

- Dry-wetting cells settings
  - Extend Waterlevel to Shorelines
  - Extend Waterline reconstruction
  - Angle Stabilizer for partly flooded cells
- Manning value
- Grid cell size

The first setting is the **extend waterlevel to shorelines**. When selected, a shoreline along a waterway will be filled with water to prevent a initial flush of the waterway during a simulation. These shoreline cells are initially filled with water to match the nearby water level, preventing the initial overflow (Horváth et al., 2015).

The second setting is the **Extend the waterline reconstruction**. In this setting it can be chosen whether to automatically fill cells near a water terrain when there is a mismatch between the extend of the water terrain and the DEM. In appendix A.3.5 the steps are further explained.

The third setting is the **Angle stabilizer for partly flooded cells**. A partly wet cell (mostly at the banks of waterways) can become unstable when a cell is very steep or the water velocity difference is large. In this case the fluxes in flow direction U and V cannot easily be solved mathematically while preserving balance using Saint-Venant. To prevent unrealistic calculations, only the watervelocity in the primary flow direction will be kept, making the SWE within the cell 1-dimensional.

These first 3 mentioned settings are all created based on the research of Kurganov and Levy (2002) and Bollermann et al. (2014). They play a crucial role in handling dry-wetting cells within the water module. In Tygron, the ability to choose the cell size for placement in a Cartesian grid over the model area is a significant constraint. Unfortunately, this means one cannot dictate how cells align with waterways, resulting in cells along the waterway boundary being partly dry and partly wet. Adjusting these settings could contribute to a more (un)stable model.

The fourth setting is the **Manning value**. This value determines the roughness value of a cell and therefor influences the water flow between cells. Every cell in a model in Tygron is given a manning value based on open data (Tygron, 2023), but can be altered to provide a more accurate model.

The last setting is the **grid cell size**, and already mentioned in the 'Rainfall overlay'. Although this setting is chosen by the modeller it is researched, because it can have an influence on the accuracy of the result even if the changes are relative small (e.g. 1 by 1 meter or a 1.1 by 1.1 meter). The grid cell size determines; the amount of timesteps during a simulation, the amount of maximum timeframes that can be saved, and the duration of the simulation.

4 Case study 1: Testcase

A test case was conducted in Tygron to assess the simulation settings of Tygron, which offers a multitude of options for generating a simulation. Each setting could impact the simulation outcome, resulting in variations in results. Despite the availability of benchmarks and previous research, there is a notable absence of information regarding the specific influences of these settings in waterways. While Tygron's guide outlines the meanings of the settings, it fails to provide details on how specific values within each setting affect the simulation. The most important options are described in section 3.3, which are:

- Extend Waterlevel to Shorelines
- Extend Waterline reconstruction
- Angle Stabilizer for partly flooded cells
- Manning value
- Grid cell size

In addition to these settings, the test case has explored the impact of **stream placement** on grid cells. As detailed in Section 3.2.2, the grid cells in Tygron are fixed and cannot be altered, except for choosing the grid cell sizes. When placing a stream in Tygron, there is no option to selectively designate which cells are in, on, or adjacent to the stream Consequently, Tygron provides a mechanism to manage the dry-wetting fronts of cells along streams that are partially dry or wet, using especially the first three settings mentioned above. However, the positioning of the stream on the grid cells is also a variable under investigation in this case. This exploration aims to determine whether the placement of the stream on specific grid cells influences the simulation results. To test all these settings the following test case is made.

4.1. Research setup - Testcase

Initially, a setup is established using contour lines, resulting in the creation of four distinct areas (see Figure 4.1), each characterized by a different bed slope or orientation. For analytical purposes, a slope of 0.1 meter per kilometer is applied to Areas 1 and 2, while a slope of 0.3 meter per kilometer is implemented in Areas 3 and 4. This slope is selected to align with the average slope in the Lage Raam region.

Channels are strategically placed in Areas 1 and 3, running from North to South along the grid cells. In contrast, in Areas 2 and 4, channels are oriented from North-West to South-East, forming a 45-degree angle on the grid cells. This configuration is showcased in Figure 4.2, which presents a digital elevation model illustrating of the test case.

In the testcase, 28 channels have been incorporated onto the Digital Elevation Model (DEM), as depicted in Figure 4.4. Each of the four areas is equipped with 7 channels, each featuring varying widths. The decision to employ trapezoidal channels in the test case is grounded in the consideration that this

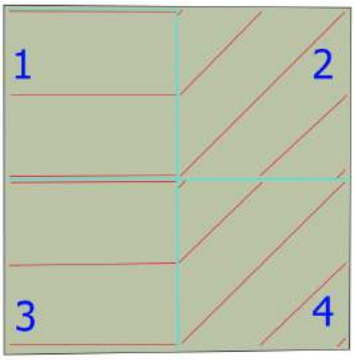


Figure 4.1: Setup contourlines (red) and slopes for the testcase, with boundary of the area 1,2,3,4 (lightblue)

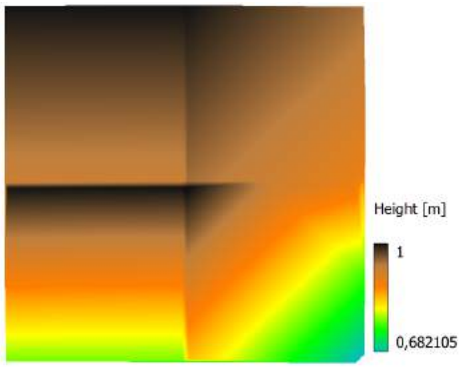


Figure 4.2: Digital Elevation model of the Testcase

Table 4.1: Channel Characteristics

	Channel A	Channel B	Channel C	Channel D	Channel E	Channel F	Channel G
Width [m]	1	1	2	3	5	10	14
m slope [-]	1	1	1	1	1	1	1
Length [m]	365	360	363	364	365	365	365
Max depth [m]	4	3	3	3	3	3	3

channel form aligns with a more 'natural' representation. The channels in the testcase are distinguished by different widths, see table 4.1.

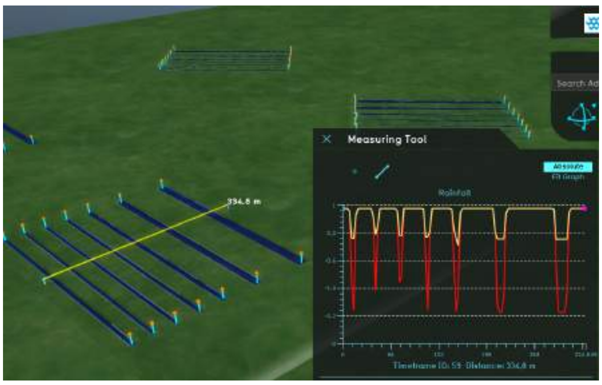


Figure 4.3: Channels created in Tygron. Showing channel 3A to 3G in Tygron from left to right.

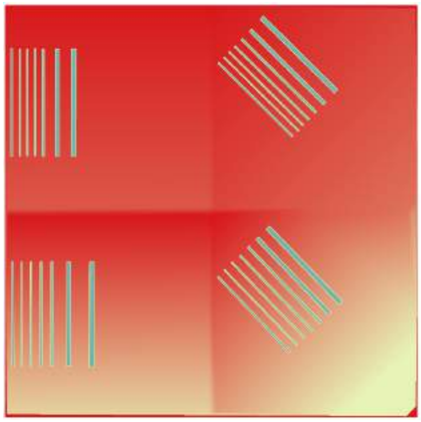


Figure 4.4: Overview of channels. Each channel is named from left to right using letter A to G as in table 4.1.

4.2. Method - Testcase

To analyze the diverse parameters and grid cell sizes, a setup has been adopted wherein water height can be computed in various channels based on the specified parameters. This computation employs the gradually varied flow calculations. Which involve determining changes in water depth and velocity along a channel over a distance, typically used to analyze open-channel flow profiles and determine water surface elevations, using the Backward Euler Method, the Manning equation, the momentum equations, and the continuity equations. At the initiation of each channel, a boundary inlet condition is established in Tygron, facilitating a constant discharge $[m^3/s]$ from the inlet. At the end of each channel, an outlet is positioned, designed to pump water out to keep the water level at the end of the waterway at a target level and thus emulate a boundary condition like the presence of a weir. The selection of an outlet offers greater flexibility with regard to changing boundary conditions in the testcase.

In the channels, with constant cross-sections, flowing water will reach a normal depth (uniform flow depth) creating a gradually varied flow. This normal depth can be calculated with the Manning's equation:

$$V = \frac{1}{n} * (\frac{A}{P})^{2/3} * S_0^{1/2} \tag{4.1}$$

With the gradually varied flow in the channels a plot can be created of the water depth over the distance in the channel. During a simulation in the testcase an steady waterlevel at the end of the channel is reached and will be given as output. The resulting waterlevel at the end of the channel can be used for the gradually varied flow calculation to calculate the backwater calculation in the channel. The result will be a theoretical water level at the start of the channel. This theoretical water level is then compared to the water level at the start of a channel created by Tygrons water module. For the gradually varied flow calculation the following equations are used (Chanson, 2004):

$$A = (b + m * y) * y \tag{4.2}$$

$$dA = b + 2 * m * y \tag{4.3}$$

$$P = b + 2 * y * \sqrt{1 + m^2} \tag{4.4}$$

$$S_f = \frac{Q * |Q| * (P^{4/3})}{(k^2) * (A^{10/3})} \tag{4.5}$$

$$MON = \frac{S_0 - S_f - \frac{(2*Beta*Q*ql)}{(g*A^2)}}{1 - \frac{(Beta*Q^2*dA)}{(g*A^3)}} \tag{4.6}$$

$$y_{next} = y - \frac{(L/n) * MON}{1 - \frac{(Beta*Q^2*dA)}{(g*A^3)}} \tag{4.7}$$

Where:

A : Cross-sectional area of the flow $[m^2]$
dA : derivative of A
P : Wetted Perimeter of channel $[m]$
Q : Flow rate in $[m^3/s]$
g : Acceleration due to gravity $[m/s^2]$
S_f : Friction slope [-] (representing energy losses due to roughness)
S_O : Bottom slope of the channel [-] slope (representing energy losses due to roughness)
L : Horizontal length of the channel [m]
b : Channel width [m]
q_l : Lateral inflow/outflow $[m^3/s]$
m : Side slope trapezoidal channel [-]
k : Strickler coefficient of roughness $[m^{1/3}/s]$, determined by 1/(manning coefficient of roughness)
MON : Abbreviation for momentum balance equation for Euler's method
$Beta$: Boussineq coefficient, Beta = 1
y_{next} : Waterheight at the end of iteration becoming next y $[m]$
y : Waterheight used for iteration calculation y_{next} $[m]$

4.3. Scenarios - Testcase

For the testcase different scenarios will be run. In each scenario the parameters mentioned in chapter 3 are different. In figure 4.5 the different scenarios are shown. Scenario 2 is the default scenario, as this are the default settings. In scenario 1,2, & 3 the *extended waterline construction* and *Extend waterlevel to shoreline* parameters are changed. Scenario 3 to 6 show the difference between the Manning value and scenario 3, 7 & 8 are for the angel stabilizer.

For each scenario, multiple simulations will be run with different grid cell sizes. With this the influence of grid cell sizes are analysed and also with each simulation the slope and channel placement are analysed. For the latter the influence per area are of more importance. In the schedule below one can find an overview of the testcase setup and the different scenarios/simulations run for the analysis of the case study.

The different scenarios are:

Scenario 1:		**Scenario 2:**		**Scenario 3:**	
Extended Waterline reconstruction:	OFF	Extended Waterline reconstruction:	ON	Extended Waterline reconstruction:	OFF
Extend waterlevel to shoreline:	OFF	Extend waterlevel to shoreline:	ON	Extend waterlevel to shoreline:	ON
Angle stabilizer for partly flooded cells:	10 [degrees]	Angle stabilizer for partly flooded cells:	10 [degrees]	Angle stabilizer for partly flooded cells:	10 [degrees]
Manning Value:	0.03 [s/m^(1/3)]	Manning Value:	0.03 [s/m^(1/3)]	Manning Value:	0.03 [s/m^(1/3)]
Scenario 4:		**Scenario 5:**		**Scenario 6:**	
Extended Waterline reconstruction:	OFF	Extended Waterline reconstruction:	OFF	Extended Waterline reconstruction:	OFF
Extend waterlevel to shoreline:	ON	Extend waterlevel to shoreline:	ON	Extend waterlevel to shoreline:	ON
Angle stabilizer for partly flooded cells:	10 [degrees]	Angle stabilizer for partly flooded cells:	10 [degrees]	Angle stabilizer for partly flooded cells:	10 [degrees]
Manning Value:	0.021 [s/m^(1/3)]	Manning Value:	0.013 [s/m^(1/3)]	Manning Value:	0.010 [s/m^(1/3)]
Scenario 7:		**Scenario 8:**			
Extended Waterline reconstruction:	OFF	Extended Waterline reconstruction:	OFF		
Extend waterlevel to shoreline:	ON	Extend waterlevel to shoreline:	OFF		
Angle stabilizer for partly flooded cells:	45 [degrees]	Angle stabilizer for partly flooded cells:	90 [degrees]		
Manning Value:	0.03 [s/m^(1/3)]	Manning Value:	0.03 [s/m^(1/3)]		

Figure 4.5: Scenarios for the testcase

With these scenarios, the following simulations have been run:

Table 4.2: Overview which simulation has been done for the given grid cell size

Grid Cell Size	0.11	0.20	0.25	0.50	0.75	1.0	1.5	2.0
Scenario 1	x	x	x	x	x	x	x	x
Scenario 2	x	x	x	x	x	x	x	x
Scenario 3	x	x	x	x	x	x	x	x
Scenario 4		x		x		x		
Scenario 5	x	x	x	x	x	x	x	x
Scenario 6	x	x		x		x		
Scenario 7				x		x		
Scenario 8				x		x		

5

Results Part 1

5.1. Results Case 1: Testcase

From chapter 3 and from section 3.3 it became clear that some settings in Tygron involve dealing with stability problems in a model because Tygron calculates models using the Saint-venant equations explicitly. Especially settings involving how the water module uses the research of Kurganov and Levy (2002) & Bollermann et al. (2014) to overcome difficulties of dry-wetting cells are important. The settings below have been tested, and the grid placement has also been taken into consideration:

- Extend Waterlevel to Shorelines
- Extend Waterline reconstruction
- Angle Stabilizer for partly flooded cells
- Manning value
- Grid cell size

By employing the methodology outlined in Section 4.2, a comparative analysis can be conducted between the water heights computed in Tygron and the theoretical water heights with 41 simulations done. These results are further detailed in histograms, providing a more in-depth analysis. The categorization is based on the different settings to better assess the performance of the water module setup in Tygron for 2D modeling of surface water

5.1.1. Dry-Wetting cells

The first three settings, *Extend Waterlevel to Shorelines*, *Extend the Waterline Reconstruction*, and *Angle Stabilizer* for partly flooded cells, effect the dry/wtting cells so have been combined in this section.

Extend Waterlevel to Shorelines & Extend Waterline reconstruction

When examining figures 5.1, 5.2, 5.3, the simulation results for the settings *Extend Waterlevel to Shorelines* and *Extend the Waterline Reconstruction* are presented.

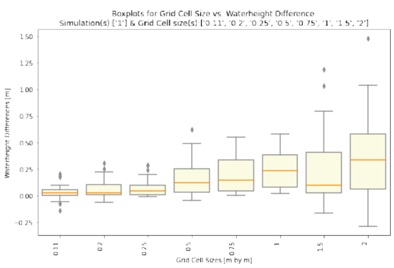


Figure 5.1: Scenario 1: all simulations

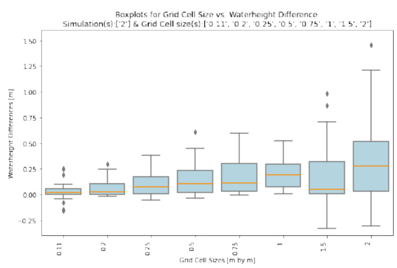


Figure 5.2: Scenario 2: Default settings of Tygron, all simulations are shown

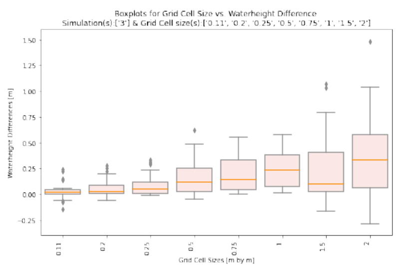


Figure 5.3: Scenario 3: all simulations

Each figure show different scenarios 1,2,3 as explained and shown in figure 4.5. Each histogram shows the the calculations done per grid cell sizes, but does not differentiate between different channel widths.

Figure 5.2 illustrates the default settings for the Tygron model, where both of these settings are enabled. Figure 5.1, the *Extend Waterlevel to Shorelines* is disabled.
Figure 5.3, *Extend the Waterline Reconstruction* is switched off.

Several observations can be drawn from these figures:

- There are minimal significant differences among scenarios 1, 2, and 3. This suggests that the settings have a limited impact on the results in the waterways of the test case.
- As the grid cell sizes increase, the median of the results becomes closer to zero indicating a more accurate result, with the exception of a 1.5 by 1.5-meter grid.
- Notably, for Scenario 3, there are fewer prominent whiskers in the boxplot for larger grid cell sizes, indicating a higher degree of accuracy for these sizes.
- In general, there are few discernible differences in the results across the scenarios.

Angle Stabilzer

Based on the results obtained from the previous settings, Scenario 3 was selected as the default setting for the subsequent simulations and scenarios. For the Angle Stabilizer results, Scenarios 3, 7, and 8 were considered, where all widths of the channel are grouped together and the position of the channel placement have been split:

- Scenario 3 (red) represents the default setting with an angle stabilizer of 10 degrees, as illustrated in Figure 5.4.
- Scenario 7 (green) features an angle stabilizer set at 45 degrees
- Scenario 8 (black) showcases an angle stabilizer set at 90 degrees

In Figure 5.5, the results are further categorized based on the stream placement within the testcase. The angle fo the placement is different with the angle of the stabilizer setting and should not be confused. Streams are positioned either 0-decree North-South or at a 45-degree angle from Northwest to Southeast, these have been split in the results to see if placement of channels as an effect on the results of different stabilizer angles. This segmentation aims to investigate whether stream placement influences the simulation results

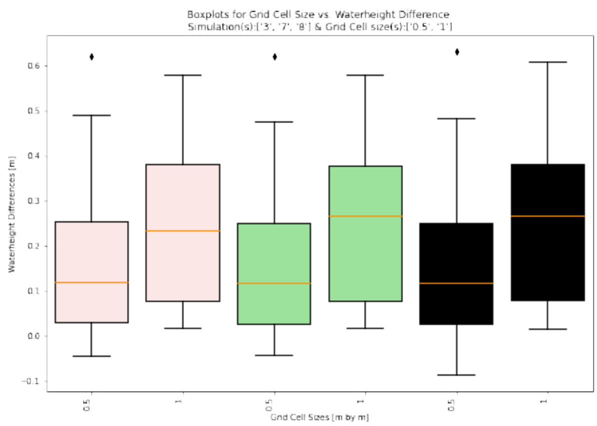


Figure 5.4: Scenario 3 (red), 7 (green), 8 (black): Results Angle Stabilizer, simulations of Grid cell size 0.5 and 1.0

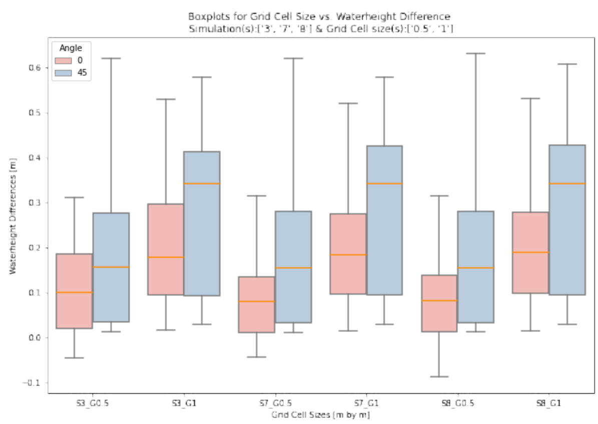


Figure 5.5: Scenario 3, 7, 8: Results Angle Stabilizer, divided by Angle placement (0 or 45 degrees)

From these results, several observations can be made:

- In Figure 5.4, it appears that the angle stabilizer, when set to different angles, does not have a significant effect on the simulation results. It could even be argued that no discernible differences are detected.

- Once again, it is evident that smaller grid cell sizes tend to yield more accurate results, although this is not attributed to these settings.
- An interesting finding is highlighted in Figure 5.5, where it seems that Tygron's water height calculations perform better when a stream is placed parallel to the waterway, rather than across grid cells at a 45-degree angle. This contradicts the hypothesis that setting the angle stabilizer to 45 degrees would result in better performance for streams placed across grid cells. It can now be concluded that this is not the case

5.1.2. Grid placement

For the results based on grid placement, all simulations were included, as each simulation varied the grid placement as a tested variable. The findings are presented in figures 5.6 and 5.7. Additionally, insights from figure 5.5 also suggest the following:

- A noteworthy observation is that the results of the testcase with the different scenarios does not significantly vary with the slope of an area. While there is a slight preference for a steeper slope in the calculations. It is important to note that, due to the test case setup, it was challenging to introduce multiple slope variations, and thus, a comprehensive examination of this aspect was not feasible.
- Tygron appears to perform better in calculating water heights in waterways when the waterway aligns parallel to cell placements. Conversely, when the alignment of a waterway and grid cell deviates, it leads to poorer estimations of water height due to an increased occurrence of dry-wetting cells. This could be attributed to grid placement, but is considered to be a problem with the amount of grid cells within the width of a stream.

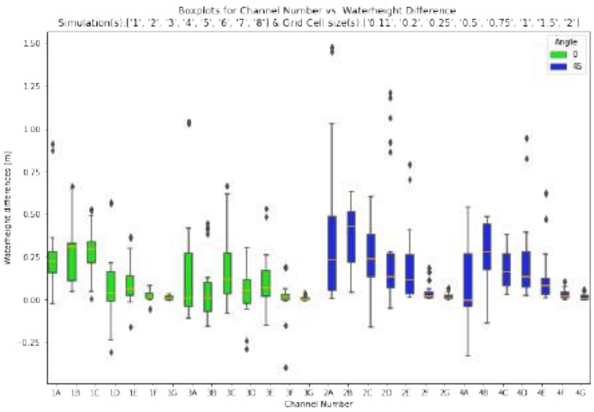


Figure 5.6: Boxplot for grid placement results divided per channel,and angle

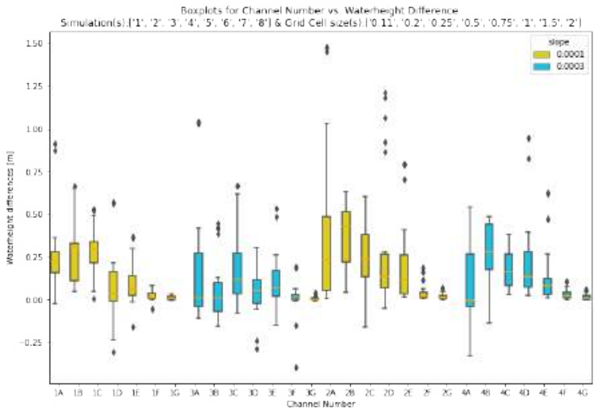


Figure 5.7: Boxplot for grid placement results divided per channel, and slope

In appendix C.3 the result of grid placement of figure 5.6 are also divided for each grid cell size to give a clearer insight in the results. These results can be seen in figure 5.8 & figure 5.9. These result can also been seen in from figures C.17 to C.26, in the appendix. In these figures it can be clearly seen that grid placement has a effect on results. When bigger grid cell sizes are used, a stream placed parallel to grid cells show better results. The most important thing to notice is however that the effect of grid placement decreases when more grid cells fit in a channel. One is able to see that when a stream placed on 45 degrees and it has sufficient cells in its width a comparable deviation in results can be seen compared to a stream on 0 degrees.

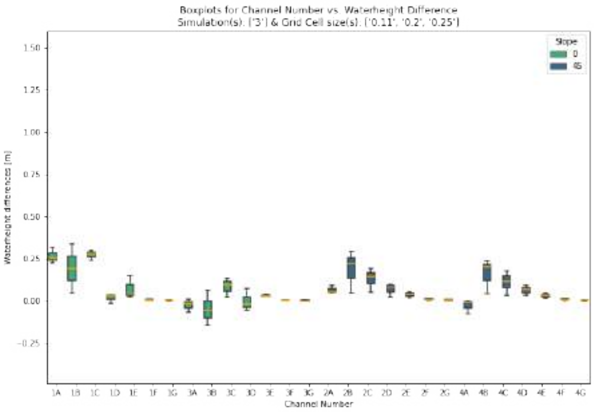


Figure 5.8: Boxplot for grid placement results divided per channel and angle. Small grid cell sizes (0.11 to 0.25 meters)

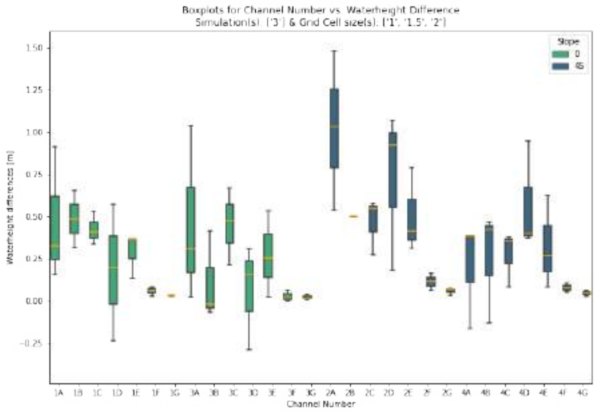


Figure 5.9: Boxplot for grid placement results divided per channel and angle. Big grid cell sizes (1 to 2 meters)

5.1.3. Manning

In figure 5.10 the result for the scenarios were the manning value is tested is shown.

- Scenario 3 shows the default value of Tygron with 0.030 [$s/m^{1/3}$]
- Scenario 4 shows a value of 0.020 [$s/m^{1/3}$]
- Scenario 5 shows the average value of waterways with 0.013 [$s/m^{1/3}$]
- Scenario 6 shows the value of 0.010 [$s/m^{1/3}$], when a waterway is considered smooth

The figure clearly illustrates that as the Manning value decreases, the accuracy of the water height results, measured against the calculated values, improves. Additionally, it highlights that smaller grid cell sizes correspond to better results. Figure 5.11 further breaks down the results based on the test grid outlined in figure 4.1 in section 4.1. This figure also reveals that results, influenced by different Manning values, are highly dependent on the placement of streams. In steeper streams, water heights tend to be more underestimated, while streams placed perpendicular to grid cells yield better results—a contrast to the findings in the previous section.

The impact of Manning on these specific results seem to be significant compared to other settings, it introduces more inaccuracies compared to theoretically calculated waterheights with the gradually varied flow calculations (section 4.2). Smoother surfaces exhibit a slightly greater tendency to underestimate, and rougher Manning values contribute to a more pronounced backwater effect. This effect is particularly noticeable in narrow streams with shallower water, where Manning's influence is more prominent. The combination of steeper and narrower slopes in narrow streams results in shallower water, leading to a heightened water stagnation in each cell.

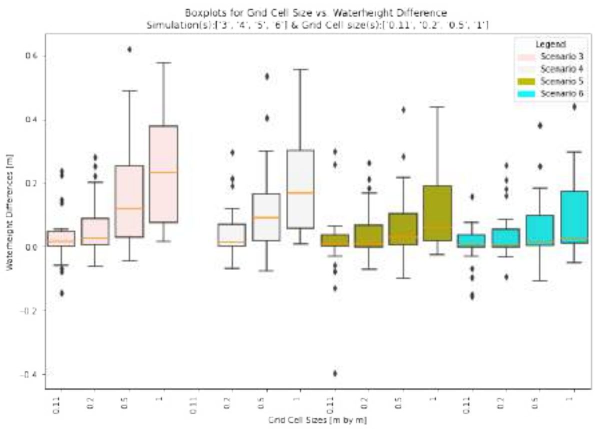


Figure 5.10: Boxplot results Manning value, Scenarios 3,4,5,6

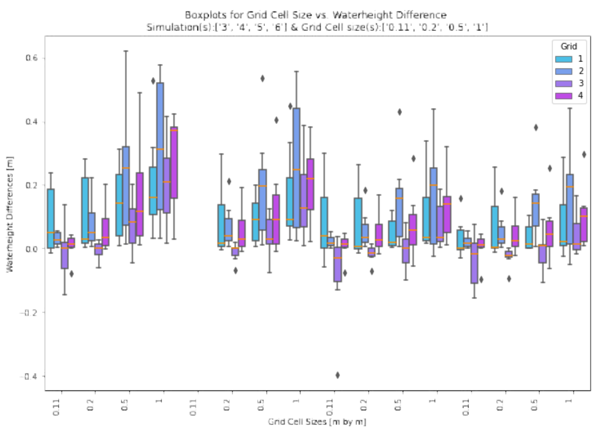


Figure 5.11: Boxplot results Manning value, seperated per testcase grid

5.1.4. Grid cell size

Regarding grid cell sizes, Figure 5.12 has been generated to illustrate all scenarios involving various grid cell sizes in Tygron. A notable observation from this figure is that smaller grid cell sizes tend to yield more accurate results compared to larger grid cell sizes. Which means that the water slope in the channels are in the 2D model of Tygron are more comparable to what is expected form the gradually varied flow calculations when choosing for smaller grid cell sizes. For a comprehensive overview of the results, please refer to Appendix C. This appendix not only presents each scenario plotted separately for different grid cell sizes but also provides individual plots for each grid cell size across different scenarios.

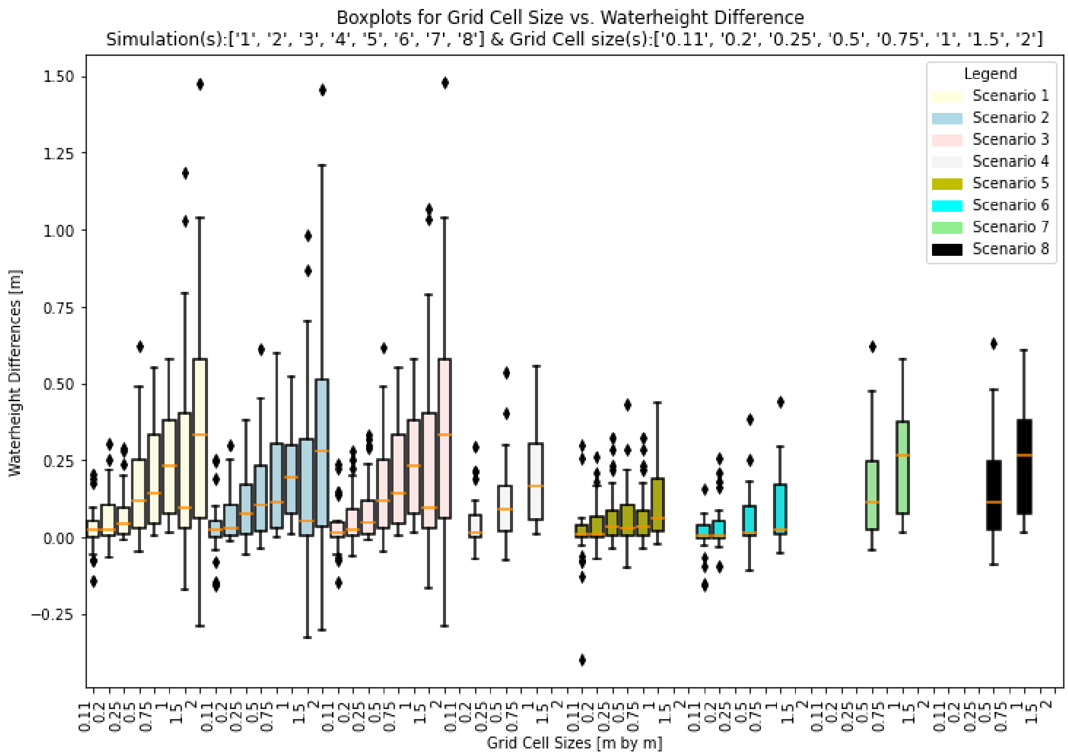


Figure 5.12: All Results of simulations on grid cell sizes and their according scenarios

The presented results reveal significant insights regarding grid cell sizes in the analysis of streams. A notable observation indicates that optimal outcomes are closely tied to the presence of approximately 5/6 cells within the confines of a stream. This finding suggests a direct correlation between the count of grid cells and the accuracy achieved in stream-related analyses.

Furthermore, the results highlight a cautionary note against employing grid cell sizes surpassing 1 by 1 meter. This observation implies potential challenges or inaccuracies associated with larger cells, shedding light on the impact of grid size choices on the quality of results in stream projects or models.

A distinct result emerges concerning smaller grid cell sizes, particularly those at 0.11 by 0.11 meters. It is evident from the results that such small cell dimensions often lead to milder water slopes than expected and thus an underestimation of water height. This outcome introduces a nuanced consideration, emphasizing the influence of grid size variations on the precision of water height measurements.

6
Discussion Part 1

The first part of this study focused on testing the influence of underlying settings in Tygron. The focus of Part 1 was to test the influence of settings in Tygron, following the demarcation of stream restoration for the entire study and the exploration of the water module of Tygron.

In the demarcation of 'Stream Restoration' it became clear that this term is a catch-all term encompassing various actions, from introducing dead wood or gravel at a specific location to the complete re-meandering of an entire river. It is crucial that the restoration process should consistently strive to restore or enhance the natural characteristics and functions of a stream or river. In case of the Raamvallei project, TAUW has chosen for a redesign of the Lage Raam. Following directives from the WFD to create a stream in line with a swamp stream type R20. It became evident that flow rate, level fluctuations, and inundations stand out as the most critical outputs of a hydrological models when considering the design of restoration measures, such as creating swamp areas, cross-sections, and water level management. While river dry-fall and stagnation are also significant outputs, their comprehensive understanding may be better suited for future study. Given the necessity for longer model runs for the latter 2 outputs these have not been considered anymore for this research due to the amount of simulation time this would cost.

In case study 1 five settings were tested with the help of a self-created testcase model in Tygron, and next to this the stream placement has been taken into consideration. Where water levels for channels were simulated Tygron and compared to calculated water heights using the gradually varied flow calculations. Although some results give some clear answer on the influence of setting some discussion is preferred on some settings. The results have yielded several observations, which have been communicated to Tygron, prompting a discussion and further clarification on these settings below (Knepfle, 2023).

Discussion on dry-wetting cell settings observations

The **extended waterline reconstruction** setting is intended to be activated during simulations with a "lake at rest" scenario. However, in the specific test case, the concept of "Lake at rest" is inapplicable, given the constant water flow. Similarly, no significant difference was observed. According with Tygron this is logical since in a test case, the created situation ensures better alignment between water and the DEM compared to open data, rendering this option inconsequential in terms of results. Tygron does recommend to put this setting off when interested in water flow, but there is not a difference in results when done.

The **extended water level to shoreline** setting aims to align waterway location data with the digital elevation model in cases of mismatches. No big differences in results was observed for water level to shoreline. It was expected that small differences were observable near the banks with this setting due to the adjusting of waterlevels by this setting. Tygron however explained that this setting as well is mainly for initial water levels and does not really influence water levels throughout a simulation as can be observed.

The third setting tested was the **Angle stabilizer for partly flooded cells**. The angle stabilizer activates when a cell water flows within the cell (U and V) is too to big. This setting allows for the option to ignore stream directions towards the shoreline/banks and perform a 1D calculation on the corresponding cell for the other velocity. The default of 10 degrees means that this setting only activates on steep cells that are 10 degrees from the y-axis, only when in such cell difference between the 2 velocity components are big a 1D calculation is executed instead of a 2D calculation, reducing issues like crawling on slopes that lead to flooding or abnormal values (Knepfle, 2023). However, despite the setting allowing for angle decrees up to 90 degrees, indicating that flat cells should also use 1D calculations, no significant difference was observed. It was argued that this setting may not be functioning as intended in the testcase due to unnatural circumstances. Discussions with Tygron revealed that the angle stabilizer might have a more pronounced effect in situations involving:

- Small grid cells
- Arrival of water at a corner (in water movement)
- Inclined cells (steep cells are more common with smaller grid cell sizes)
- Water that goes directly/perpendicular towards the shoreline

The second and fourth statement can not directly be confirmed with the setup of this testcase. For the first statement it is visible that results are better for smaller grid cells, but it can not confirmed if this is necessarily due to the angle stabilizer. The third statement seems to be the happening in the testcase as there is a little bit of an improvement on results, but this is also in combination with the first statement for small grid cell not clear to observe in the results as smaller grid cells tend to created steeper cells therfore these 2 statement influence each other.

Discussion on other settings observations

For the **Manning values** it was observed that smoother surfaced contribute to better results. An important side-note must be given that only very smooth surfaces of the manning value have been explored in the testcase ranging from 0.030 to 0.010 $s/m^{\frac{1}{3}}$. This was done, because at the time these manning values were the most common found values in the setup phase of the 2D model of the Raamvallei in Tygron (study area of case study 2). This was due to exporting a list from Tygron also including manning values of materials, building and structures next to manning values of surfaces which were often grouped.

Still with these values it can be observed that with rougher surfaces more water build-up is expected in the narrower waterways. Although this build-up results in a bigger offset compared to the theoretical water heights it is not incorrect. The theoretical waterlevels that are calculated using the formulas in section 4.2 use assumptions more common for 1D models such as uniformity of velocity over the cross-section, cross-sections perpendicular over the stream, uniform water level across the cross-section. Whereas in Tygron a 2D model is created where there is no uniformity of velocity over a cross section and no uniform water level across the cross-section. If cells are on the slopes of a stream there is a lower water height in those cells and the effect of manning is bigger. With narrower streams the effect of manning was more visible, but this is due to relative more cells on the slopes compared to wide streams and therefor on average have more build-up.

Concerning **grid cell sizes** setting it became clear that it is crucial that at least 5 to 6 cells fit within the width of a stream to achieve satisfactory results. Tygron confirms this finding, but argues that even more cells would be advised given the fact that 5 or 6 cells may not cover all stream placements. Another finding was that the smallest grid cell size (0.11 by 0.11 meter) tended to underestimate water heights. Tygron however states that for both observations on grid cell sizes this is not something they see in their other projects and could be very case depended (Knepfle, 2023). For this more research could be used with different cases/projects to see the influence of larger grid cell sizes than 1 by 1 meter and for the influence on the smallest grid cell size.

Grid placement emerges as a challenging parameter to draw conclusive findings from. From the results it seems that the testcase shows slight favourable results in stream along the grid cell than when a stream is not aligned parallel to grid cells. However this is not a conclusion that can be taken for grid placement based on those results alone. grid cell size is also important. It seems that streams that are on 45 degree with grid cells have inaccurate results, because there are less grid cells in the streams width and not because of stream placement/alignment with the grid cells. Due to the fact that this is not a setting that is adjustable, as explained in section 3.2.2, it can be said that grid placement can not be improved for better results. As of yet is not possible to implement a different grid cell structure in a 2D model in Tygron than the current Cartesian grid. To improve a model when interested in a stream placed skew on grid cells the best way is to account for the amount of cells that fit in the width with the grid cell size setting.

Part II

Practical assessment for the applicability of Tygron

7 Study Area & Stream Restoration design

For this research, the 'Lage Raam' stream in the Raamvallei has been selected as the study area, strategically aligned with the broader 'Raamvallei' project, a collaborative project between TAUW and WSAM. For this research noundary conditions for the 2D model were already made available by WSAM. Additionally, WSAM has provided measured water level data, enhancing the precision and reliability of the study. The redesign of the Lage Raam stream within the Raamvallei is prompted by new environmental goals, as outlined by Groot and vd J. (2023) and outlined in chapter 2. The overarching objectives for the Raamvallei include accommodating sustainable agriculture, ensuring clean and sufficient water, and restoring the ecological balance of the stream.

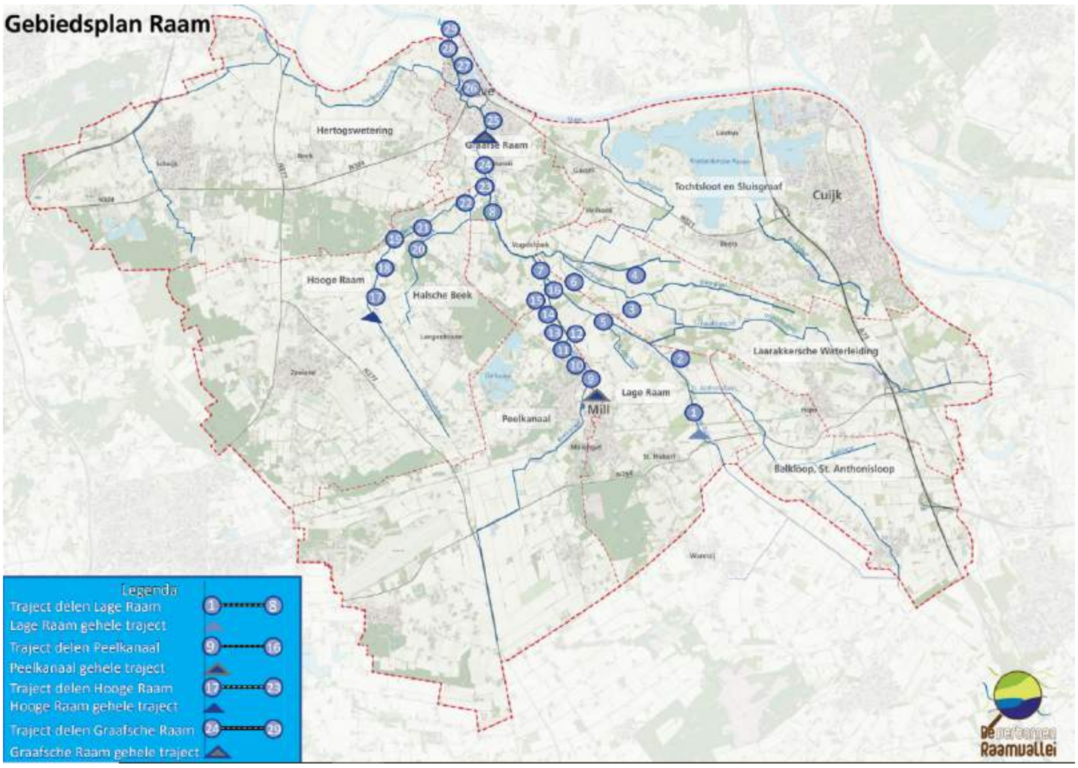


Figure 7.1: The Raamvallei presented in Gebiedsplan Lage Raam (Besselink, 2016)

7.1. The Raamvallei

Situated between the cities of Boxmeer and Mill in the province of Noord-Brabant, the Raamvallei spans approximately 10,000 hectares, featuring a diverse landscape of river terraces, wetlands, and agricultural fields. This area provides a habitat for various plant and animal species. A Digital Elevation Model of the Raamvallei is depicted in figure 7.2, offering insights into the natural flow and direction of water in this region.

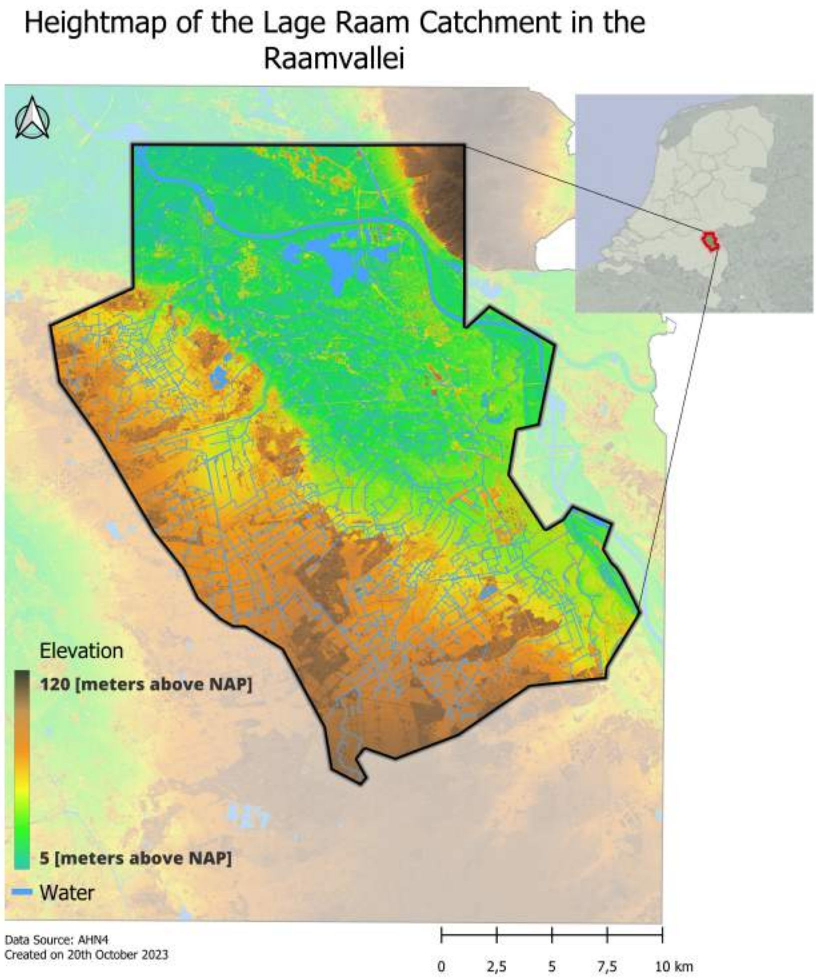


Figure 7.2: Heightmap and location of the Raamvallei

The water system in the Raamvallei comprises interconnected streams and watercourses, including the 'Graafsche raam,' 'Hooge raam,' 'Halsche beek,' 'het Peelkanaal,' 'St. Anthonisloop,' 'Biestgraaf,' and the 'Lage raam' between 1-8 (see Figure 7.1). These watercourses are influenced by surface runoff and groundwater seepage, leading to significant variations in water levels and flow rates based on location and season. The Lage Raam serves as the primary stream, where all other watercourses converge into. It is a man-made/ modified waterway with a slope of approximately 0.30 meters per kilometer, flowing from southeast to northwest (Maas & Mo, 2018).

7.2. Water system & Hydraulic Structures

In the context of the Lage Raam area, the utilization of 'peilgebieden' (water level areas) is not commonplace. Instead, the water management approach predominantly relies on a 'oppervlakteafvoersysteem' (in english: surface run-off system). The water naturally flows across the surface of the land, conforming to the contours of the terrain, and waterlevels are controlled by hydraulic structures. Figure 7.3 provides a comprehensive overview of the primary, secondary, and tertiary waterways in the Raamvallei. Additionally, Figure 7.4 illustrates the locations of all hydraulic structures mentioned below. These figures collectively contribute to an understanding of the water system in the Raamvallei, showcasing the intricate network of waterways and the placement of hydraulic structures.

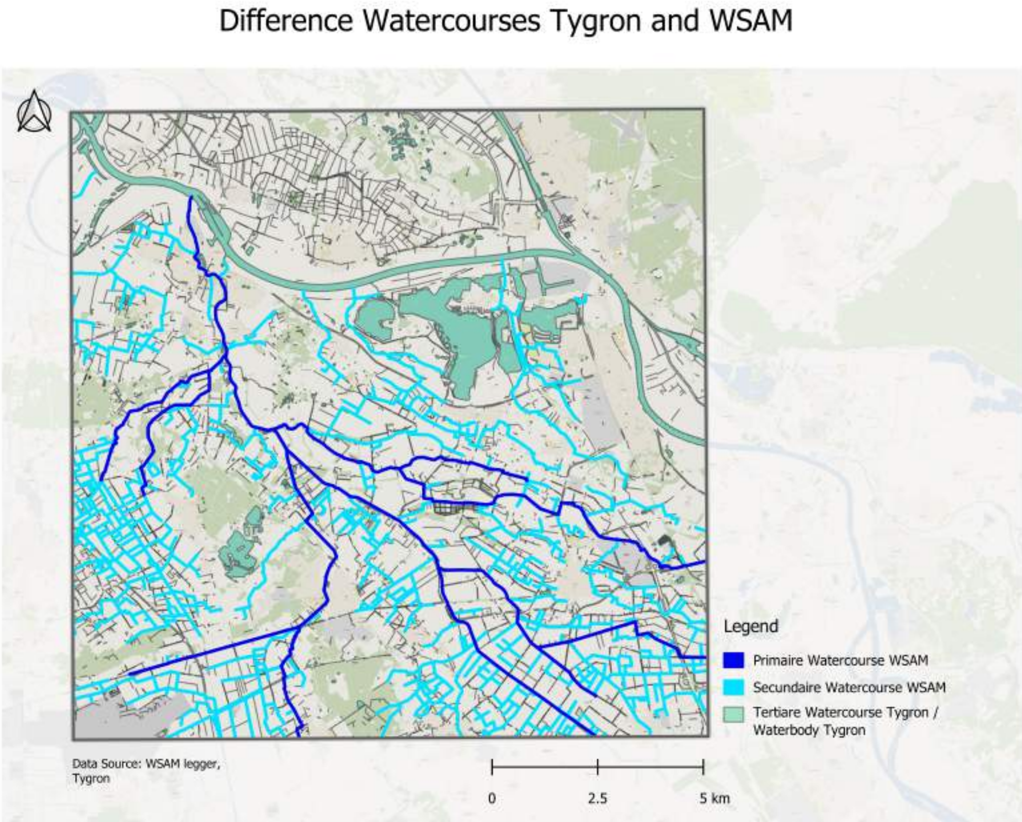


Figure 7.3: Shows the waterways in managemant by WSAM and all waterways in Tygron

A prominent feature in the surface water system of the Raamvallei area is the presence of weirs. Weirs are strategically placed structures, constructed across watercourses to regulate water levels and control flow rates (figure 7.4). Playing an important role in managing water within the surface water system, these height of the weirs can be adjusted, which is mostly done automatically. This adjustment capability enables the control of water levels, ensuring a balance between water supply, drainage and ground water levels.

In addition to weirs, another integral aspect of the water management system in the Raamvallei area is the use of culverts. Culverts are hydraulic structures allowing water to flow beneath roads, railways, or other obstacles. These structures facilitate the movement of water without disrupting the infrastructure above. In the Raamvallei there are a lot of culverts that play an important role in maintaining natural drainage and preventing waterlogging in low-lying areas. Culverts contribute significantly to connectivity across the Raamvallei.

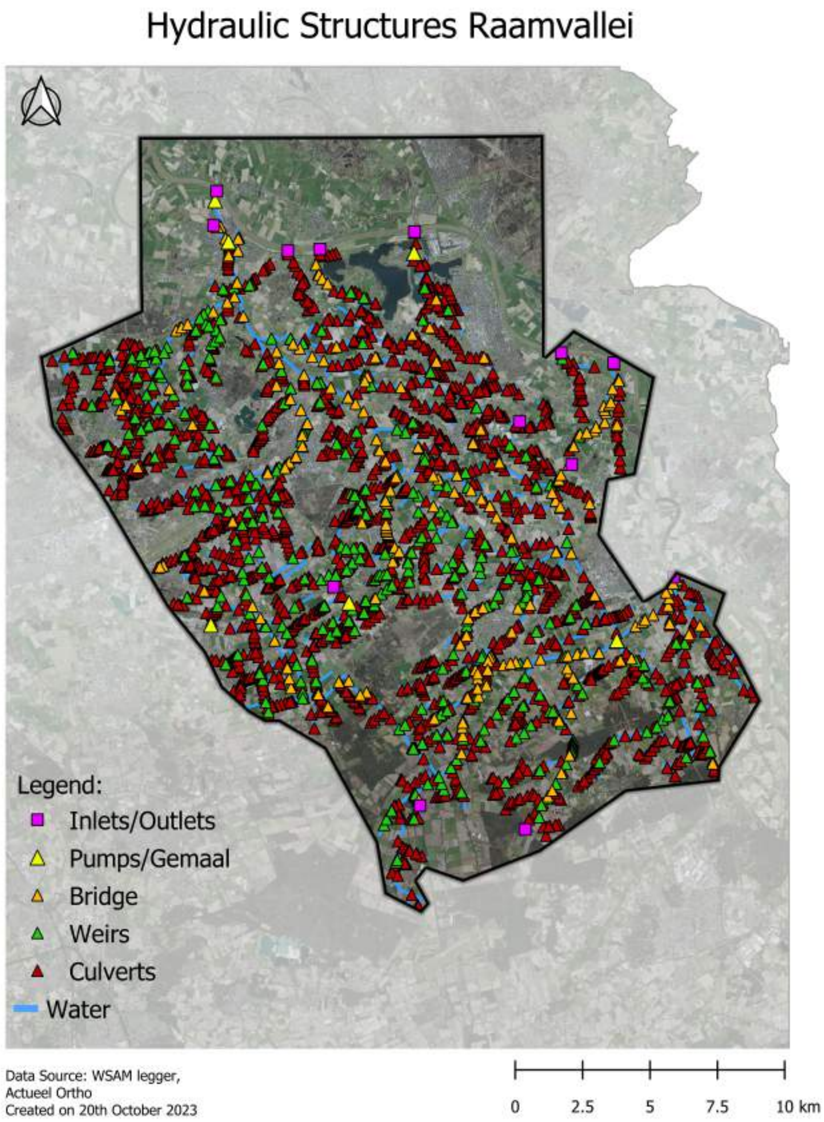


Figure 7.4: Hydraulic Structures Raamvallei

One significant water management structure in the Raamvallei area is the Gemaal van Sasse, situated in Grave. This pumping station serves as the junction point where the Raam river meets the Maas river. Dating back to 1928, the Gemaal van Sasse's primary function is to pump excess water from the hinterland during periods of elevated water levels. By doing so, it plays a vital role in preventing flooding and maintaining desired water levels in the Raamvallei.

Apart from the Gemaal van Sasse, several other pumping stations in the Lage Raam area contribute to overall water management efforts. These pumping stations address specific water management challenges in different parts of the region, each with its own function crucial for maintaining water levels and preventing flooding. Employing pumps for efficient water movement, these stations are designed to handle various scenarios, including high water levels, heavy rainfall, or excessive water accumulation. Despite having a fraction of the pump capacity of the Gemaal van Sasse, these pumping stations actively pump out water from low-lying areas, contributing to the balance of the surface water system and protecting surrounding lands from inundation.

In summary, water management practices in the Lage Raam area revolve around surface run-off and natural drainage patterns, supported by weirs and culverts. The Gemaal van Sasse, weirs and culverts stands as the most critical infrastructure elements, playing an important role in managing water levels and preventing potential flooding events in the Raamvallei.

7.3. The Lage Raam - Sector 2

Within the Raamvallei the Lage Raam will be used for the study area with a focus on stream restoration. This smaller area is also known as Sector 2 in the Raamvallei project (for location see figure 9.2).

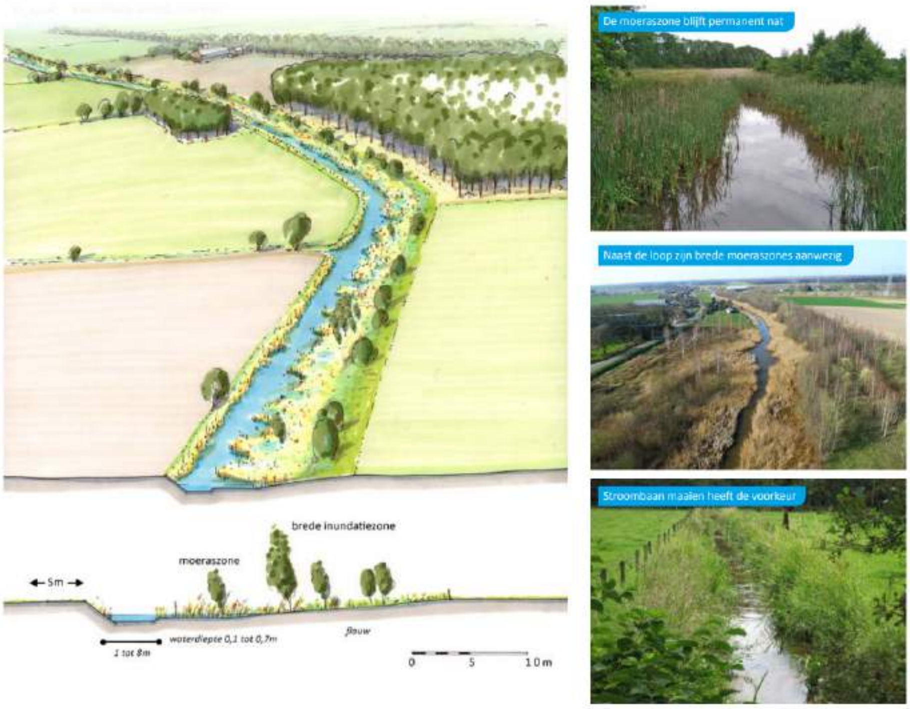


Figure 7.5: Target Image of the Lage Raam, R20 type stream with woven nature-friendly banks

In the watershed of the Lage Raam, efforts are underway to identify a suitable water retention area. At the same time, stream development along the Lage Raam poses a challenge, particularly in the upstream agricultural lands. These areas need robust water systems to manage significant fluctuations in water levels caused by climate change (Groot & vd J., 2023). For these reasons a new design for Sector 2 of the Lage Raam has been made, see figure 7.5.

Based on the R20 stream of 'Ecologische streefbeelden watersysteem' WSAM & TAUW has proposed a design with mitigation measures in Sector 2 (figure 7.5. The characteristics and design requirements for an intertwined swamp stream are derived from the ecological target images of Waterschap Aa en Maas. The proposed profile introduces a narrower, gently meandering stream. A deeper section is kept open from the bank to ensure effective water level management during low flow. Adjacent to this is a broader, shallower section designed to buffer flow peaks and achieve ecological goals for the swamp stream. The connectivity to a floodplain helps keep water level fluctuations small during high flow situations. A maintenance path along the open water section, accessible to the public, enhances the experience of the Lage Raam up close (Groot & vd J., 2023).

The main 'Building with Nature' measures in swamp streams with interwoven functionality include the construction of gentle banks and adapted mowing practices (Reeze & Winden, 2021). Shading and deadwood are primarily applied in the flowing sections, with deadwood also used (limited) in the marsh zone. Adapted mowing practices and deadwood are only employed if they do not lead to undesirable effects (inundations).

The focus of TAUW and WSAM has primarily been on implementing a couple of mitigation measures

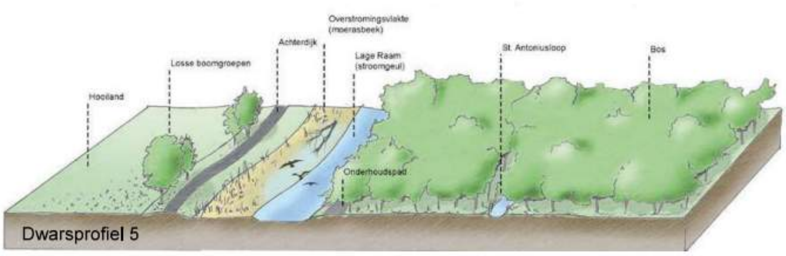


Figure 7.6: Cross-section sketch of Swamp stream Lage Raam

to improve the ecological condition. For the Lage Raam project, TAUW has proposed several ideas to restore the Lage Raam, mostly involving changes to cross-sections in different parts of the system. This may include expanding the width of riverbanks, deepening inundation zones, and creating mild slopes to promote swamp areas. An example of a sketch of such cross-section is shown in 7.6. A more detailed design of the cross-section is shown in figure 7.7 and is also explored in section 9.

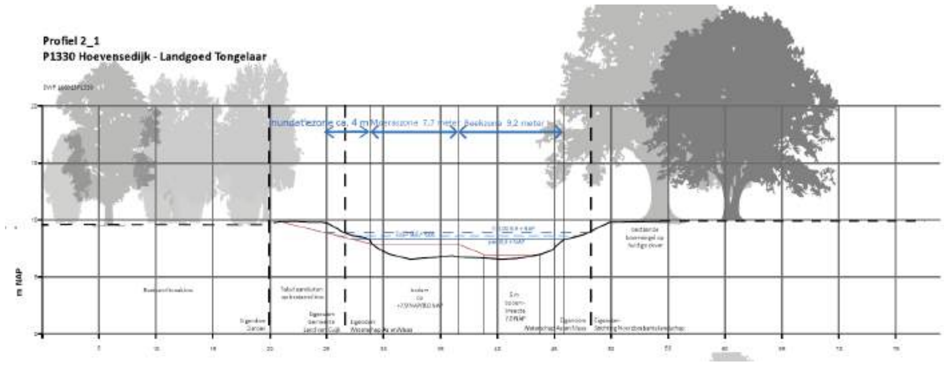


Figure 7.7: Restoration design by TAUW

7.4. Overview initialization 2D model in Tygron

With the given study areas of the Raamvallei and the Lage Raam, a 2D model has been created in Tygron for the the second and third case study. A short overview of initialization is given in this section.

Watersystem of the Raamvallei

The waterboard Aa en Maas has provided a 'Legger,' encompassing comprehensive information about hydraulic structures and waterways in the Raamvallei. This information extends to waterways managed by the WSAM. The WSAM manages primary and secondary waterways. Tertiary waterways are not under the direct management of WSAM but fall under private authority or the jurisdiction of farmers.

Figure 7.3 provides an overview of the waterways in Tygron. Next to the waterways in the legger of the WSAM a lot of tertiary waterways (often under the jurisdiction of farmers or private sectors) are added, as well as lakes/ponds.

Connectivity of the model

In figure 7.4, it is evident that numerous hydraulic structures exist in the Lage Raam. These structures are situated on primary or secondary waterways in the Raamvallei. However, as illustrated in figure 7.3, Tygron includes tertiary waterways in the model. Since these waterways are not present in the Legger of WSAM, information regarding hydraulic structures in these waterways is also unavailable. Consequently, tertiary waterways may not always be properly connected to the main waterways, due to the absence of structures such as culverts.

The 2D model in Tygron requires the connection of these tertiary waterways to the primary/secondary watersystem to create a complete water system (Keulen, 2023a). Without this connection, some rainwater that should reach the Lage Raam, will not. To address this, a culvert generator in Tygron is utilized to connect tertiary waterways to secondary waterways. The outcome of this process is depicted in figure 7.8, illustrating the locations of generated culverts versus culverts present in the Legger.

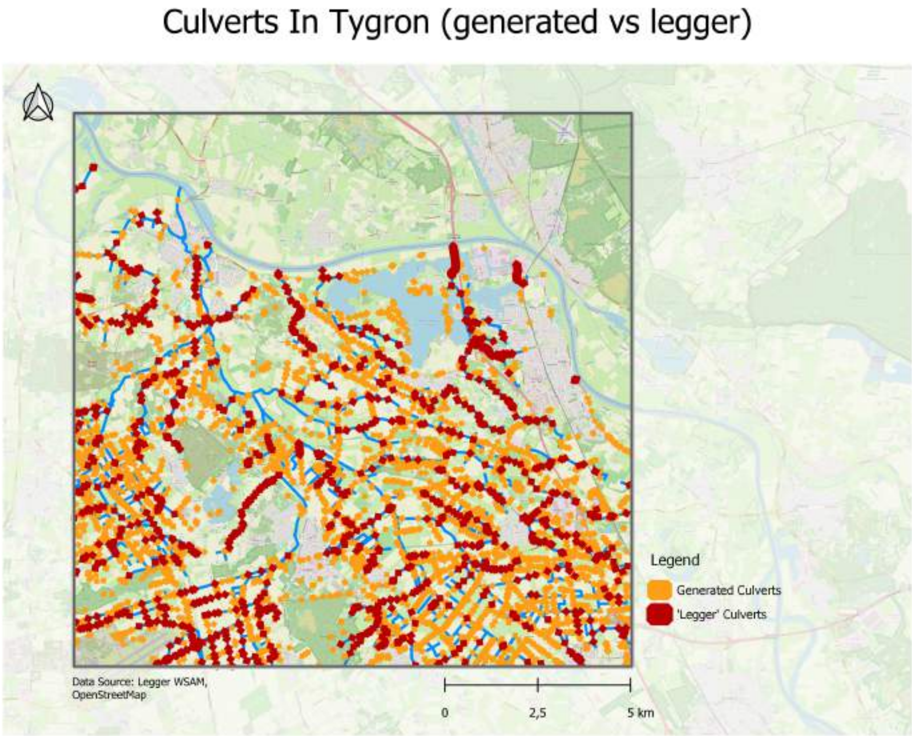


Figure 7.8

Initial Waterlevels

For the initial water level the values depicted in Figure 7.9 are employed. This ensures uniform starting values and boundary conditions for water levels in streams. These values have been made and provided by the WSAM.

As mentioned, WSAM does not utilize peilgebieden for the Raamvallei, and consequently, no values or data are available for initial water levels in streams or for groundwater levels. In the Raamvallei, water levels are predominantly controlled by hydraulic structures, each having a corresponding "Streefpeil" for its associated streams. These streefpeil water levels are considered as close to the initial water levels as possible for the Lage Raam. The resulting water levels (shown in Figure 7.9) are employed for the initial water depth in the streams. These values are further used for interpolation, employing an Inverse Distance method, to determine groundwater levels in Tygron.

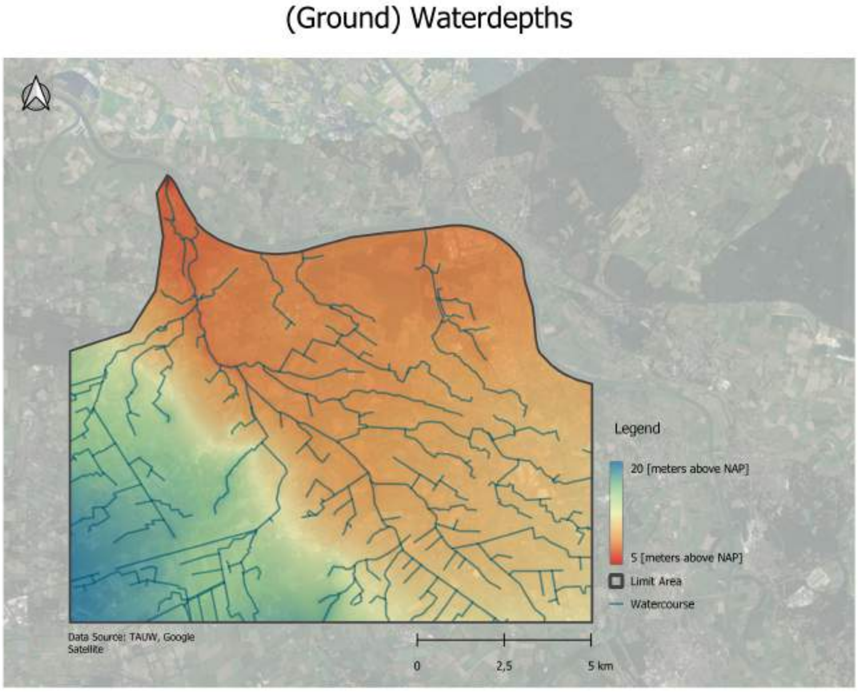
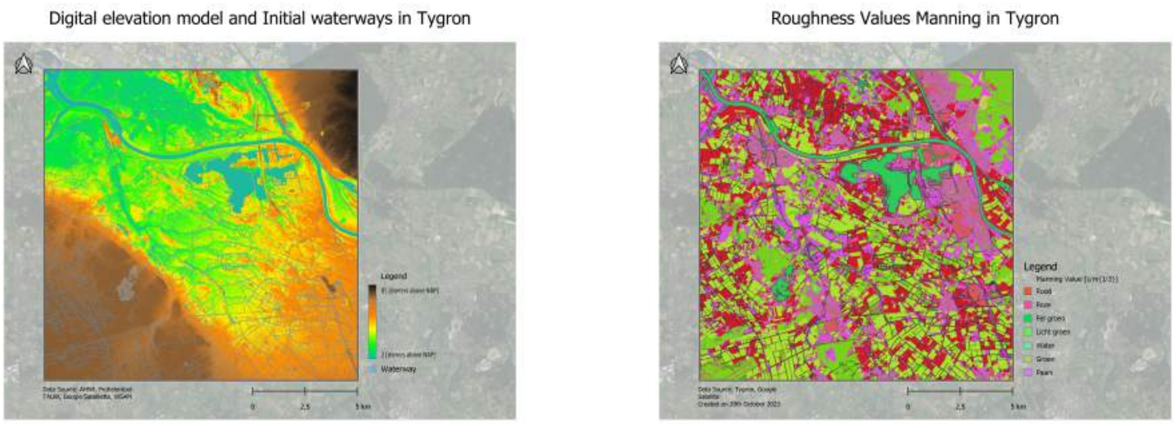


Figure 7.9: Initial Waterdepths

Rainwater discharge

In Tygron's Water Module, as detailed in Section 3.2, a rainfall event is simulated on the 2D model. However, not 100% of the rainwater will discharge into the Lage Raam. Some water will evaporate or infiltrate, but also a lot of water will stay where it falls. Tygron simulates surface water flow using elevation and resistance factors. The simulation takes into account the natural topography using a Digital Elevation Model (DEM), and water movement is influenced by surface roughness. The Manning Values in the model (figure 7.10b affects the retention of rainwater in the simulation, consequently influencing the total water discharge from rainfall into the Lage Raam stream.



(a) DEM and waterways in Tygron

(b) Roughness value Manning in Tygron

Figure 7.10: Surface run-off of rainwater

8
Case Study 2: Raamvallei

This chapter presents the second case of this study. The first case study has provided valuable insights and enhanced understanding of certain settings in Tygron. However, before creating a 2D model for stream restoration purposes in the Lage Raam, it is crucial to assess the Tygrons suitability for a water system. The second case examines the entire Raamvallei region, focusing on investigating the applicability of Tygron for an integrated water system with a holistic perspective on projects.

Key considerations for ensuring the 2D model is fit for purpose include:

- Connectivity
- Hydraulic Structures & Water Levels
- Influence of Grid Cell Size

These aspects are paramount in evaluating Tygrons adequacy for stream restoration in the Lage Raam water system.

8.1. Research Setup - Raamvallei case

In Section 7.2, essential hydraulic structures were highlighted, and Section 7.4 provided an overview the setup of the model in Tygron. In this context, additional information specific to this case has been presented. These steps collectively contribute to the creation of a tailored Tygron model for the Raamvallei case study:

- Adoption of the same initial water levels from WSAM (Figure 7.9).
- Implementing hydraulic structures from the WSAM Legger, along with their parameter values, including target levels.
- Using inlets to maintain a steady stream discharge upstream in the Raamvallei, based on boundary conditions provided by WSAM.
- Integration of AHN4 as the Digital Elevation Model (standard open data in Tygron, see Figure 7.10a).
- Incorporation of tertiary watercourses not included in the WSAM Legger (see Figure 7.10a).
- Generation of culverts to connect tertiary watercourses to secondary watercourses (Figures 7.8 and 7.3).
- Implementing landuse and soil type in the Tygron model (open data (Tygron, 2023) such as: AHN, PDOK, BRP, Waterschapadata) for infiltration and roughness coefficients.

As discussed in Section 7.4, the connection of the entire Raamvallei region to the Lage Raam necessitated the inclusion of tertiary watercourses. Additionally, the generation of culverts was crucial, accomplished through the *Culvert generator* tool in Tygron. Figure 7.8 displays the locations of these generated culverts.

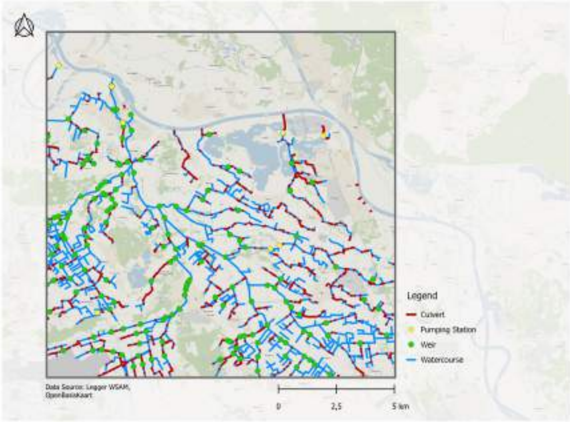


Figure 8.1: Hydraulic Structures in Tygron

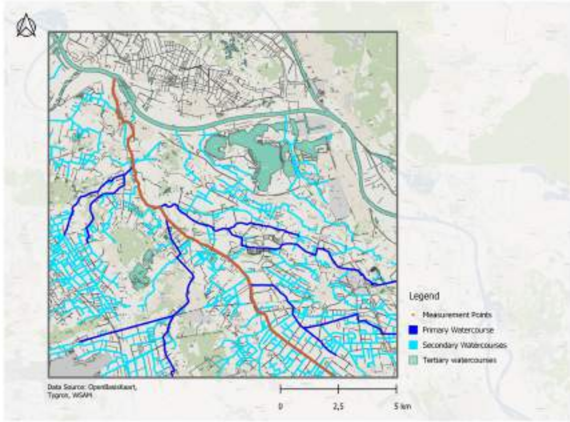


Figure 8.2: Measurement point along the Lage Raam

Also in section 7.2, the hydraulic structures in the Raamvallei were introduced. From these, the structures depicted in Figure 8.1 have been imported into Tygron. These imported structures, along with the generated culverts shown in Figure 7.8, contribute to the comprehensive representation of the hydraulic system.

8.2. Method - Raamvallei case

To verify if the model in Tygron is suitable to be used for the Raamvallei water system it eventually should be the case that the model functions accordingly. This means it is fit for purpose and show results that are expected of this study area. In other words the model should closely resemble real life scenarios and measurements. To do this, this Tygron model is calibrated and validated. In total the process of building the model, calibrating and validating was as followed, where part 5 to 8 are iterative:

1. Collect data: Gather data on topography, river/channel cross-sections, flow velocities, and water levels.
2. Define boundary conditions: Determine the inflows, outflows, boundary conditions for the model and initial conditions.
3. Define parameters: Determine the values for model parameters such as river bed roughness, cross-sections and other relevant parameters.
4. Set up the model.
5. Calibrate the model: with a custom rainevent to see if the model shows an expected hydrological response in the Raamvallei water system, a correct watershed, and search for leaks or stagnation points.
6. Validate the model: Compare the model's output to real-world observations to check for accuracy and identify areas where adjustments are needed.
7. Adjust settings: Tweak the (PID) controllers values/hydraulic structures to better match the observed data and improve the model's accuracy. Change the manning value in streams. Choose different boundary conditions for initial stream water levels and water flow.
8. Validate again: Repeat the validation process to check whether the changes have improved the model's performance.

Measurement points

When a simulation is run in Tygron a rain event scenario was run in the model to be used for the validation of the model. Since the WSAM only had stream measurements data in the Lage Raam, a decision was made to gather all values using measurement points along the Lage Raam in Tygron, as illustrated in Figure 8.2.

Comparative analysis

Using the obtained results from the measurement points, the model is subjected to analysis. Various performance metrics are employed to evaluate their effectiveness. The assessment is conducted through the application of the Root Mean Square Error (RMSE), the Kling-Gupta Efficiency, and the Percent Bias. Where the computed data (or predicted/simulated/modelled data) from the 2D model in Tygron will be compared to the observed data from the WSAM.

The Root Mean Square Error (RMSE) is a measure of the differences between predicted values (see, eq 4.7) and observed values in a dataset. It is commonly used to evaluate the performance of regression models. To calculate RMSE, the following steps are used:

1. For each data point, find the difference between the predicted value (ŷ) and the actual observed value (y).
2. Square each of these differences.
3. Calculate the mean of the squared differences.
4. Finally, take the square root of the mean to obtain the RMSE.

Mathematically, the formula for RMSE is as follows, lower values of RMSE indicate better predictive performance of the model:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{8.1}$$

Where:

$RMSE$: Root Mean Square Error
n : The number of data points in the dataset
y_i : The actual observed value of the dependent variable for the i-th data point
$\hat{y}_i$: The predicted value of the dependent variable for the i-th data point
$\sum_{i=1}^{n}$: The sum of all data points from i = 1 to n
$\frac{1}{n}\sum_{i=1}^{n}$: The mean of the squared differences between actual and predicted values

The Kling-Gupte Efficiency (KGE) is a way to evaluate the performance of your model's simulation or prediction of water heights compared to observed water heights. It's a widely used metric in hydrology to assess the accuracy of hydrological models.

The KGE metric was introduced by Gupta et al. (2009) and combines three statistical measures: correlation coefficient (r), bias ratio (β), and variability ratio (α). The formula for KGE is:

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\alpha-1)^2} \tag{8.2}$$

Where:

r : Correlation coefficient between simulated and observed water heights
β : The ratio of the standard deviation of simulated water heights to the standard deviation of observed water heights
α : The ratio of the mean of simulated water heights to the mean of observed water heights.

KGE values range from -∞ to 1, where a value of 1 represents a perfect match between the simulated and observed data. A higher KGE value indicates a better fit of the model to the observed data.

The step-by-step approach for the Tygron case study is given below:

1. Obtain both the simulated water heights from your model and the observed (measured) water heights from the real-world data.
2. Calculate the mean and standard deviation of both the simulated and observed water heights.
3. Calculate the correlation coefficient (r) between the simulated and observed water heights.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 * \sum(y_i - \bar{y})^2}} \tag{8.3}$$

where:

x_i : individual data points from the observed dataset
y_i : individual data points from the calculated dataset
$\bar{x}$: mean of the observed values
$\bar{y}$: mean of the calculated values

If the calculated value of r is positive, it indicates a positive correlation between the two datasets (as one increases, the other tends to increase as well). If r is negative, it indicates a negative correlation (as one increases, the other tends to decrease). The magnitude of r represents the strength of the correlation, with values closer to 1 or -1 indicating a stronger relationship between the datasets.

4. **Calculate bias ratio (β)**: Divide the standard deviation of the simulated water heights by the standard deviation of the observed water heights. β = (Standard deviation of simulated values) / (Standard deviation of observed values)
5. **Calculate variability ratio (α)**: Divide the mean of the simulated water heights by the mean of the observed water heights. α = (Mean of simulated values) / (Mean of observed values)
6. **Calculate KGE**: Use the KGE formula mentioned above to calculate the final KGE value.

A perfect model will have a KGE value of 1, and higher KGE values indicate better model performance. Generally, KGE values above 0.6 are considered satisfactory for most hydrological modeling applications.

The Percent Bias (PBIAS) is a widely used statistic to assess the performance of a hydrological model by comparing observed (actual) data with simulated (predicted) data. It provides an indication of the overall bias or tendency of the model to overestimate or underestimate the observed values. The formula for calculating percent bias is as follows:

$$PBIAS = \frac{\sum(y - x)}{\sum x} * 100\% \tag{8.4}$$

Where:

y : simulated (predicted) water heights from your hydrological model
x : actual measured water heights

A positive percent bias indicates that the model tends to overestimate the water heights, while a negative percent bias indicates an underestimation. A value close to zero indicates a model with little to no bias.

The interpretation of a ”good” or ”bad” percent bias (PBIAS) value depends on the context of the hydrological model. A PBIAS close to zero is considered desirable, as it indicates that the hydrological model is unbiased and accurately simulating the observed data.

However, the acceptability of PBIAS values can vary depending on the application and the available data. Some general guidelines to help you interpret PBIAS values:

- Positive PBIAS: A positive PBIAS (e.g., greater than +10%) indicates that the model tends to overestimate the observed values. This might suggest that the model is not representing the system's dynamics accurately, and there might be a systematic bias towards higher values. Overestimations are more desirable if looking at inundations or dam breaches.

- Negative PBIAS: A negative PBIAS (e.g., less than -10%) indicates that the model tends to underestimate the observed values. This could imply that the model is not capturing the system's characteristics well and tends to predict lower values systematically.

The acceptability of a certain PBIAS value also depends on the specific application of the hydrological model. In some cases, a small positive or negative bias might be acceptable if the primary concern is the model's ability to reproduce extreme events or long-term trends rather than absolute accuracy in every individual data point.

8.3. Scenarios - Raamvallei case

For the validation part of the model for this case it is chosen to use rain events based on precipitation data of the KNMI and corresponding river measurements of the Lage Raam provided by the WSAM. These scenarios were chosen to capture the dynamics of the system and evaluate the model's performance under different circumstances: (see figure 8.3)

1. Extreme rain events: Intense rainfall events with significant changes in water levels or discharge were identified. These events are essential for testing the model's ability to capture rapid responses, peak flows, and the dynamics of flood events.
2. Low-flow condition: Periods characterized by low water levels or discharge, such as during dry spells or droughts, were considered. Calibrating/Validating the models for these conditions is crucial for understanding the impacts of water scarcity or low-flow scenarios.
3. Seasonal variations: The models were evaluated during different seasons or hydrological regimes. This involved analyzing wet and dry seasons, transition periods, or periods with distinct hydrological behavior. Calibrating/Validating for seasonal variations helps capture the temporal dynamics of the system.

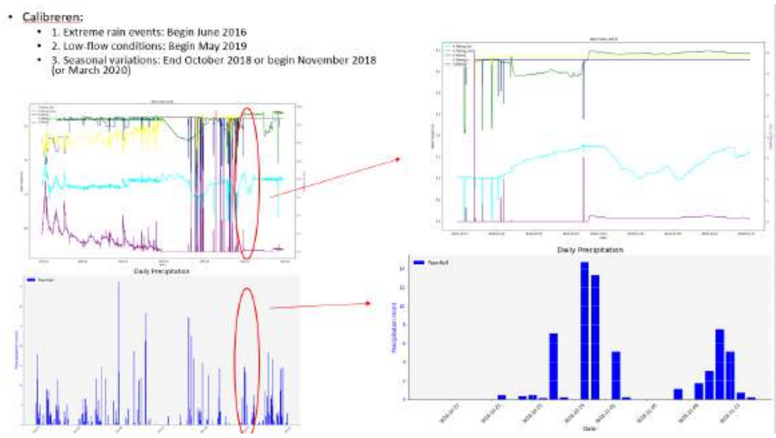


Figure 8.3: Selection of Rainevents from KNMI and WSAM data

Altogether the following rainevents have been chosen, the corresponding measurements from the Lage Raam can be found in appendix B:

1. Extreme rain events: Begin June 2016
2. Low-flow conditions: Begin August 2019
3. Seasonal variations: End October 2018 or begin November 2018 (or March 2020)

9
Case Study 3: Stream Restoration

This chapter presents the third case of this study, focusing on a smaller segment of the Lage Raam. It specifically addresses the applicability of Tygron for project purposes. The Testcase examined how certain settings work for the 2D calculations for surface and shallow water. The Raamvallei case study demonstrated that a 2D model in Tygron can successfully represent a water system in the Raamvallei. Based on these findings, the third case study explores the potential of using Tygron for stream restoration projects.

9.1. Research setup - Stream Restoration

As explained in section 2 & 7.3 the Lage Raam objectives for a better ecological status set by the WSAM. To reach this the focus by TAUW and WSAM is primarily on form-based stream restoration. To realize the stream objectives it had been chosen to implement swamp area zones and change cross-sections. For this case study the design of these cross-section areas will be implemented in the 2D model in Tygron and then 3 different scenarios are run to for more insights in shortcomings or benefits of such designs in Tygron.

Figure 9.1: Design of Stream Restoration Lage Raam

Figure 9.1 provides an overview of the planned stream restoration implementation along the Lage Raam (location see figure 9.2). The stream restoration strategy chosen for the Lage Raam involves modifying cross-sections through dredging and removing the Hoevensedijk. In general the cross-section comprises five distinct areas, as illustrated in figures 9.3 & 9.4. For additional details, see also Section 7.3:

- Stream area
- Slope area 1 (between stream and swamp)
- Swamp area
- Slope area 2 (between swamp and inundation area)
- Inundation Area

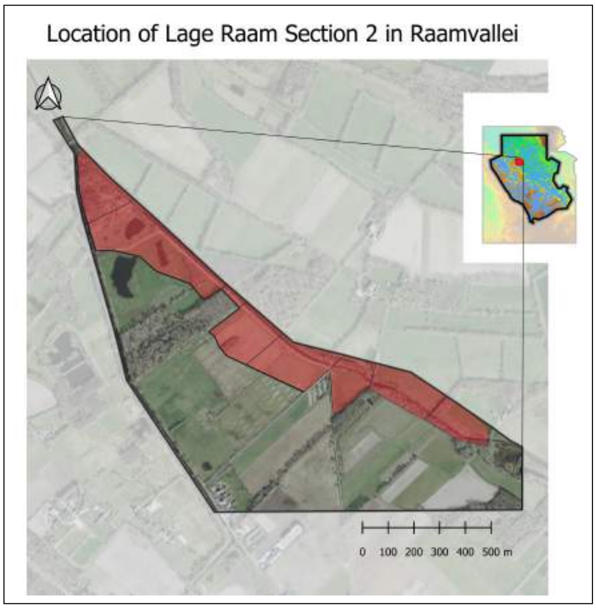


Figure 9.2: Location of Lage Raam Section 2

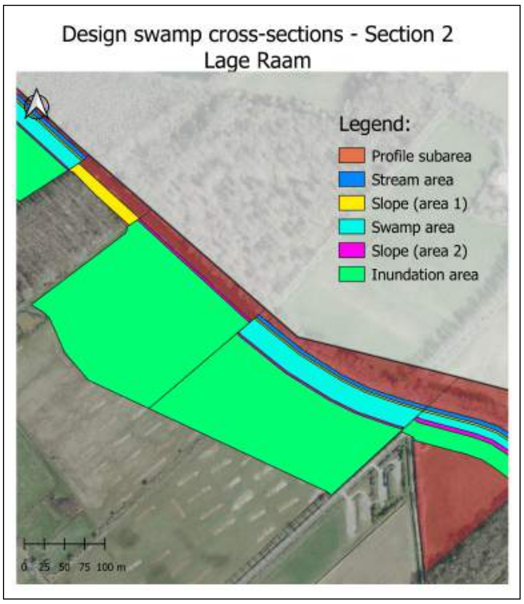


Figure 9.3: Overview of cross-section input in Tygron

To prevent high-water events (T > 1 in 25years) the creation of additional storage capacity becomes necessary. This is achieved by removing the Hoevensedijk and adjusting the inundation areas to accommodate increased water levels from flooding in adjacent plots outside the marsh stream profile. Typically, the stream and swamp areas are situated in the old stream locations; however, these areas will be expanded. Swamp areas, designed to foster more vegetation growth and slower water velocities, will be elevated compared to their former stream locations. Additionally, the slopes between the stream, swamp, and inundation areas will be modified to gentler gradients. A completer overview of the cross-sections along the Lage Raam can be found in the appendix F, in total there are 8 cross section profile created by TAUW for the Lage Raam These restoration efforts are implemented in Tygron at the location illustrated in Figure 9.2, with Figure 9.4 showcasing an example of the input in Tygron for creating the case study area.

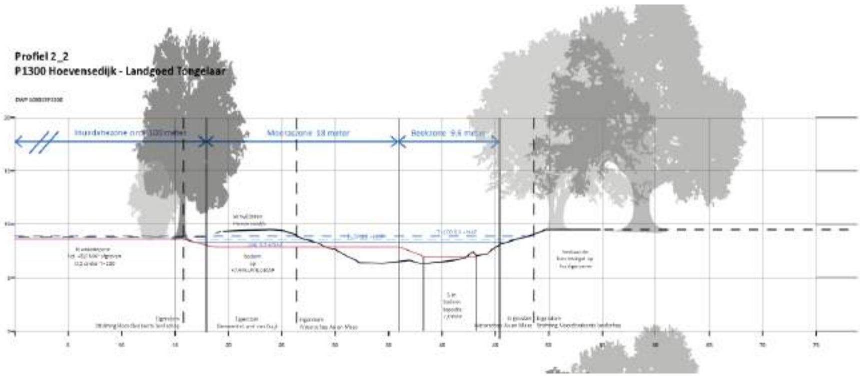


Figure 9.4: Cross section Lage raam - Section 2

9.2. Method - Stream Restoration

Because the design for the nature-friendly banks for the Lage Raam has not been implemented yet, it is not possible to evaluate Tygron on results obtained from the model. Therefor an comparison from observed and measured data is also not possible. In this case study, the evaluation of Tygron's performance will rely on specifications outlined in the WSAM (refer to Section 2), and the expert judgment of TAUW and WSAM. The primary emphasis in our assessment will be on flow rate and level fluctuation. As detailed in Chapter 2 and 6, the characteristics are:

- Flow rate
- Level fluctuations / water level management
- Inundations

9.3. Scenarios - Stream Restoration

In the second case study The entire Raamvallei model has undergone calibration and validation using historical rainfall events and observed data along the Lage Raam. Those specific rainfall events are not used in this case study to prevent using the same events in both cases and therefor prevent bias on water level results in the Lage Raam. Instead, three distinct scenarios have been selected for examination.

Boundary conditions

For this third case study the 2D model in Tygron is extracted from the larger 2D model of the second case study. Then a limit area was added to keep the simulation only in the area of interest. Upstream of the Lage Raam a inlet is introduced before the Garrisveld weir. This inlet functions as a boundary conditions and give the Lage Raam in sector 2 a steady water level.

Scenarios

The first scenario the study area experiences no rainfall, but a dynamic discharge is introduced before the Garrisveld weir, implemented through an inlet boundary condition in Tygron. This dynamic discharge is derived from a T > 1 in 25 years rainfall event upstream of the Lage Raam. The simulation for the stationary T=25 discharge in the 2030 climate scenario is based on a dynamic discharge hydrograph.

Figure 9.5: Hydrograph discharge design for T>1x25

The second scenario is centered around a T=1 rain event lasting 4 hours, serving as the foundational rainfall event based on STOWA measures (Backx & Beers, 2018). In this scenario, the base flow of the inlet boundary is characterized by a stationary winter discharge derived from a design factor established by WSAM. To diversify the analysis, two distinct precipitation patterns are applied in this scenario: uniform, 1 peak as based on (Backx & Beers, 2018)

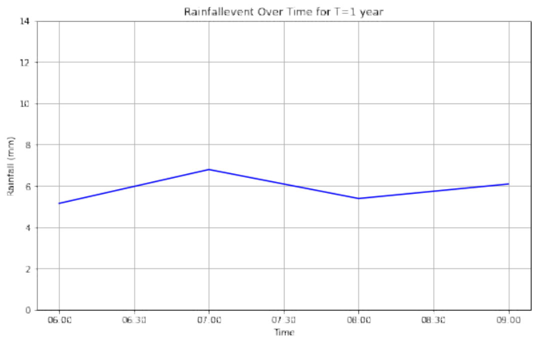


Figure 9.6: Design uniform rainevent for T=1 year (Backx & Beers, 2018)

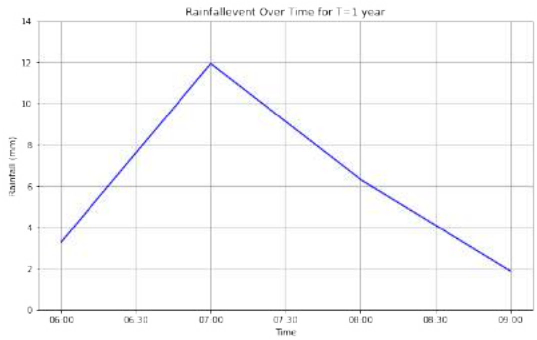


Figure 9.7: Design 1 peak rainevent for T=1 year (Backx & Beers, 2018)

The third scenario incorporates a T=100 rainevent, derived from STOWA and inspired by the June scenario in the second case (Backx & Beers, 2018). This rainfall event closely resembles the peak storm event in June 2018, providing valuable insights into the differences between the current Lage Raam situation and the stream restoration scenario. Furthermore, this event also has two distinct precipitation patterns applied to it.

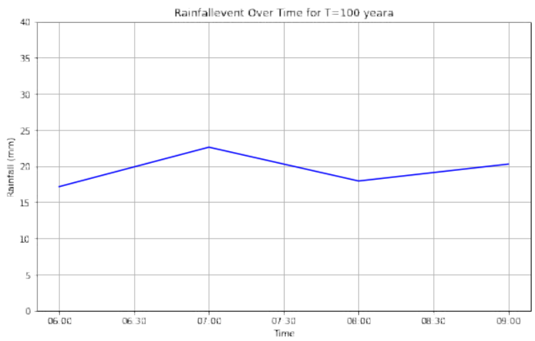


Figure 9.8: Design uniform rainevent for T>1x100 years (Backx & Beers, 2018)

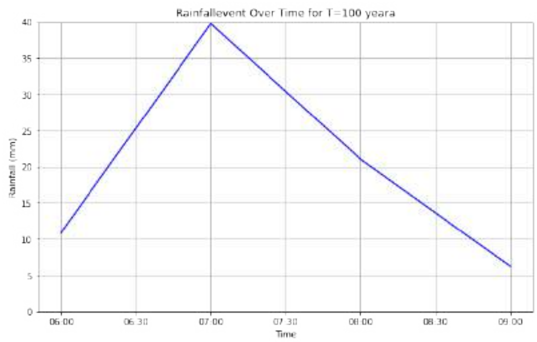


Figure 9.9: Design 1 peak rainevent for T>1x100 years (Backx & Beers, 2018)

10

Results part 2

In this chapter the results for case 2: Raamvallei and case 3: Stream restoration are presented.

10.1. Results Case 2: Raamvallei

For the second case study, where the Raamvallei is the study area, the aim was to to assess the model's suitability for a large water system. Key considerations for ensuring the Tygron model is fit for purpose include:

- Connectivity
- Hydraulic Structures & Water Levels
- Influence of Grid Cell Size

The validation process in the case study was important in addressing the first two points, where three distinct rain events were thoroughly examined in Section 8. During this phase, error estimates were calculated to indicate how effectively the 2D model aligned with real-life measurements.

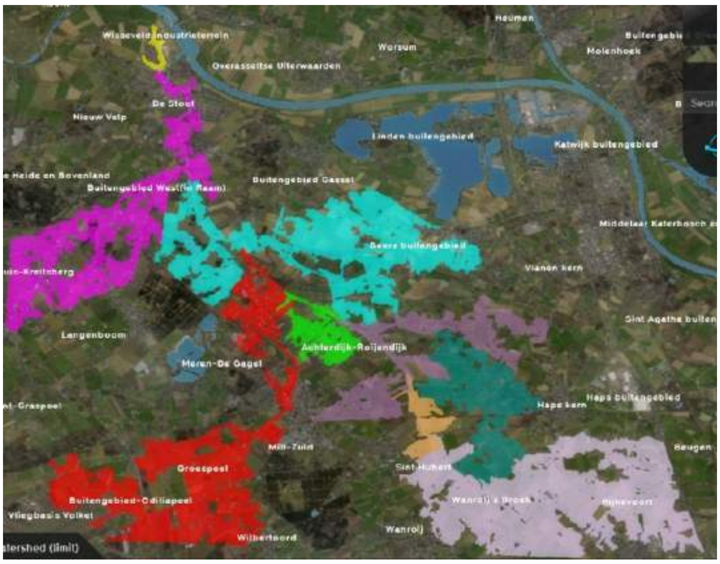


Figure 10.1: Correct connectivity watershed Raamvallei

A crucial prerequisite for this validation process was ensuring a good connectivity of the watershed in the model Given Tygron setups, it was necessary to establish connections between primary and secondary waterways with tertiary waterways. However, a challenge arose as there were no culverts available in the Legger of WSAM. To facilitate a better connectivity culvert where generated using the culvert generator of Tygron where necessary (see Section 7.4 and 7.2). Figure 10.1 illustrates the eventual watershed created for the Tygron case study. Collaboration with WSAM confirmed that this watershed and connectivity closely matched expectations (Keulen, 2023b). Achieving this result involved an iterative process, including numerous trials and adjustments to the culvert generator and hydraulic structures within the Legger. Eventually the following procedures where followed to generate the culverts:

- Culverts can not be generated between parallel waterways
- Culverts can not be generated on existing culverts
- Culverts can not be generated on/through other hydraulic structures
- Culverts can not be generated through dikes
- Tertiary waterways can not connect to primary waterways
- The maximum height difference between the waterways can not exceed 1 meter

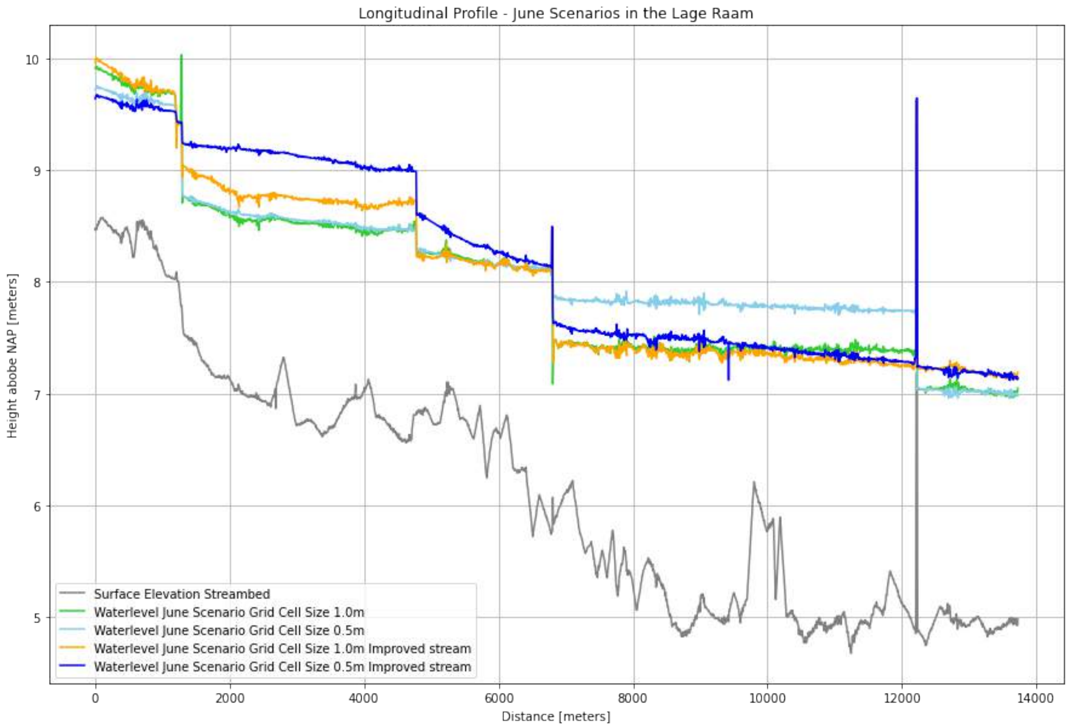


Figure 10.2: Example of a waterway incorrectly implemented by open data in Tygron causing bad drainage

With an established and acceptable connectivity of the Raamvallei model, the subsequent step involved the tasks of model calibration and validation (Keulen, 2023a). This process relied on water height measurements from the Lage Raam and KNMI rain events. Figure 10.2 highlights instances where open data imported by Tygron resulted in incorrect waterways within the water system causing for a 2D model that could not be used. These obstacles were often bridges generated with soil underneath, causing the inability for water flowing under the bridge. Other obstacles were: old weirs still implemented (no updated data), misplaced hydraulic structures (aligned wrong), or structures not connected to water.

Shown in figure 10.3, it eventually became possible to have an setup of the model that caused for a good calibration of the where in each scenario the Raamvallei model would show favourable hydrological responses.

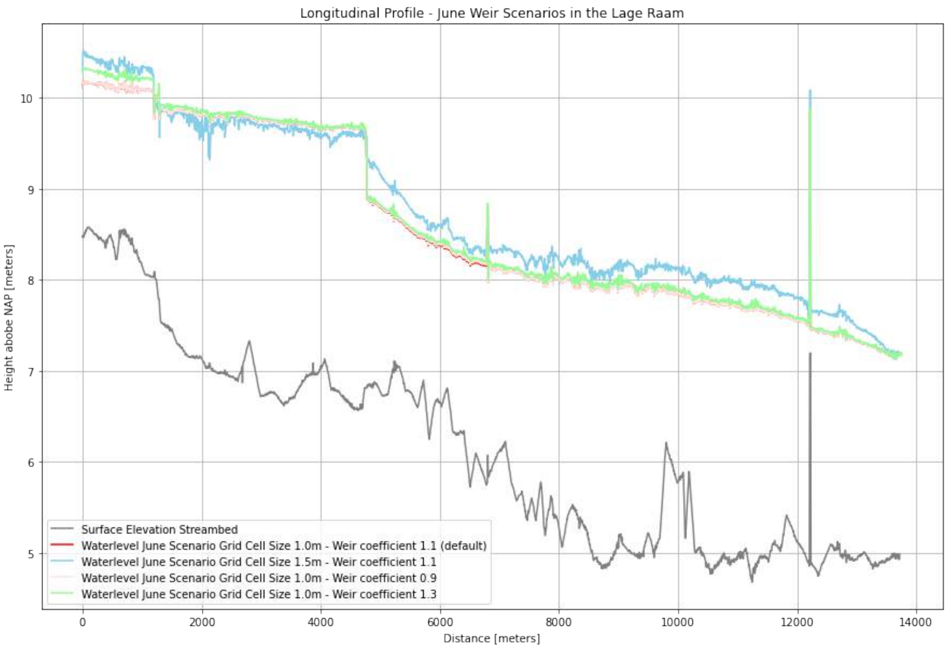


Figure 10.3: Longitudinal profile of 1 by 1 calculations in Raamvallei, June and weir settings

In the model validation process, various error estimates, including KGE, RMSE, and PBias, were employed to assess the correspondence between calculated water heights and measured data. Figure 10.4 displays the error estimates of RMSE and Pbias plotted against each other for the June 2020 scenario across different grid cell sizes. Figured 10.4 & 10.5 illustrates that as grid cell sizes decrease, the model aligns more closely with the measured data from WSAM. Only when the grid cell size is 1 by 1 meter (blue) or 0.5 by 0.5 meters (lightblue) the PBias is bigger than measured data. Not only the RMSE is closer to zero with smaller grid cell size, but the PBias becomes closer to zero or bigger than zero with smaller grid cell sizes. Following minor adjustments to the data associated with hydraulic structures and open data, the water levels and estimate errors, particularly RMSE, reached a satisfactory level, indicating the model's reliability for practical use.

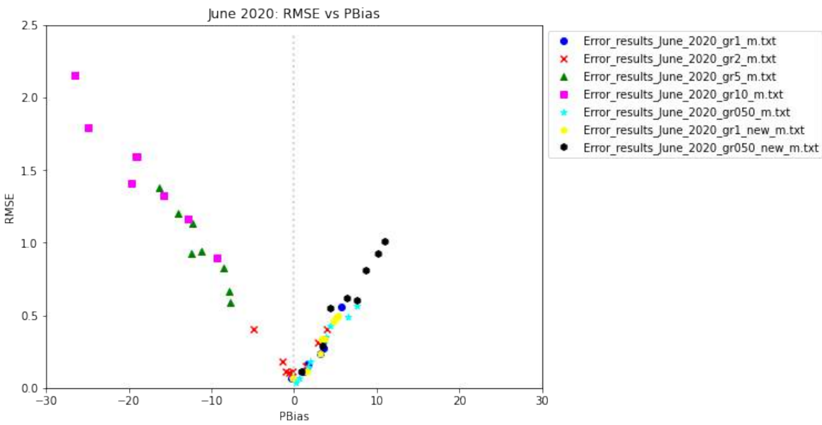


Figure 10.4: RMSE vs PBIAs for June 2020 scenario, each simulation run with different grid cell sizes (gr)

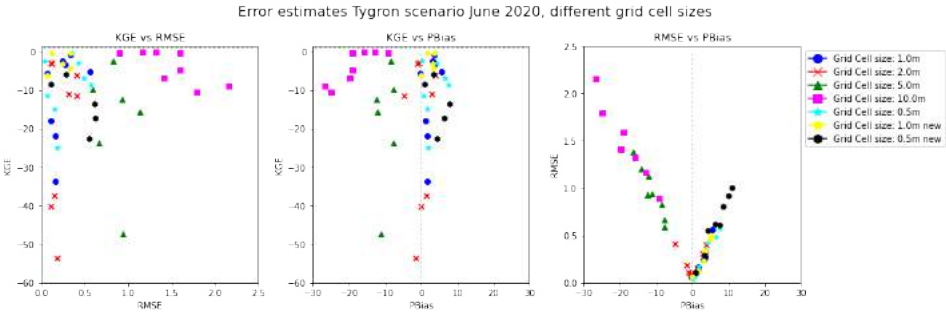


Figure 10.5: Estimate error for June 2020 scenario together, each simulation run with different grid cell sizes (gr)

Figure 10.6 shows the estimate errors of the model the validation on grid cell size and weir coefficients.

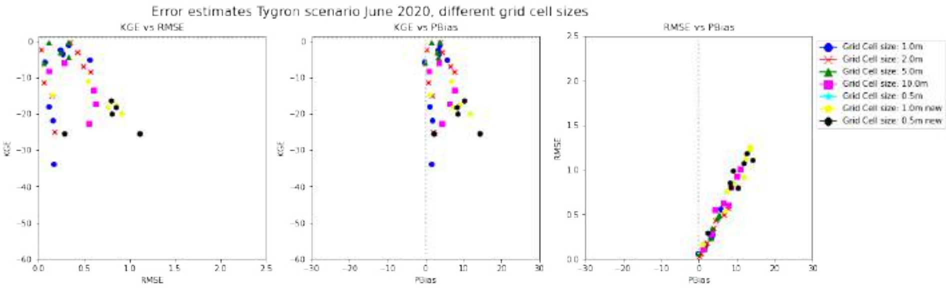


Figure 10.6: Estimate error for June 2020 scenario together after validation of the model, each simulation run with different grid cell sizes (gr)

For a more comprehensive understanding, additional results of error estimates are presented in Appendix E. This appendix provides a clearer picture of the model's performance. Moreover, it includes figures exploring the impact of different grid cell sizes. From the detailed testcase analysis, it became evident that grid cell sizes of 1 by 1 or smaller were suitable. This conclusion was further affirmed by the additional confirmation that smaller grid cell sizes, specifically 0.5 by 0.5, did not significantly improve the results. In appendix E, some simulations have been done with gird cell sizes ranging from : 0.5x0.5m ; 1x1m ; 2x2m ; 5x5m ; 10x10m. It becomes apparent that choosing a grid cell size from 2 by 2 meter or larger that a loss of water in the Lage Raam is expected. Water will flow over the boundaries of the stream and stay in adjacent fields. Thus, it is recommended to opt for grid cell sizes of at least 1 by 1 or smaller, indicating a higher resolution for enhanced accuracy in model outcomes.

Other observations where:

KGE Sensitivity to Measurement Intervals
The KGE metric exhibits a remarkable sensitivity to the interval between measurements. Smaller intervals result in minimal variation in actual measurements but lead to larger variation in the model results, resulting in a KGE greater than -10%. Conversely, a large grid cell size of 10m shows an increase in values, primarily due to the the lack of water, where surface elevation is compared to water levels, resulting in reduced variation of larger grid cell sizes and a better KGE.

Effect of Grid Cell Size on Bias
Notably, for grid cell sizes of 2 meters or smaller, the Tygron model demonstrates a bias of 0% or higher. This underscores the importance of carefully selecting the appropriate cell size.

Influence of Cell Size on RMSE
The consistency of RMSE across scenarios suggests that cell size plays a more significant role than the specific scenario in determining the model's accuracy. It also emphasis the 2D model in Tygron is capable of simulating the types of scenarios described in chapter 8.

Relationship between KGE and Underestimation (Pbias)
Lower KGE values are associated with a higher degree of model underestimation, emphasizing the need for careful consideration in the interpretation of model results. The month of October exhibits a notably higher KGE due to a different choice of time frames due to the longer event, resulting in a smaller relative difference between observed and measured data.

Water Levels and Accumulation
Cell sizes of 2 meters and smaller lead to more constant water levels. But a 1x1m grid cell sizes allow for better water accumulation during heavy rain events.

Weir Displacement Consideration
Some measuring points appear to be located on the weir, suggesting a potential need for a slight displacement to better simulate how Tygron models water flow over a weir. Notably, the behavior of weirs in Tygron appears slightly different during extreme rain events, leading to a more pronounced gradient in the watercourse.

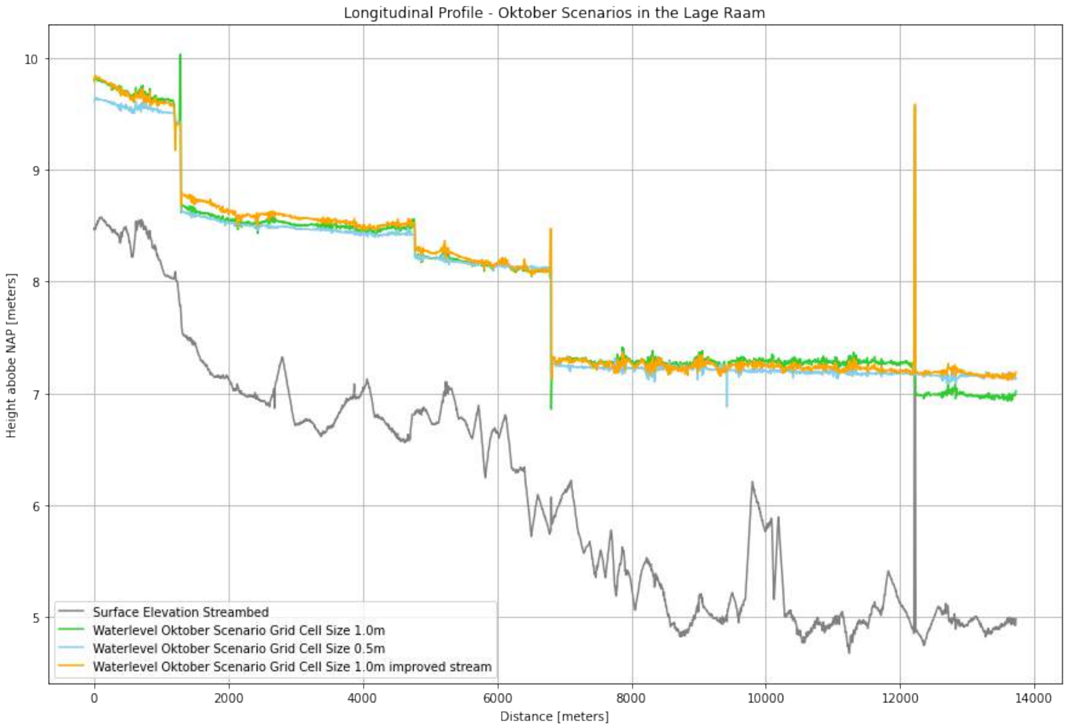


Figure 10.7: Longitudinal profile October scenario over time

10.2. Results Case 3: Stream Restoration

In the third case, a stream restoration scenario was created in Tygron to assess its suitability for stream restoration purposes. The initial step involved implementing the stream restoration profiles, as illustrated in Figure 10.8, into the Tygron platform.

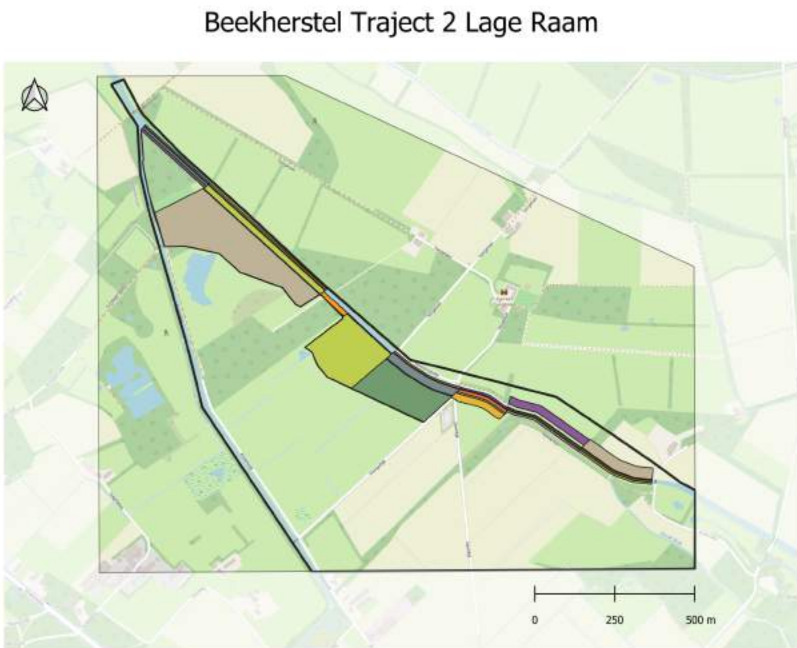


Figure 10.8: Location of stream restoration profiles in the Lage Raam

This leads to the creation of two elevation models in Tygron, both of which will be employed in the scenarios to discern differences between a Lage Raam with and without the stream restoration measures designed by TAUW and WSAM.

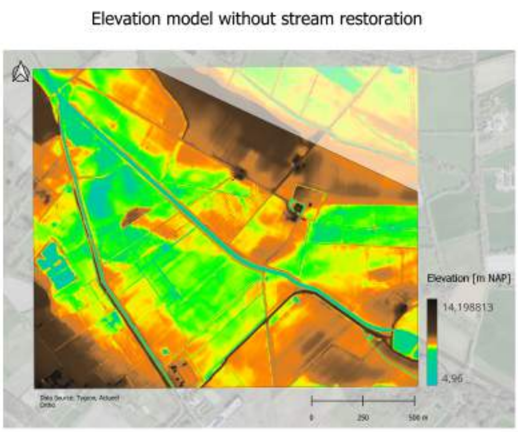


Figure 10.9: Case study are without stream restoration changes

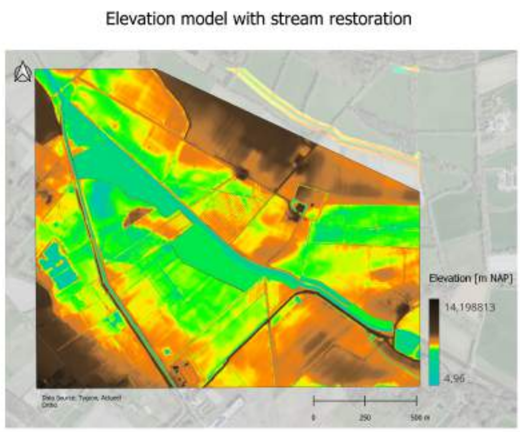


Figure 10.10: Case study are with stream restoration changes

From the hydrological characteristics depicted in Figure 2.2 from section 2.3, it was described that flow rates, level fluctuations, and inundations are the characteristics to look at to evaluate the model made in Tygron. In figures 10.12 & 10.11 it becomes evident that the design measures implemented in Tygron result in fewer inundations in the surrounding area of the stream. Additionally, it showcases effective control of water levels in the Lage Raam, maintaining a good water height in the swamp stream zones.

Figure 10.11: Lage Raam case: Scenario 3 without stream restoration profiles

Figure 10.12: Lage Raam case: Scenario 3 with stream restoration profiles

For level fluctuation

The model in Tygron shows that the implemented measures for the Lage Raam successfully create waterlevels within the specified ranges for water levels (fluctuations should be under 0.5 meter). Meaning that the design provided by TAUW and WSAM do keep the waterlevels within the range of fluctuations of the given objective. This can be seen in figures 10.13 to 10.18.

On the left the old situation is shown and on the right the new sitation with the design cross sections from chapter D. Below only some results of section 1 is shown with the corresponding scenarios from chapter 9.3.

- Standard situation, with upstream boundary conditions and no rainfall
- discharge situation with upstream rainfall event of T>1X25 years
- T => 1x1 year event using a uniform rainfall pattern and using a 1 peak pattern.
- T => 1x100 year event using a uniform rainfall pattern and using a 1 peak pattern.

In appendix F all results for all the scenarios and all the sections are shown.

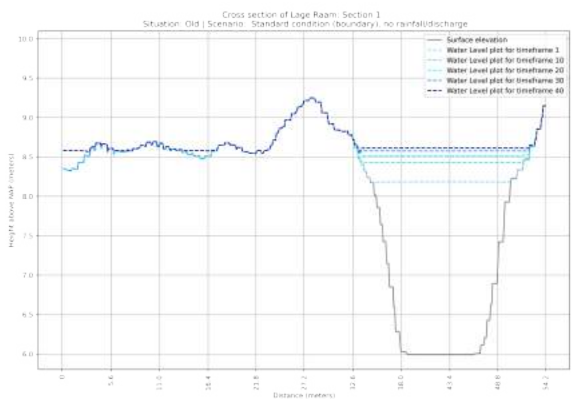


Figure 10.13: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: Standard situation

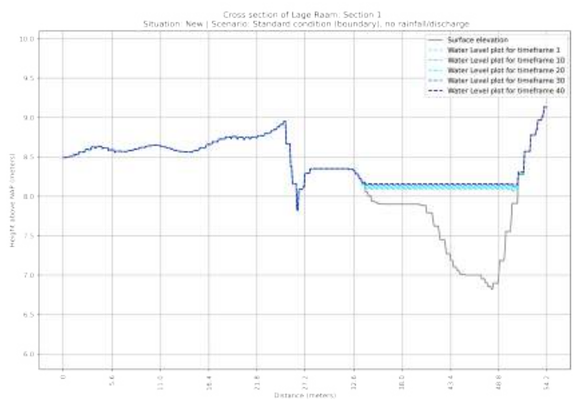


Figure 10.14: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: Standard situation

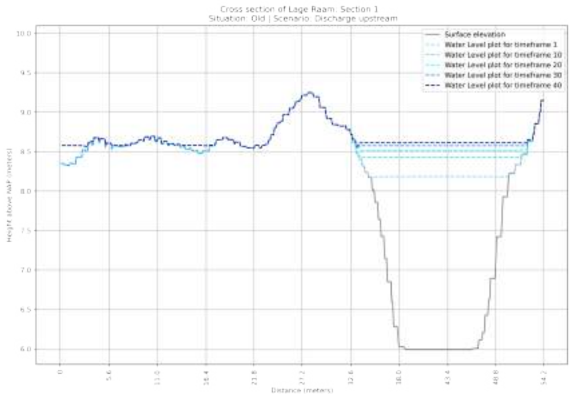


Figure 10.15: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: Scenario: Discharge T > 1X25 year

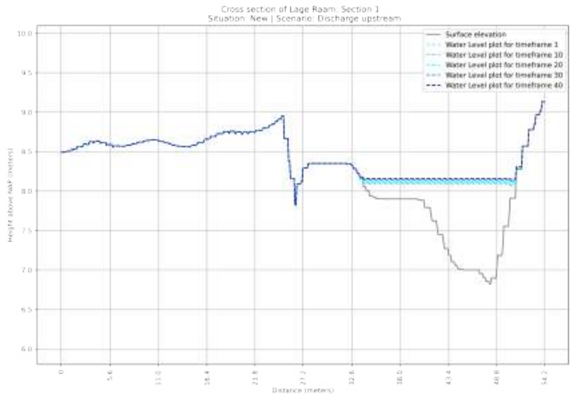


Figure 10.16: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: Discharge T > 1X25 year

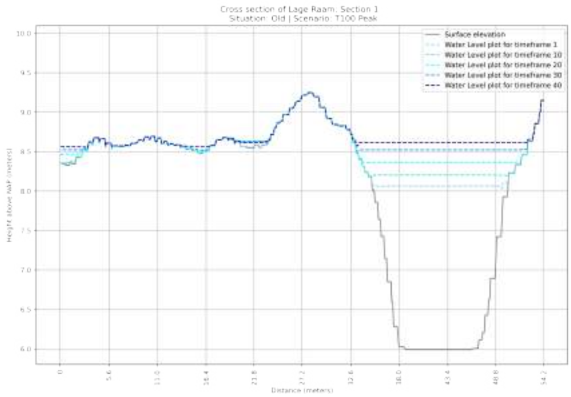


Figure 10.17: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

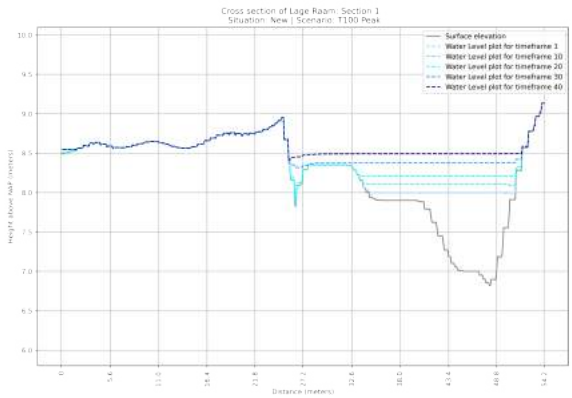


Figure 10.18: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

For flow rates

The way data can be collected in Tygron causes that this parameter can not be correctly shown in figures. During a simulation only the data in certain timeframes are collected. This means only a snapshot of the interested parameter can be shown. Wihtin Tygron interface there are some more options to look at the simulation see figures (10.19 & 10.20). The new design for the Lage Raam appears sufficiently robust in the swamp area exhibiting a little faster flow velocities then the objective whjich was a water speed between (0.05 and 0.5 m/s). However due to the fact that the parameter only shows the max speed during the whole simulation it can not be said this speed is reached for only a short moment (which is bad) or only for a couple of seconds (which would be good). The way to see into the data in the timeframes however does not give conclusive figures.

Figure 10.19: Maximal flow rate result for Old situation Lage Raam

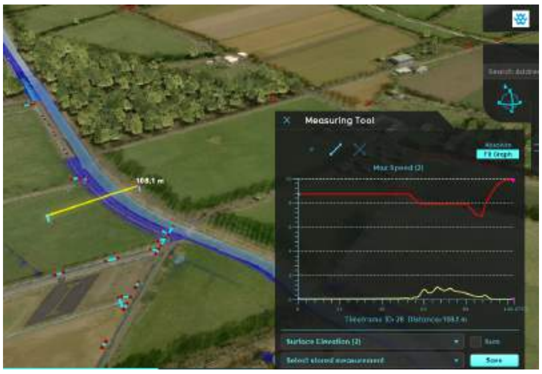


Figure 10.20: Maximal flow rate result for NEw situation Lage Raam

11 Discussion Part 2

The second part of this study focused on creating a 2-dimensional hydrological model in Tygron for restoration project and to test the applicability of Tygron for a water system. The applicability of a 2D model in Tygron (case 2) was important to see if this was even possible to use Tygron for a large water system and to find if any settings had influence on making a model fit to be used for a water system of the Raamvallei.

For the applicability of the 2D model in Tygron, three considerations are used to see if the model could be used for a water system. Those where; *Connectivity*, *Hydraulic structures & waterlevels*, and *Influence of grid cell sizes*. For these consideration it became clear that, next to the results in chapter 8 some setup from the rainfall overlay mentioned in section 3.2.2 were important for the applicability of the model. Those were:

- Timesteps and grid cell sizes
- Culvert generator
- Hydraulic structures
- Timeframes and measurement points
- Limit area

First the *influence of grid cell sizes* needs to be highlighted. Namely, both the testcase and the Raamvallei case highlighted the importance of using grid cells no larger than 1 by 1 for more accurate results. In the testcase it already was apparent that grid cell sizes larger than 1 by 1 meter are not recommended. The Raamvallei casestudy confirmed that this is also the case for a 2D model in a different project. Tygron advised that this would be very case/project specific, but the result do not agree with this when looking at the watersytem of the Raamvallei. When using larger grid cell sizes for a water system, water can potentially overflow in a stream to adjacent surfaces and not flow back. Causing a leakage of water in the model. Although it can be still different when looking to a river system or other types of bigger project, based on the results it is still highly recommended to adhere to grid cell sizes of 1 by 1 meter or smaller. It is not a universal rule and the required level of accuracy is dependent on the specific characteristics of the case or geographical project area chosen.

Another setting that significantly influences results and data retrieval from the model is the choice of*time steps* for a simulation. Unfortunately, it is not possible to change this setting due to how Tygron determines its Courant number. Currently, the Courant of the most extreme cell in the project impacts the time steps for the entire model (see section 3.2.3). Tygron's philosophy assumes there is sufficient computational power to overcome this challenge. However, exploring different options for this setting is intriguing. For instance, choosing the 99th percentile for the Courant number, excluding extremes outside the area of interest, could be considered. Tygron acknowledges that this could be possible, but for specific projects, such as breaches (dike breakthroughs), including these extreme courant values might be necessary (Knepfle, 2023). The introduction of an advanced setting or deriving the Courant time step from the area of interest could be potential options, though not available presently.

From the second case, it becomes apparent that Tygron is well-suited for modeling a water system. However, challenges arise due to the absence of water level areas in the Raamvallei, demanding additional effort to develop a model with accurate boundary conditions. The interconnected nature of a 2d model in Tygron emerges as a critical consideration, posing challenges in ensuring seamless alignment. In Tygron it is not a choice to not implement tertiary waterways in the model, this concept of Tygron relies on the fact that computing power can overcome difficulties with large study areas. However, due to this the *connectivity* of the model becomes very important to create a realistic model. For these case studies the *culvert generator* and watershed tool in Tygron needed to be used. Although the watershed overlay is utilized for this purpose, its adequacy hinges significantly on expert judgment. The culvert generator, while convenient, lacks certain features for refining choices during the generation process, leading to requirement of an external software, such as FME, for advanced use of culvert generation.

The results also revealed that obtaining calibration and validation based on measured data is relatively straightforward. However, pinpointing problem locations in a large Tygron model poses a challenge. Tygron utilizes open data for certain aspects in the model, making it difficult to identify problematic areas. For instance, in Figure 10.2, various scenarios exhibited different reactions to water level stagnation along the Lage Raam. Eventually, an old weir was implemented in the Lage Raam and bridges were not implemented correctly This weir was not documented in the legger of WSAM anymore, but was implemented by Tygron automatically leading to a mismatch in information and an unexpected stagnation pattern. This highlights the complexities introduced by open data sources and the need for careful consideration and cross-referencing when incorporating such information into Tygron models.

The third case study demonstrated that Tygron is capable of providing information on level fluctuations, inundations, and water flow. However, using Tygron introduces some challenges in creating clear figures for water flow results. The need for small grid cell sizes, confirmed by the test case and the Raamvallei case, requires a large number of timesteps for the scenarios and simulations, leading to increased data storage requirements. Tygron employs timeframes, allowing the modeler to save specific simulation intervals, typically in the range of 0-500 timeframes. However, these timeframes represent only a fraction of all timesteps in a simulation, potentially leading to a loss of the comprehensive picture of results and limiting the amount of data analysis that can be performed per simulation. Limit areas were used to try to reduce the number of cells in a simulation, but this led to even longer simulation runs. An example from the Stream Restoration case is provided below to illustrate these issues:

- The area of the case study was 1870 by 1560 meters (2,917,200 m^2).
- The grid cell size used was 0.5 by 0.5 meters, resulting in 11,668,800 cells. For each parameter of interest, the total number of cells doubles because each parameter is calculated separately.
- The number of timesteps for the 11 million cells in the third case study was 552,487.
- From these half a million steps, only a maximum of approximately 1,800 steps could be generated as timeframes. However, due to the need to obtain information from multiple output parameters, such as velocity, water height, or surface elevation, this was reduced to only 55 timesteps per parameter.
- This means that only about 55 timeframes out of half a million timesteps could be exported as data for analysis.
- The data can be retrieved in multiple ways. For this case study, measurement points were used due to their ease of use. This meant that data could only be retrieved from these points and not from other locations within the model.
- Values retrieved from the measurement points can be highly dependent on where in the cell the data is collected, such as in the centerline of a stream or at the border of the waterway and land.

The Stream Restoration Case showed that the designed cross-section performed within the expected range. However, it also highlighted the potential for significant improvement in data storage and retrieval for certain types of data analysis.

12 Conclusion

This study delves into the application of Tygron, a 2D hydrological modeling software, for stream restoration projects within a low-lying area like the Netherlands. The first part focused on investigating the setup of the Tygron software identifying and testing simulation settings. The second part involved a practical assessment through two case studies, examining the benefits and challenges of employing Tygron for a water system, determining its suitability for modeling a water system, and Tygron's applicability for a water system project.

The overarching aim was to address the research question: ***"Can Tygron be used to create a 2-dimensional hydrological model to effectively be employed in stream restoration projects within a low-lying area, and what are the underlying settings that influence the applicability of Tygron for a water system"***. After this research, it can be said that Tygron is capable of using the explicit Saint-Venant scheme to calculate 2D shallow water equations where it accurately simulates a complex large water system in the Netherlands. Additionally, it can be said that Tygron can be used for projects such as the Lage Raam to provide insights into stream restoration designs. However, for a model to be successfully used and have results that can be easily understood, some settings are important to look at and some changes in data collection are needed. The most important setting to keep in mind is the grid cell sizes; a wrong choice in grid cell size can influence the results in many ways, such as water leakage, inaccurate water build-up, and inaccurate water levels. Another important note on the use of Tygron is how data can be extracted from a model. Due to how timeframes and collecting data are done right now in Tygron, some data that one is interested in is not collected. A simulation takes a lot of data, and only data within the chosen timeframes are kept.

Furthermore, for the first part, the main focus for testing the influence of settings was on 3 settings for dry/wetting cells and changes in grid cell size, the Manning value, and stream placement. In general, the settings for dry/wetting cells showed little to no impact on the results in the test case. These settings were introduced in Tygron to overcome stability issues due to incorporating an explicit Saint-Venant scheme, and it was expected beforehand that changing these settings would result in different outcomes/effects on water levels. This was not the case. In a test-case simulation and discussion with Tygron, it became evident that for both the *extended waterline reconstruction* and *extended water level to shoreline* settings, these results were expected. These two settings are mainly incorporated in Tygron to enhance stability for the initial water levels rather than during a simulation.

For the *angle stabilizer*, it was assumed that this setting should show some influence on water levels in narrow channels with small grid sizes. The results were not conclusive for this but could potentially have more influence when used in waterways with corners, steeper banks, or bigger differences in U,V water velocities in a cell.

One setting that showed more influence on results was the *grid cell sizes* used in different simulations, which can sometimes be related to *grid/stream placement*. For a 2D model in Tygron, it is evident that at least 5 to 6 grid cells are needed in the width of a stream to provide accurate results; a bit more is even advised. If fewer cells fit in the width of a channel, this can lead to creep on stream banks, inaccurate water levels, and larger build-up of water. The first case showed that grid placement has a effect on results. The most important thing to notice is however that the effect of grid placement decreases when more grid cells fit in a channel.

The study on *Manning values* found that smoother surfaces provided better results in the Tygron 2D hydrological model. Rougher surfaces caused more water build-up in narrower waterways, leading to larger offsets compared to theoretical water heights. This effect was more noticeable in narrower streams due to a higher proportion of cells on slopes, resulting in greater water build-up. Therefore, careful selection of Manning values is crucial for accurate simulation results.

The second part of this study was focused on the applicability of a 2D model of Tygron in a water system. In short, it can be said that Tygron is capable of providing an accurate model that will meet the needs for its uses in restoration projects for level fluctuations, inundations, and water flow. However, users need to be mindful of some limitations, especially in cases where abundant data or extensive analysis is required, particularly for very large study areas. The usage of time frames and limit areas promised a better way of reducing the amount of data and using more effective data, but it is not something that works perfectly right now.

Furthermore, Tygron has a fast initial setup where some open data can be used to make a 2D model, so there is no reason to start from scratch. However, for a complete water system in the 2D model, Tygron requires a lot more attention to ensure the model is suitable for practical use. Due to the fact that in Tygron, it is necessary to use a whole study area instead of a simplified schematization of a water system. Making a model in Tygron becomes complicated if one is not interested in all parts of a water system. Some open data may be unavailable or may affect the model, necessitating a thorough calibration/validation process for the water system before the model is fit for purpose. Integrating a large project area demands meticulous attention to details, as does every model. The fact that in Tygron, connectivity is important to create a realistic model, necessitates design choices such as using the culvert generator if there is insufficient data on hydraulic structures.

The second part also emphasizes that the critical parameter for the Tygron model is the grid cell size of the project. When dealing with relatively small streams, a high resolution becomes imperative. Larger grid cell sizes, indicative of lower resolution, can lead to water leakage from the stream, ending up on the adjacent land or waterways behind dikes where it cannot flow back to the stream. The second case study also reaffirms that when using Tygron, grid cell sizes of at least 1 by 1 meter (or smaller) must be employed for optimal results, as it emerges as one of the most influential settings affecting simulation accuracy. This necessitates more time steps, less timeframes for data analysis, and a greater demand for computational power, leading to longer simulation times.

13 Recommendations

Based on the findings of this study, it is recommended to implement Tygron to model a 2-dimensional model of a water system. As mentioned in the conclusion it is especially useful when interested in a complete water system with primary/secondary/tertiary waterways that includes not just a simplified schematizing of a water system to make a 2D model. Tygrons approach for a model setup provides a comprehensive overview of how different factors interact within the environment, but some recommendations can be given based on the discussions and conclusion.

New Data Storage Approaches
While Tygron supports data analysis through API integration, Python scripting, and FME (Feature Manipulation Engine), the current data storage and extraction methods have limitations for in-depth analysis. Exploring new approaches to data storage could lead to more efficient handling of extensive datasets from Tygron. Adopting new storage technologies or optimizing existing ones may improve data accessibility, retrieval speed, and overall model responsiveness. This is particularly relevant to the handling of timeframes and measurement points in Tygron, now only a small range of timeframes can be exported from Tygron while a lot more timesteps have been calculated due to limit on data storage on Tygrons server.

The main problem is that the current timeframes output is low because also a lot of data is in the timeframe a modeller is not interested in is also included. If for timeframes the output of the area of interest could be smaller, this would take at least less storage and should provide for more timeframes to be saved by Tygron on their server. Exploring alternative methods for determining time steps to optimize simulation efficiency, such as using a percentile-based approach for the Courant number. Introducing advanced settings for time step adjustments could enhance model performance for large projects.

Simplification of the water system
As of now in when a 2D model is made in Tygron the whole area surrounding the watersystem in incorporated to create a model. But sometimes it is desirable to create a simplified model of a water system. Right now it is not possible to do this in Tygron, unless maybe using limit areas. However, the limit areas implemented in Tygron cause for even longer simulation than when not using this option. Therefore it is recommended to try to optimize this option and to investigate whether it is possible to not use the whole watersystem. Even though, the inclusion of additional water bodies, such as lakes, introduces an intriguing dimension to the water system and make the model interesting and more integral in comparison to a simplified model. The fact of not being able to do this with shorter simulation time should be overcome.

Improving Connectivity Tools
Improve tools for ensuring model connectivity, such as the culvert generator and watershed tool. These tools should provide more refined options and better (automatic) integration with external data sources to enhance the accuracy and reliability of the hydrological models when making a large water system

model. Although possible to asapt this using external tools, not every modeller can do this or has the accessibility to such tools.

Settings Documentation and User Guidance
Provide detailed documentation and guidelines on the influence of various settings, such as dry/wetting cell configurations, angle stabilizers, and grid cell sizes. Not only explanation what a setting does, but numerical and practical examples should be provided. This would help users better understand how to optimize their models for specific scenarios.

Create other test cases with different scenarios
Another recommendation for this study is to use more or different test cases than the ones provided in this research. Especially since Tygron is updating its model yearly, this comes with a lot of new and different features. Currently, only certain parameters are tested with specific scenarios mainly based on rainfall. It could be very interesting to observe how certain hydraulic structures react to different scenarios or using a dam breach instead of rainfall scenarios could also significantly impact insights into the use of the Tygron model. To further advance the understanding of Tygrons potential in stream restoration, future research could focus on exploring additional restoration scenarios, refining the model's parameters, and assessing its applicability in diverse geographical and environmental contexts. This broader testing would help generalize the recommendations and improve the applicability of Tygron for diverse hydrological projects.

Compare to other full 2D models
Some insights from this research are inherent to modelling a water system completely in 2D, other insights are very Tygron specific. Doing additional research and similar studies with other 2D models makes it easier to distinguish between the two. Gaining additional insights in how to best use Tygron for these questions or consensus on how the solve 2D problems in general could be a fundamental step towards an more complete 2D model made in Tygron.

Long-Term Simulations
Enabling the capability for year-long simulations could be beneficial for assessing long-term trends and understanding seasonal variations in hydrological processes. This feature would prove valuable for projects focusing on sustainable water management, climate change impact assessments, and other studies requiring extended simulation durations. With longer scenarios possible is can be possible to also investigate Tygrons applicability on river stagnation and river dryfall. Then year-long scenarios should be implemented, but this would cause a to computational heavy model in a project the size of case study 2.

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A

Water Module Tygron

A.1. Water Module

To better understand Tygron this section will explore the hydrological background of Tygron. Tygron calls this the 'Water Module'. The Water Module in the Tygron Platform serves as a powerful tool for simulating the movement of liquid water and assessing its impact on a project area. Its main purpose lies in analyzing spatial water-related issues encountered in both urban and rural regions. These issues encompass scenarios such as heavy rainfall, flooding, evacuation protocols, as well as management simulations concerning ground and surface water.

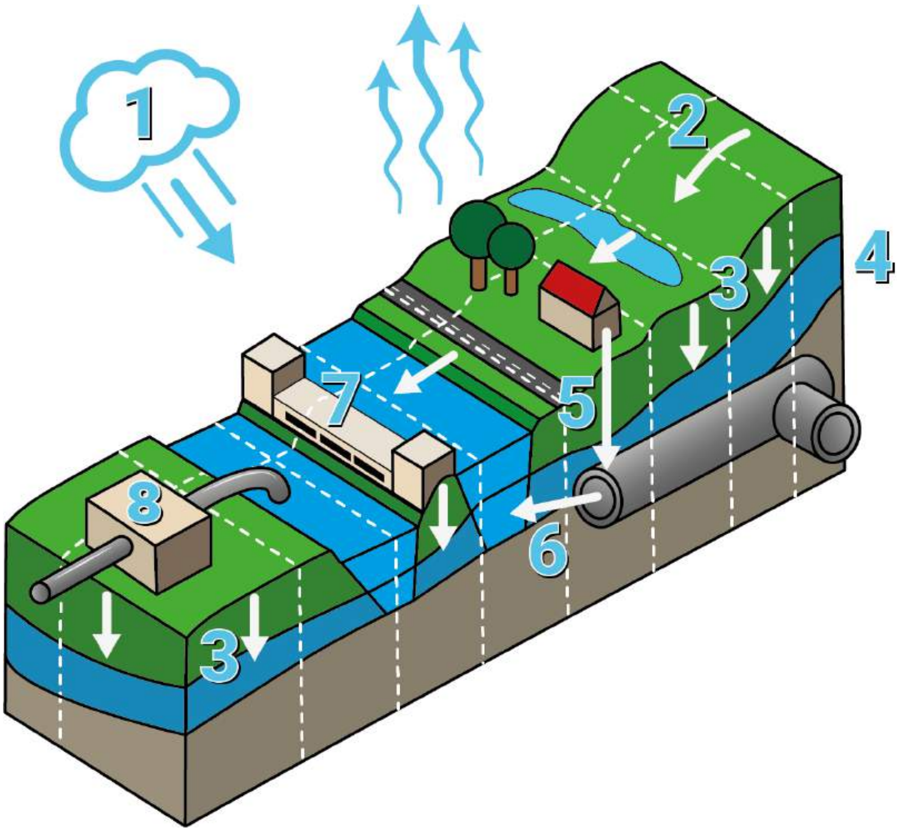

Figure A.1: Water module

The Water Module in the Tygron Platform implements a 2D grid-based shallow water model based on the Saint Venant equations. It incorporates features like infiltration, evaporation, groundwater flow, and hydraulic structures. The project area is divided into gridcells, and calculations are performed in discrete timesteps, with each cell exchanging water with adjacent cells based on various factors. The module undergoes testing against hydrological benchmarks to ensure accuracy. The calculations are executed on high-performance GPU servers for faster results. The Water Module consists of multiple ”overlay models” that collectively create a comprehensive water simulation (Tygron, 2023).

Overlays

The Water Module in Tygron provides a flexible and customizable framework for analyzing, managing, and visualizing water-related data. It utilizes grid-based overlays, which can be tailored to specific analyses, configurations, and desired outcomes. The Water Module allows for the storage and examination of both final simulation results and intermediate results once the calculation process is completed.

The Grid Overlay is a overlay that divides the project area into a grid consisting of equally sized square cells, and performs specific calculations based on the type of overlay being calculated. The calculations rely on data obtained either from properties or attributes associated with the overlay or from features within individual cells. The maximum number of cells for any overlay or result type is 1 billion individual cells, and within a project, it is possible to have multiple overlays with result types, where the maximum number of grid cells is 2 billion for both the overlay and its associated result types combined. The total maximum number of cells allowed in a project is 50 billion individual cells, and exceeding this limit will result in the inability to perform further calculations.

The Rainfall Overlay is a water overlay that performs 2D grid-based water simulations using input data and parameters, and stores the resulting data based on the selected result type in certain timeframes. It can also store data from multiple intermediate simulation results, providing valuable insights into the dynamics of water behavior. Input mainly is a certain rainfall event with given precipitation amounts and moments of rainfall. Custom rainfall events van also be implemented, such as to recreate a rainfall event based on data.

The watershed overlay function is utilized to predict the flow path of surface rainfall water, primarily relying on elevation data or direction data obtained from a Water Overlay. It is amenable to user input, as users can define indicative discharge regions that subsequently expand into watershed areas. Additionally, for enhanced precision, it can incorporate directional data from overlays like surface average direction results from rainfall overlays. This tool serves multiple purposes, including debugging water systems, determining the significance of waterways within a system by evaluating discharge area sizes, resolving landowner disputes concerning water runoff, and facilitating the integration of discharge area information with external water simulation tools beyond the Tygron Platform for rainfall analysis and management.

A.2. Order of Calculattion

As explained for the grid overlay a project has a number of grid cells depending on the project area and the grid cell size chosen. Depending on the length of the rainfall event used in the rainfall overlay Tygron will choose the amount of timesteps for a simulation. For each timeframe that is calculated an order of calculations is performed in Tygron in each cell:

- Horizontal surface flow and horizontal underground flow
- Rain
- Building storage
- Sewer inflow
- Surface evaporation
- Groundwater evaporation (saturated zone)
- Groundwater evaporation (unsaturated zone)
- Underground infiltration
- Surface infiltration
- Underground seepage

- Exfiltration
- Hydrological constructions (culverts, weirs, pumps, in- and outlets)
- Hydrological areas (sewer overflow, breach in- and outflow)
- Tracer movement, based on the water flow and infiltration which has occurred

As the focus for this research is on surface water flow the important steps are:

1. Horizontal surface flow and horizontal underground flow
In the first step during a timestep the horizontal surface flow and horizontal underground flow is calculated in a grid cell.

2. Rain
Is where the input rainfall overlay is used. During this step the accumulation of rainfall during 1 timestep will 'fall' on the grid cell.

3. Surface evaporation
Surface evaporation is an given amount during a time period. Which can also been given a real life situation or custom situation based on data in the rainfall overlay.

4. Surface infiltration
Surface infiltration is the process where water from the surface seeps into the ground, and its speed is determined by certain attributes. The slowest of these attributes among surface terrain, underground terrain, or building characteristics sets the rate of infiltration. You can also adjust this speed using a factor to simulate various conditions like saturation or temperature. Surface infiltration happens when the groundwater mode is set to either Complete or Infiltration Only. Surface Infiltration Only is a simplified mode that operates when the groundwater mode is set to Infiltration Only. In this mode, it focuses solely on the speed of infiltration and has a fixed limit on how much water the ground can hold in its unsaturated layer.

5. Hydrological constructions (culverts, weirs, pumps, in- and outlets)
Within Tygron, hydraulic structures can be implemented in the water system as buildings that transport water. In chapter 7.1 the current structures in the system have already been shown. Per category each structure can be adjusted to have correct attributes. In the Raamvallei mostly weirs and culverts are used for water level control, and pumps are used to remove excess water from the raamvallei to the Maas.

The most important hydrualic structures are:

- **Culverts:** connection between waterways
- **Weirs:** control of waterheight
- **Pumps:** in the context of this research also used as outlets for boundary conditions or as "gemaal"
- **Inlets:** used for boundary conditions

In this schematic one can see how the important order of calculation will turn out:

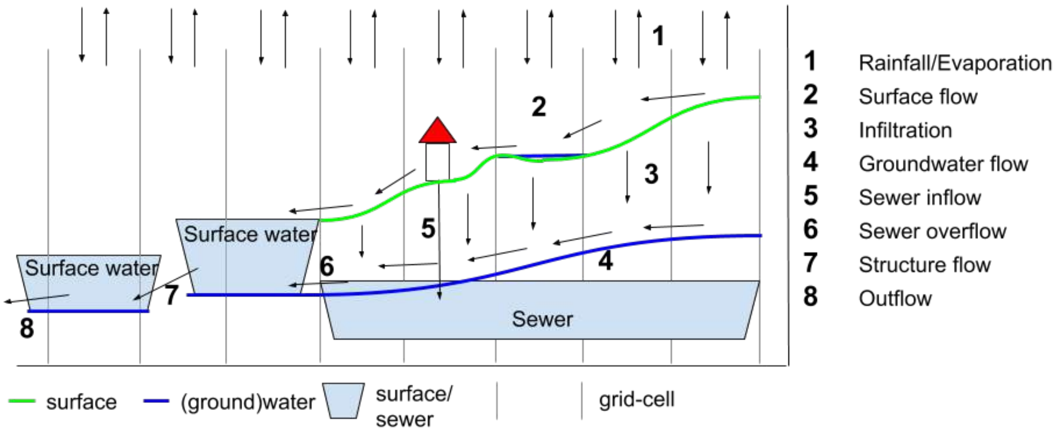

Figure A.2: Order of calculations

The scheme uses a special quadrature for the approximation of the cell averages of the source term and a piecewise linear reconstruction of the water surface, which is properly corrected near dry areas without switching to a reconstruction of the fluid depth there.

The document proves the positivity preserving property of the scheme, which is crucial for the reliability of the numerical method. The scheme is tested on various numerical examples, and the results show that it is accurate and efficient.

A.3. Surface Model

The main function for the water module is to simulate a 2D water flow accross the surface. As Tygron uses open data or inserted data it could be that the implemented data is not in the same grid-size as is used in the grid-overlay. In order to have a simulation the project area is first discretized into cells and then water is initialized in the model. A.2

A.3.1. Piecewise Linearization

The surface elevation in Tygron is constructed using a rasterization of the AHN4 height map and a piecewise lineair reconstruction of the bottom thereof. Kurganov and Petrova (2007) discusses that the piecewise linear reconstruction in the second-order central-upwind scheme is crucial for ensuring the preservation of positivity in the computed fluid depth.

According to Bollermann et al. (2014), piecewise linear discretization of the bottom topography is used for reconstruction of the water level at wet/dry fronts for the shallow water equations. Piecewise linearization is a method for approximating a function by breaking it into multiple linear sections. In other words it means that they approximated the bottom topography using a series of linear segments.

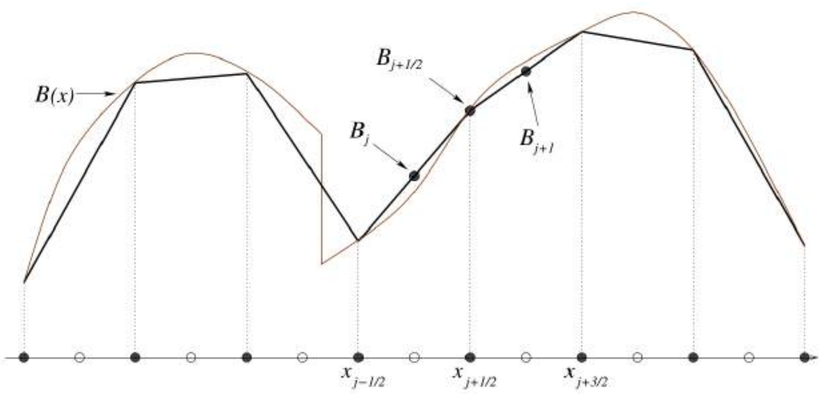

Figure A.3: Visualisation of 1D piecewise linearization (Horváth et al., 2015)

Kurganov and Petrova (2007) uses the piecewise linearization for a well-balanced positivity preserving central-upwind scheme for solving the Saint-Venant system of shallow water equations. Where the original bottom function is replaced with its continuous piecewise linear (bilinear in the 2-D case) approximation.

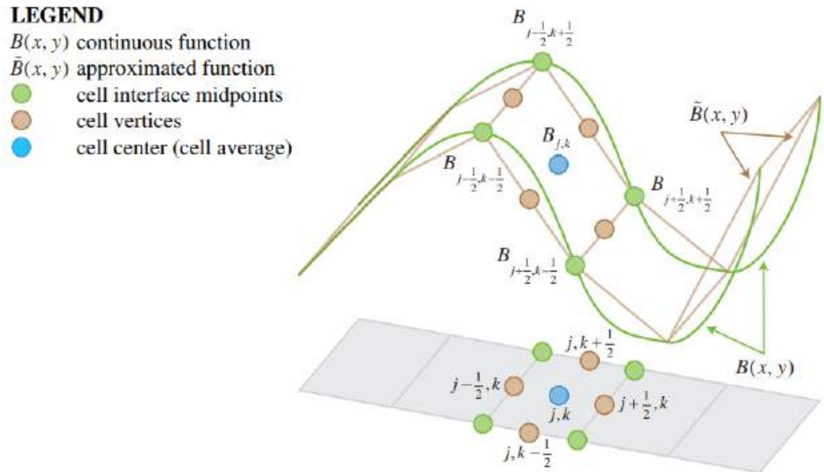

Figure A.4: Visualisation of 2D piecewise linearization (Bollermann et al., 2014)

The Water Module uses a specific type of scheme for reconstruction of the bottom known as the second-order semi-discrete central-upwind scheme by Kurganov and Petrova. In order to create a well-balanced and positive scheme, the surface elevation is adjusted using this process. This involves:

1. Pick or calculate the height points for the 4 corners of the cell. A height point is picked when an override height is provided, such as a Weir Height.
2. Form a rectangle with the 4 corners and calculate the centers of these edges. (These are the points that have to meet for continuity).
3. Calculate a new center point based on the 4 edge center points.

Given that the adjacent cells share the same corner points, and thus share an edge center point, the bottom will be continuous in the x and y direction. Furthermore, the cell has an linear slope in both the x- and y-direction. The only downside is that the new center point might have been placed higher or lower in a situation where the terrain's slope was originally not linear within the cell.

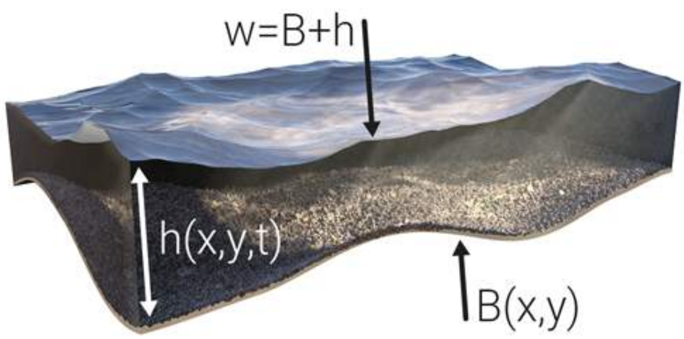

Figure A.5: Surfave Model Bottom level

The key objective of the reconstruction is to accurately represent the variables w and hu near dry areas, where the fluid depth h approaches zero. In these regions, it is essential to maintain the positivity of h to avoid nonphysical results. To achieve this, the reconstruction uses a modified bottom topography function $\tilde{B}$, which is obtained by replacing the original bottom topography function B with $\tilde{B}$. This replacement does not affect the formal order of the central-upwind scheme, as the piecewise linear interpolant remains second-order accurate for smooth B . By reconstructing the variables w and hu using the modified bottom topography function $\tilde{B}$, the scheme ensures that the computed fluid depth h remains positive throughout the computational domain, even in the presence of dry areas or discontinuous bottom topography (surface elevation). In figure A.5 one can see that Tygron uses B for vottom instead of z. In figure A.3 one can see the 1D lineair reconstruction.

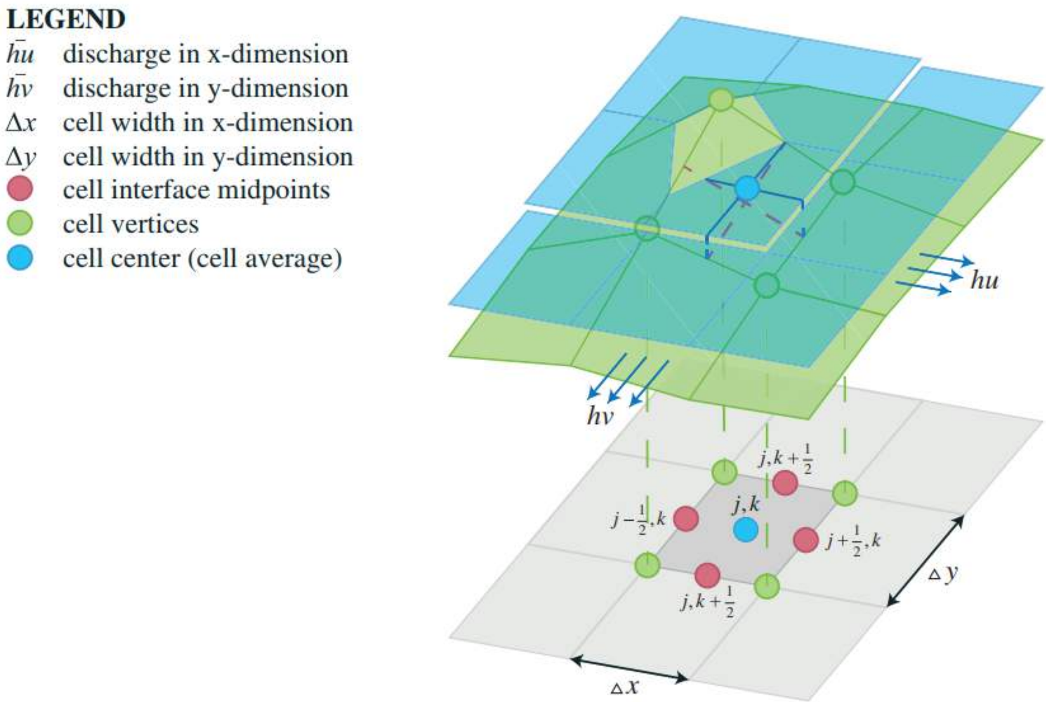

Figure A.6: Visualisation of 2D piecewise linearization on grid (Bollermann et al., 2014)

A.3.2. Saint-Venant Equations

The Saint-Venant equations, also known as the Saint-Venant open-channel flow equations, are a set of partial differential equations used to describe the one-dimensional flow of water in open channels like rivers, canals, and streams. These equations are named after the French engineer Adhémar Jean Claude Barré de Saint-Venant, who developed them in the mid-19th century. The basic form of the Saint-Venant equations comes from the conservation of mass (continuity eqaution) and the moment equation:

The Continuity Equation expresses the conservation of mass along a channel reach. It states that the rate of change of water depth with respect to time is equal to the negative of the rate of change of flow velocity with respect to distance:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{A.1}$$

Where:

$$
\begin{aligned}
h &: \text{Water depth} \\
t &: \text{Time} \\
Q &: \text{Flow rate (product of cross-sectional area and velocity)} \\
x &: \text{Distance along the channel}
\end{aligned}
$$

The Momentum Equation describes the variation of flow velocity along the channel and is derived from the principles of fluid dynamics. It takes into account the forces acting on the flow, including gravity, friction, and pressure gradients. The momentum equation can be written in various forms depending on the assumptions made for friction and other factors. The most common form is:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} = -gAS_f \tag{A.2}$$

Where:

$$
\begin{aligned}
Q &: \text{Flow rate} \\
A &: \text{Cross-sectional area of the flow} \\
g &: \text{Acceleration due to gravity} \\
S_f &: \text{Friction slope (representing energy losses due to roughness)}
\end{aligned}
$$

based on research of (Kurganov & Petrova, 2007) the water model of Tygron uses the following 2D saint venant eqaution:

The 2D Saint-Venant equations describe shallow water flow in two dimensions and are given by:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{A.3}$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) = -gh\frac{\partial z}{\partial x} - \tau_x \tag{A.4}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) = -gh\frac{\partial z}{\partial y} - \tau_y \tag{A.5}$$

Where:

$$
\begin{aligned}
h &: \text{Water depth} \\
u &: \text{Velocity component in the } x\text{-direction} \\
v &: \text{Velocity component in the } y\text{-direction} \\
t &: \text{Time} \\
g &: \text{Acceleration due to gravity} \\
z &: \text{Bed elevation} \\
\tau_x &: \text{Shear stress in the } x\text{-direction} \\
\tau_y &: \text{Shear stress in the } y\text{-direction}
\end{aligned}
$$

These equations describe the conservation of mass and momentum for shallow water flow in two dimensions. The first equation represents the conservation of mass, while the second and third equations represent the conservation of momentum in the x- and y-directions. The only difference is that Tygron instead of using ”z” they use B which is the Bottom elevation as shown in section A.3.1. This method relies on a continuous piecewise linear approximation of the surface.

A.3.3. Second-order well-balanced positivity preserving Central-upwind scheme

A second-order well-balanced positivity property for the Saint-Venant equations refers to a mathematical property of a numerical scheme or method used to solve these equations. Preserving central-upwind schemes, also known as CUSP schemes, are a class of numerical methods used in computational fluid dynamics (CFD) to solve hyperbolic partial differential equations like the Saint-Venant equations for open-channel flow(Kurganov & Levy, 2002). These schemes are designed to address specific challenges associated with hyperbolic conservation laws and aim to capture both the central and upwind behavior of the solution accurately.

Second-Order: This means that the numerical method or scheme used to approximate the solutions of the Saint-Venant equations is second-order accurate. In numerical methods, accuracy is often described in terms of order, where higher order indicates better accuracy. Second-order accuracy means that the method has a convergence rate of $O(\Delta x^2)$, where Δx is the spatial grid spacing. This implies that as you reduce the grid spacing (make it finer), the error in the numerical solution decreases at a rate proportional to Δx^2.(Kurganov & Petrova, 2007) (Bollermann et al., 2014)

Well-Balanced: In the context of the Saint-Venant equations, a well-balanced scheme is one that can accurately and stably handle situations where there are discontinuities in the flow variables, such as water depth or velocity. For example, in hydraulic problems, a river might have a dry bed in some areas and flowing water in others. A well-balanced scheme ensures that the numerical solution respects the physical conservation laws, such as mass and momentum conservation, even in the presence of these discontinuities.(Kurganov & Petrova, 2007) (Bollermann et al., 2014)

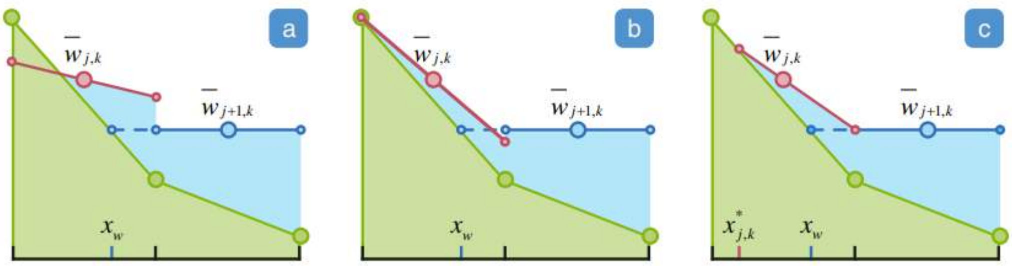

Figure A.7: Approximation of the wet/dry front reconstruction. Theblue dashed line represents the waterline of the fully flooded cell. (a) Wrong approximation by the piecewise linear reconstruction, which produces a negative value. (b) Positivity preserving but unbalanced piecewise linear reconstruction. (c) Positivity-preserving and well-balanced piecewise linear reconstruction (Bollermann et al., 2014)

Positivity: Positivity means that the numerical scheme guarantees that certain physical quantities, such as water depth or flow velocity, remain non-negative throughout the simulation. In the context of the Saint-Venant equations, it's important to ensure that these quantities do not become negative, as negative values would not have a physical interpretation (e.g., negative water depth) and could lead to unphysical results.(Horváth et al., 2015)

Preserving: in this context refers to the ability of the numerical scheme to maintain certain important physical properties of the solution. In the case of the Saint-Venant equations, it's crucial to preserve properties like positivity (ensuring that water depths and velocities remain non-negative) and the conservation of mass and momentum. A scheme that is preserving ensures that these physical properties are not violated during the simulation.(Kurganov & Levy, 2002)

Central-Upwind: "Central" and "upwind" are terms that describe different ways of approximating the numerical solution at each grid point in a computational grid. Central schemes typically calculate the solution at a grid point by considering information from both sides of that point (all sides in 2D such as Tygron). They are known for their ability to capture smooth variations in the solution accurately. Upwind schemes are designed to prioritize information from the upwind (or "upstream") direction, where the flow is coming from. Upwind schemes are good at capturing sharp discontinuities and shocks in the solution. (Kurganov & Levy, 2002) (Kurganov & Petrova, 2007)

Concluding: when you have a second-order well-balanced positivity property for a numerical scheme applied to the Saint-Venant equations, it means that the scheme is accurate (second-order), capable of handling flow discontinuities (well-balanced), and ensures that key physical quantities like water depth and velocity remain non-negative (positivity) as it computes solutions to these equations. It uses central differencing in regions where the flow is smooth and continuous to capture those variations accurately. It switches to upwind differencing in regions where there are sharp changes or discontinuities in the flow.

This property is highly desirable because it allows for more accurate and physically meaningful simulations of open-channel flow, which is crucial for applications in hydraulic engineering, flood modeling, and water resource management.

A.3.4. Time-step calculations

To ensure numerical stability, an adaptive timestep (formula A.6 is implemented based on Kurganov and Petrova's method.

$$\Delta t = min(\frac{\delta x}{4a}, \frac{\delta y}{4b}) \tag{A.6}$$

Where:

$x = y$: Cell size
a : max of one-sided speeds in y-directionn
b : max of one-sided speeds in y-direction

The selection of an appropriate timestep is crucial, particularly when dealing with shallow depths, to prevent numerical instability. Hence, the timestep is carefully chosen to ensure that all computation cells adhere to one of the following criteria:

- The timestep is chosen so that each computation cell meets one of the following criteria:
    1. If a cell's water depth is below 5×10^{-3} m (the flooding threshold), there is no flow assumed between that cell and its neighboring cell.
    2. If a cell's water depth is above the flooding threshold, the maximum timestep is 100 times the water depth at the cell.
    3. If the water depth increases, the timestep is not larger than the formula above.
- If the numerical flux decreases, larger timesteps may be allowed than those set by Kurganov and Petrova, depending on the configured calculation.

In general, to fulfill this requirement, the Courant-Friedrichs-Lewy (CFL) condition is applied. Tygron has chosen to keep the courant-number below 0.25 for every active computation cell at each timestep. This CFL condition allows for each wave to travel at most one quarter of a grid cell per time step thus limiting the propagation of the information by limiting the time step. ((Horváth et al., 2015) & (Knepfle, 2023). Because of this condition a water in the middle of a grid cell can not suddenly travel to a neighbouring cell.

The timestep formula for the scheme proposed nu Bollermann et al. (2014) is given by the CFL condition. It is defined in formula 3.2 where t is the time step, x is the cell size, and a±j+1/2 are the maximum wave speeds at the cell interfaces. This CFL condition restricts the time step and is used in the numerical experiments of Bollermann et al. (2014). The numerical experiments show that the proposed scheme is well-balanced and positivity preserving, and it can handle shocks running into dry areas and simulations including Manning's bottom friction term, which is singular at the wet/dry front. The formula is written in Overleaf format as:

$$CFL := \frac{\Delta t}{\Delta x} * max_j|a^{\pm}_{j+1/2}| \leq \frac{1}{2} \tag{A.7}$$

Due to this conditon Tygron has chosen to keep the courant-number below 0.25 for every active computation cell at each timestep.

A.3.5. Dry-wetting fronts

The problem with having all water height non-negative is that this can cause partially flooded cells which can lead to large errors for small water heights. Another issue related to this modification is that the water climbs up on the shores at the dry/wet boundaries. Finally, if a cell becomes wet, it will almost never be completely dry again (Horváth et al., 2015). Horváth et al. (2015) has come up with a 2 dimensional central upwind scheme which just as the piecewise lineair reconstruction of Kurganov and Petrova (2007) changes the batrymetry of the inputed data but then for in the both x and y dimensions. Next to the 2D schemetization another technique for the reconstruction of the water surface for partially flooded cells is introduces by Horváth et al. (2015) while maintaining a positive preserving property of the scheme of Kurganov. et al. In figure A.8 of Horváth et al. (2015) one can see how the given method deals with shallow water at the dry/wet front.

The first one is the **Extend the waterline reconstruction**. This setting can be chosen whether to automatically fill cells near a water terrain when there is a mismatch between the extend of the water terrain and the DEM. When selected, a well-balanced reconstruction method for drying and wetting fronts described by Bollermann et al. (2014) is used. This approach is useful when interested in a lake at rest situation. When water flow is more important, this option should not be chosen

The second one is the **extend waterlevel to shorelines**. When selected, a shoreline along a waterway will be filled with water to prevent a initial flush of the waterway during a simulation. Incorrect positioning of a Waterway polygon relative to the DEM can cause adjacent land to fill with water at the simulation's onset, resulting in a lower than anticipated water level. To address this issue, a ”shoreline” is introduced in neighboring cells. These shoreline cells are initially filled with water to match the nearby water level, preventing the initial overflow (Horváth et al., 2015). This method ensures better numerical stability at the wetting and drying fronts of a flood wave. In (Horváth et al., 2015) the steps are further explained as below, these steps collectively ensure accurate and stable calculations throughout the process:

- Elevation value B of each cell is assigned to be equal to the value at its center and the interface midpoints.
- Reconstruction of slopes for conserved variables (continuity and momentum) in the x- and y-directions.
- Comparison of conserved variable values at cell interface midpoints with left-sided and right-sided values relative to the cell's center.
- Modification of slopes for partially dry cells to prevent negative depth values and ensure numerical stability.
- Computation of fluxes at each cell interface to determine the values of conserved variables at the cell centers for the next time step.
- Calculation of the largest allowable time step.
- Incrementing time using the calculated time step, followed by the application of changes in water level and fluxes.

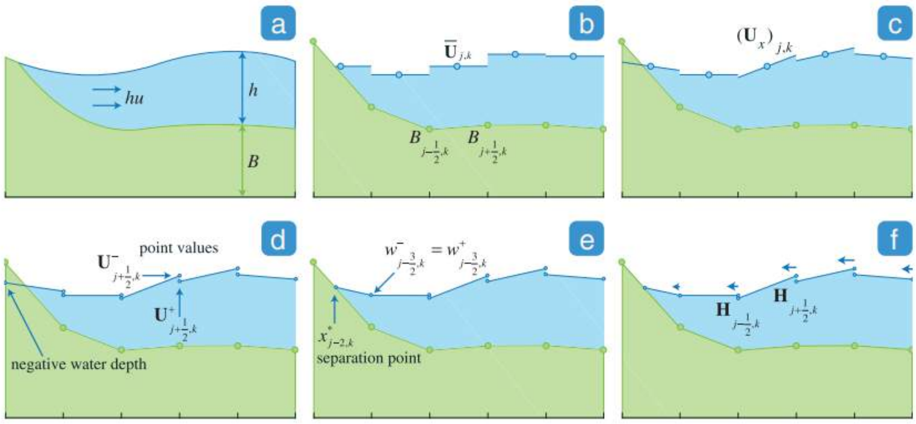

Figure A.8: Schematic overview: (f) Fluxed are computed using the central-upwind function at each cell interface (Bollermann et al., 2014)

Lastly, one could change the **Angle stabilizer for partly flooded cells**. A partly wet cell (mostly at the banks of waterways) can become unstable when a cell is very steep or the water velocity difference is large. In this case the fluxes in flow direction U and V cannot easily be solved mathematically while preserving balance using Saint-Venant. To prevent unrealistic calculations, only the watervelocity in the primary flow direction will be kept, making the SWE within the cell 1-dimensional.

A.3.6. Cross-sections

Tygron uses open-data waterways, but more accurate raster data with waterways can be imported. As the former does not always give perfect waterways (figure A.9. These waterways have been created using the measured cross-sections along the waterwaysin the Raamvallei. Every 250 meter a cross sections has been made. With the help of interpolation the waterways can be simulated.

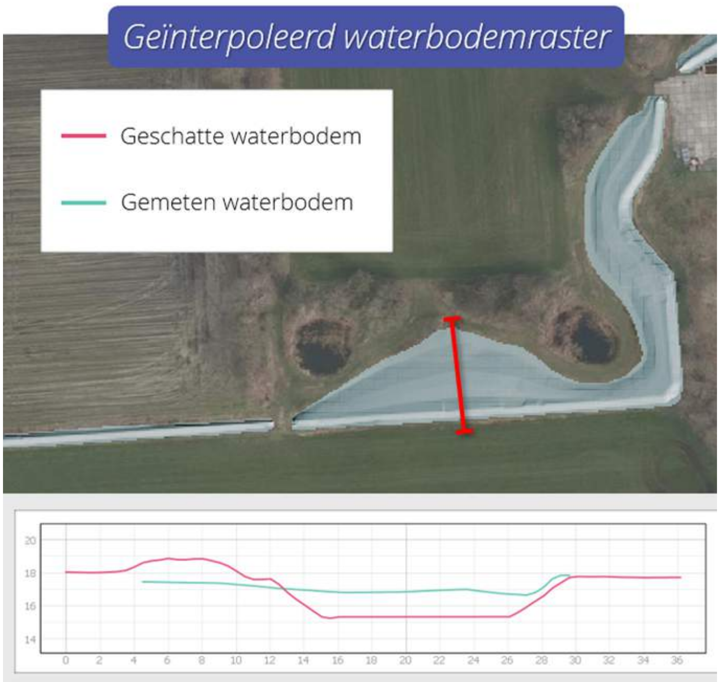

Figure A.9: Cross-sections automated in Tygron made of open data vs. cross-sections based on measured profiles in the the Raamvallei

B

Measurements Waterboard Aa en Maas in the Raamvallei

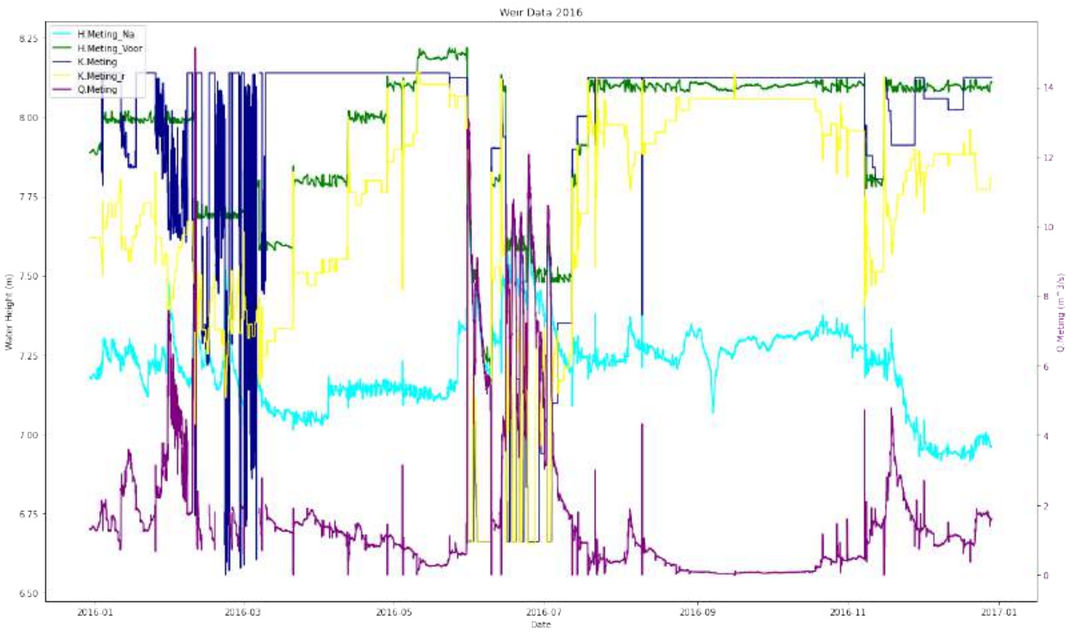

Figure B.1: Measurements of 108KAM in 2016

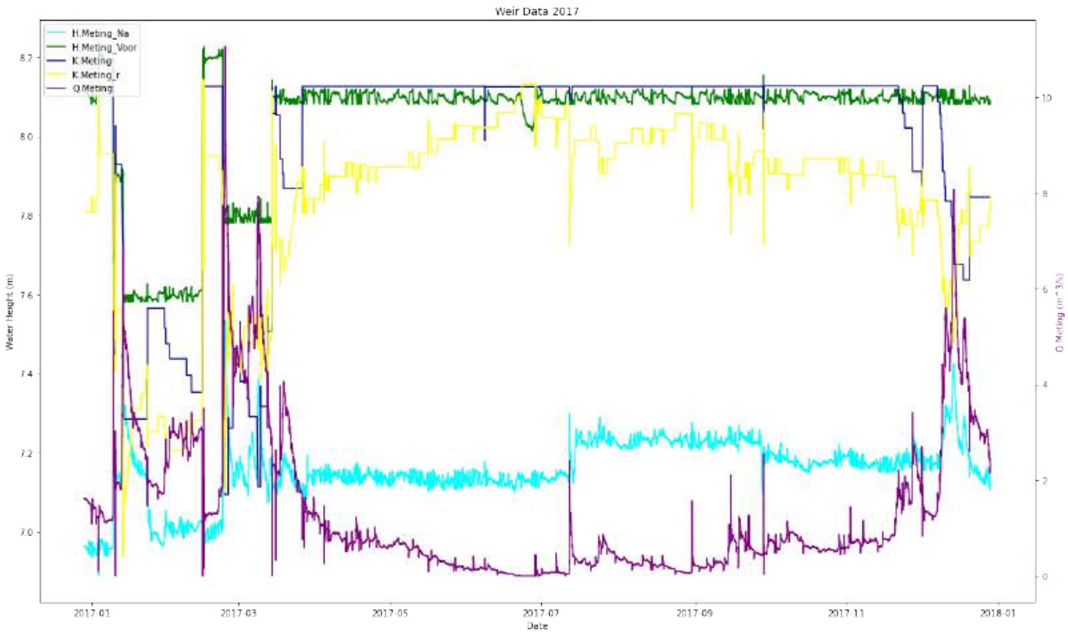

Figure B.2: Measurements of 108KAM in 2017

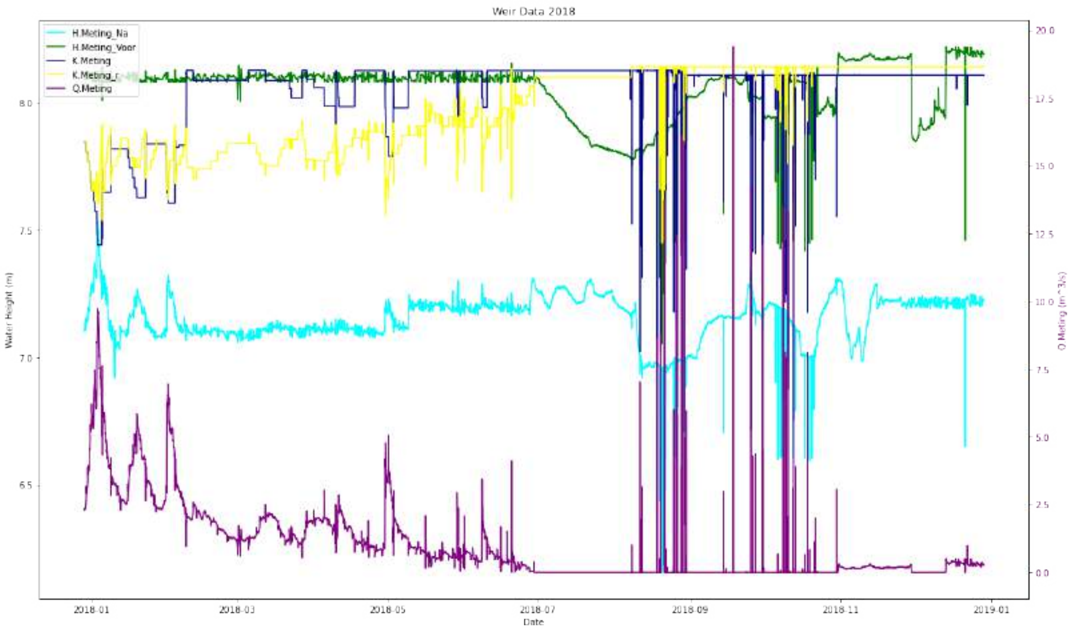

Figure B.3: Measurements of 108KAM in 2018

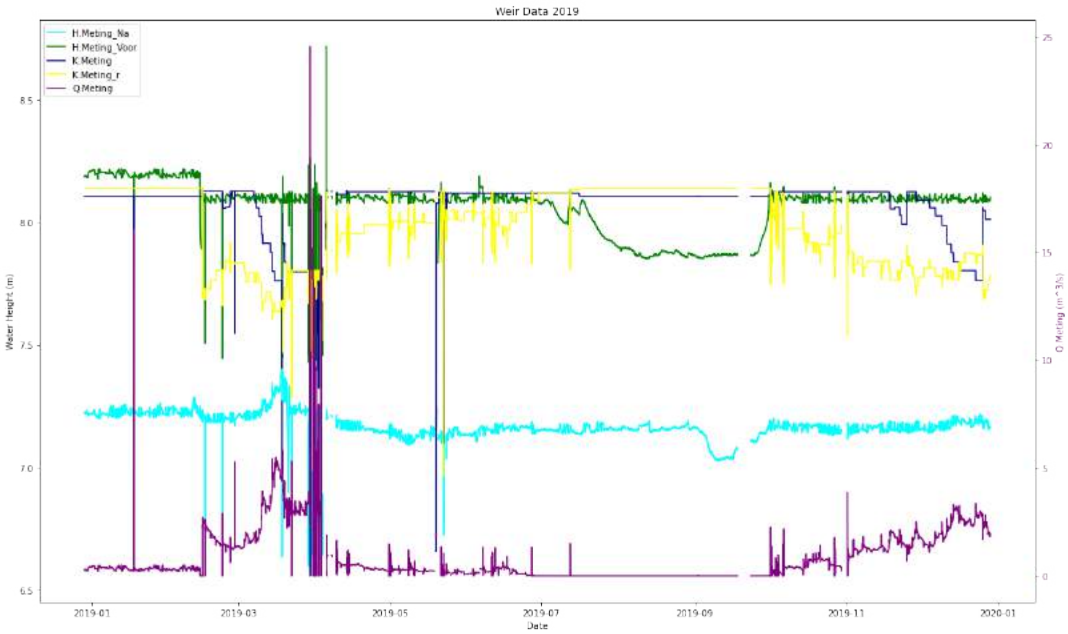

Figure B.4: Measurements of 108KAM in 2019

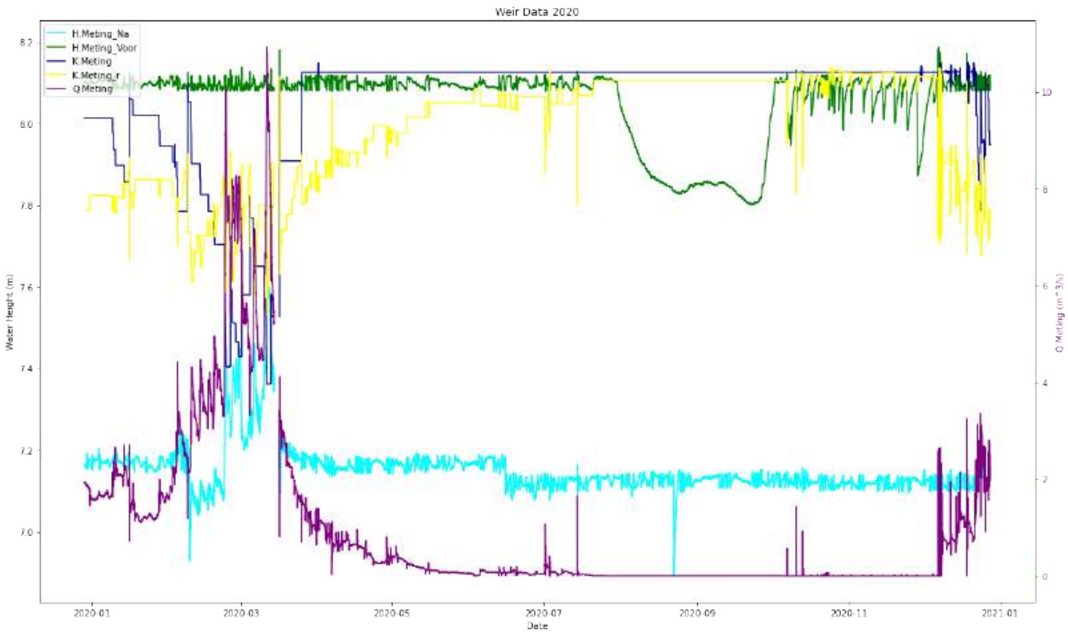

Figure B.5: Measurements of 108KAM in 2020

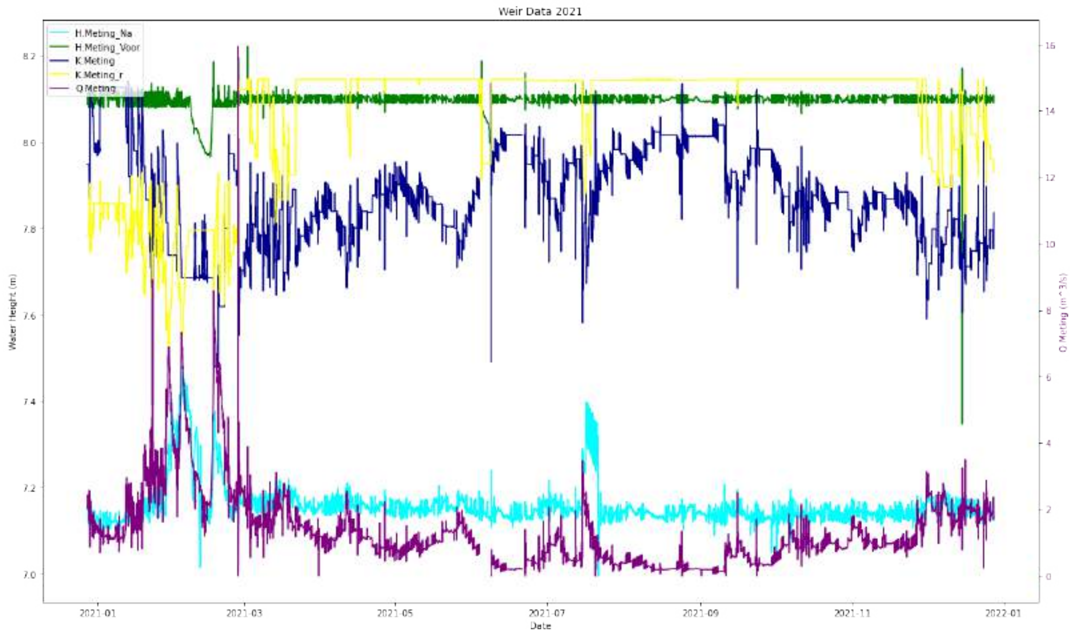

Figure B.6: Measurements of 108KAM in 2021

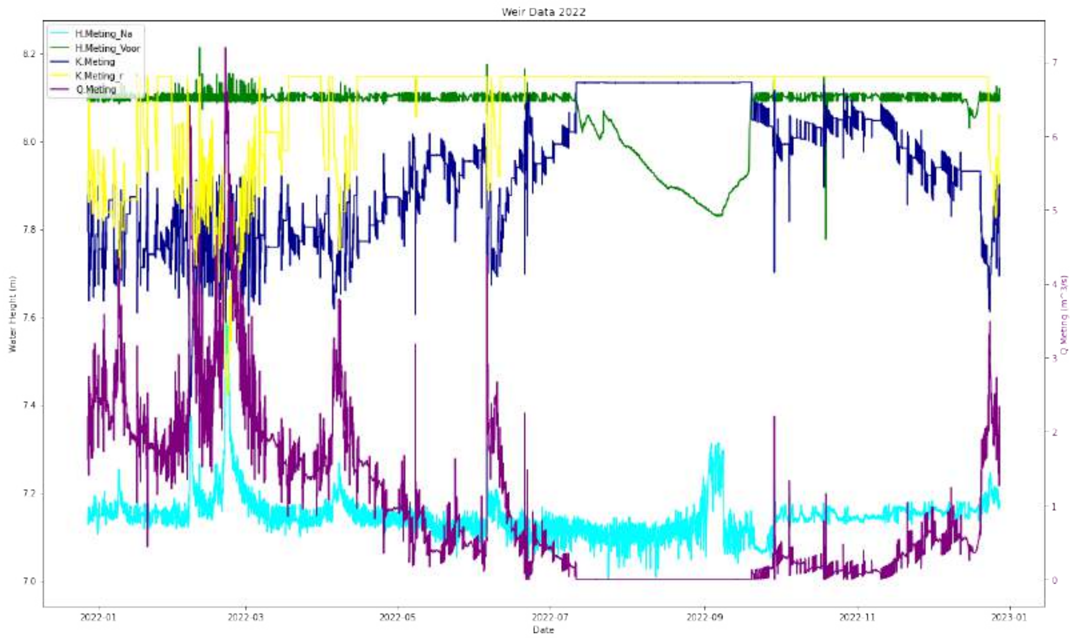

Figure B.7: Measurements of 108KAM in 2022

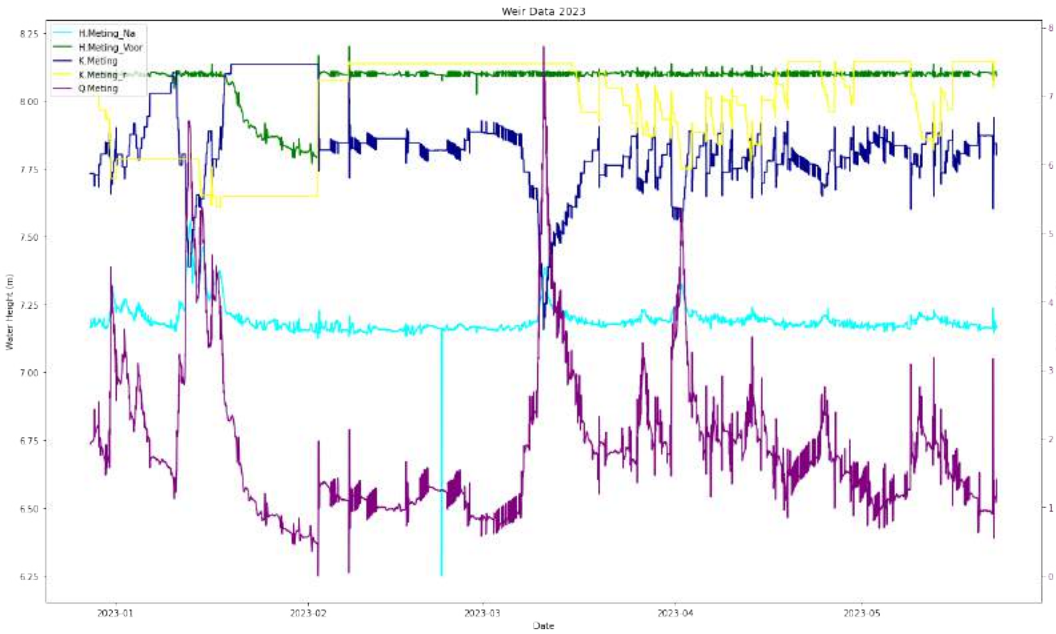

Figure B.8: Measurements of 108KAM in 2023

C
Results Testcase

In this appendix extra results are shown too highlight some findings in the results presented in chapter 10

C.1. Boxplots with all scenarios divided per grid cell size

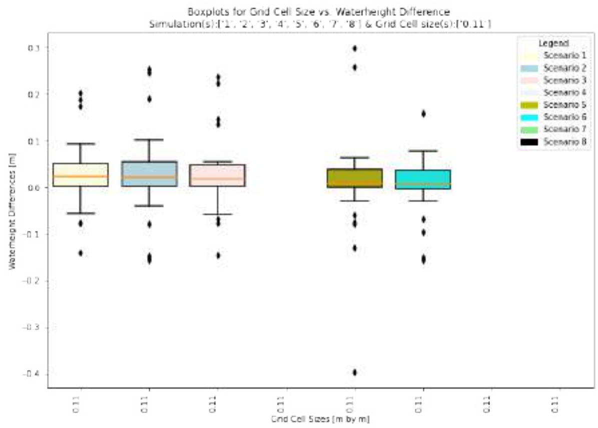

Figure C.1: Boxplot all scenarios grid 0.11 meter

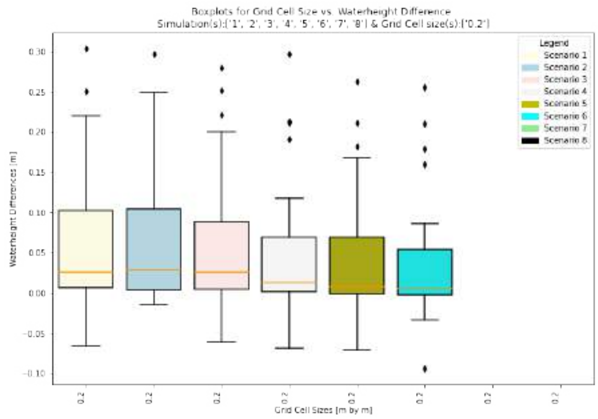

Figure C.2: Boxplot all scenarios grid 0.2 meter

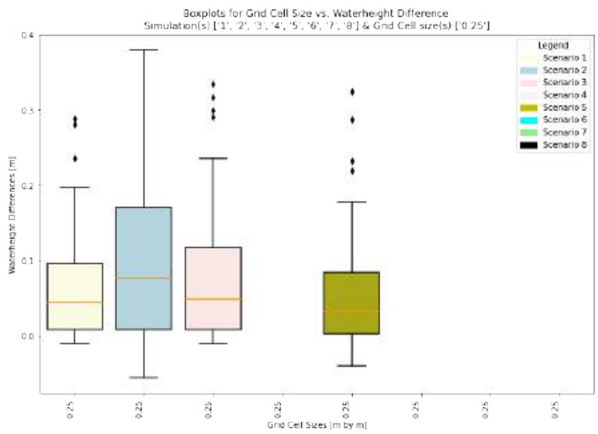

Figure C.3: Boxplot all scenarios grid 0.25 meter

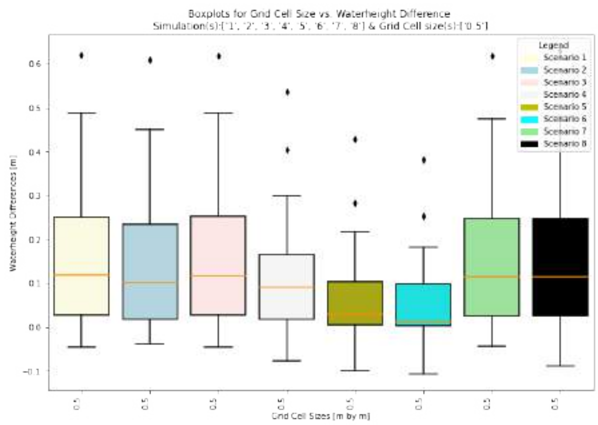

Figure C.4: Boxplot all scenarios grid 0.5 meter

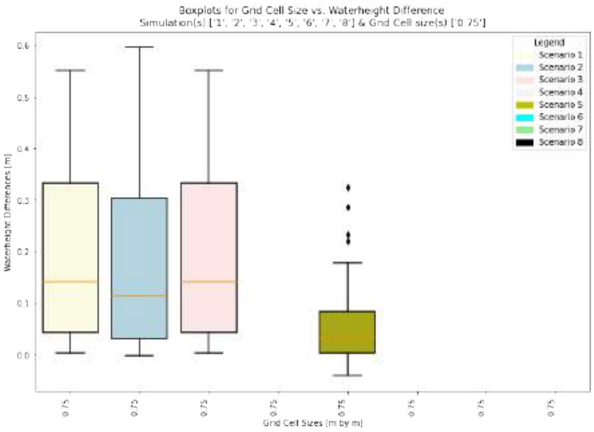

Figure C.5: Boxplot all scenarios grid 0.75 meter

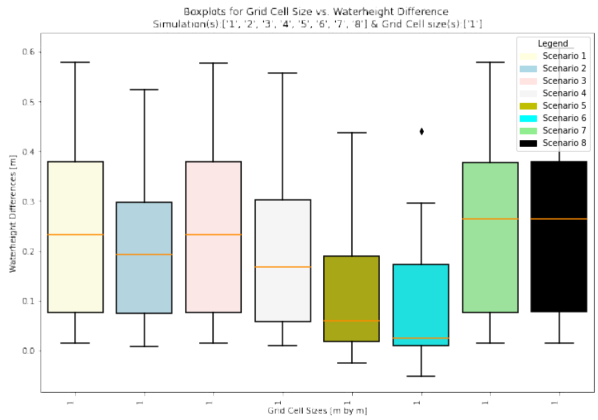

Figure C.6: Boxplot all scenarios grid 1 meter

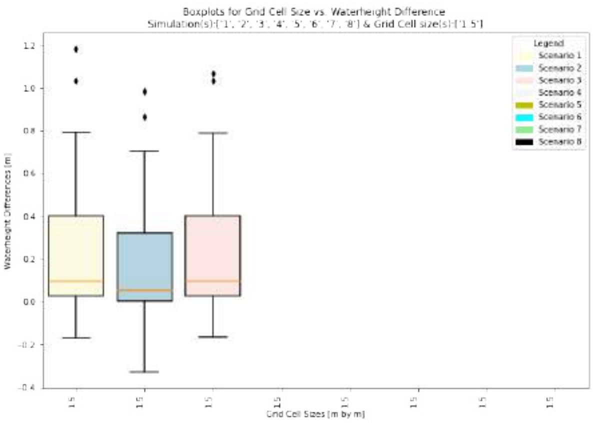

Figure C.7: Boxplot all scenarios grid 1.5 meters

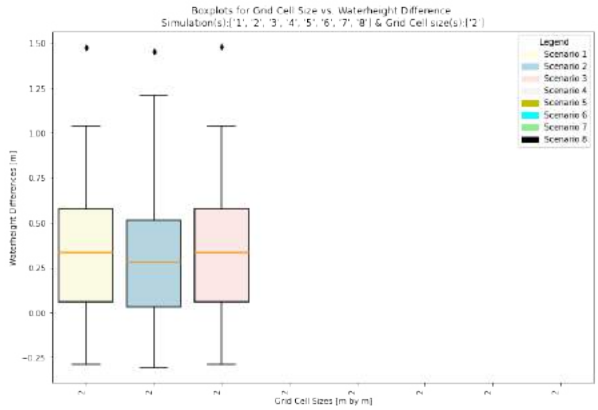

Figure C.8: Boxplot all scenarios grid 2.0 meters

C.2. Boxplots divided per scenario for all grid cell size

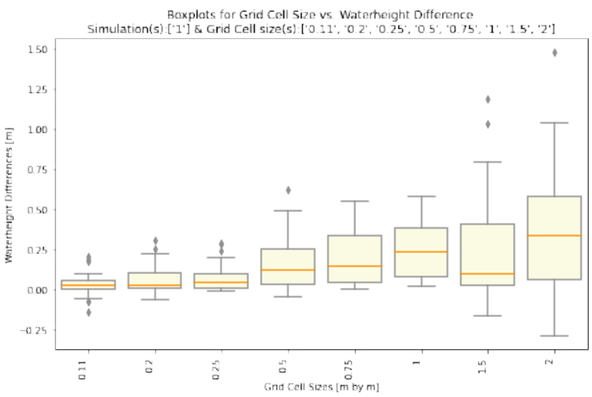

Figure C.9: Boxplot all grid cell size for Scenario 1

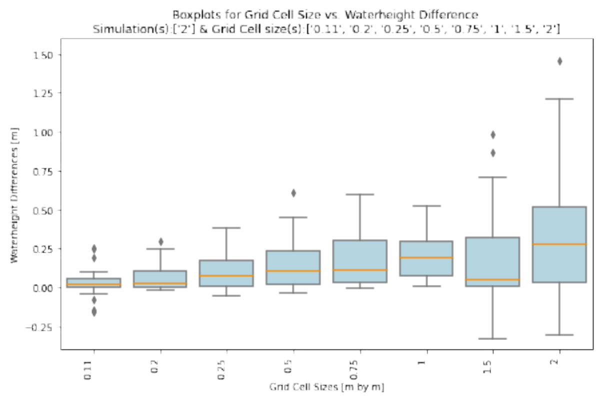

Figure C.10: Boxplot all grid cell size for Scenario 2

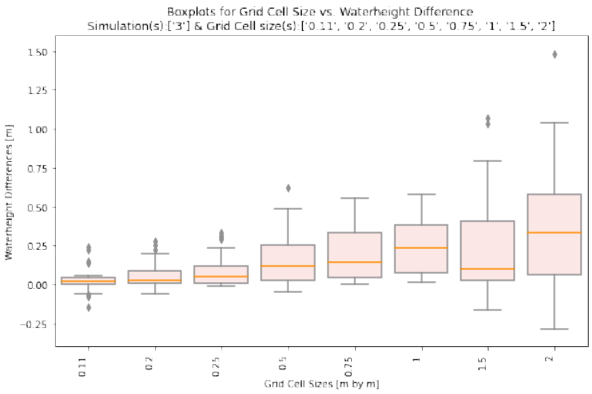

Figure C.11: Boxplot all grid cell size for Scenario 3

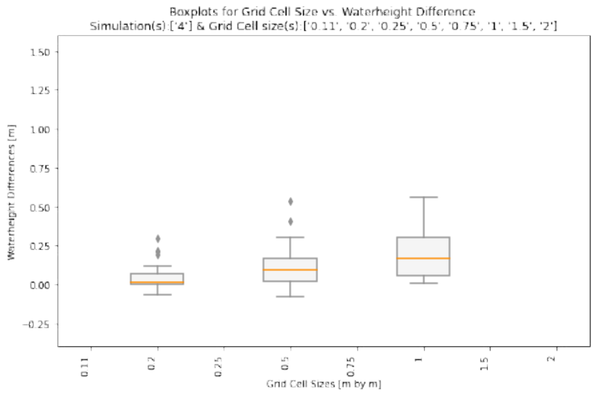

Figure C.12: Boxplot all grid cell size for Scenario 4

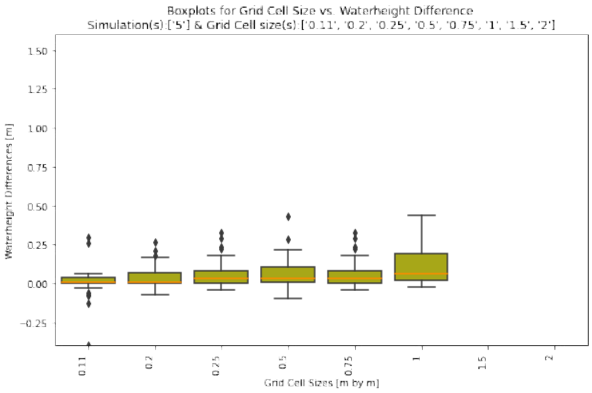

Figure C.13: Boxplot all grid cell size for Scenario 5

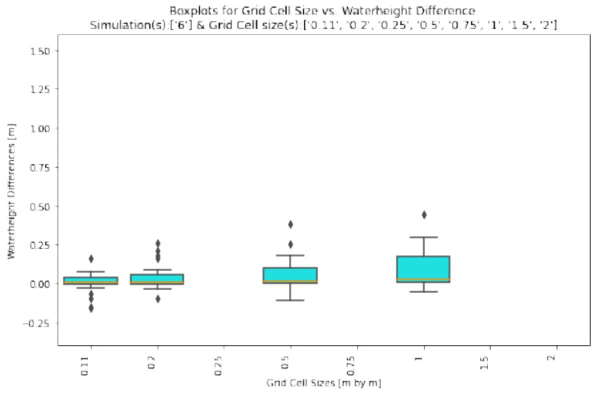

Figure C.14: Boxplot all grid cell size for Scenario 6

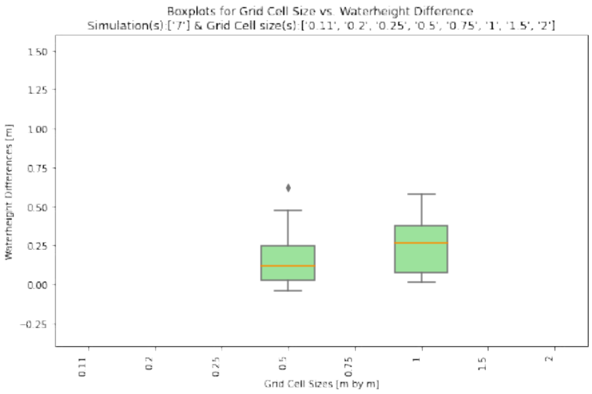

Figure C.15: Boxplot all grid cell size for Scenario 7

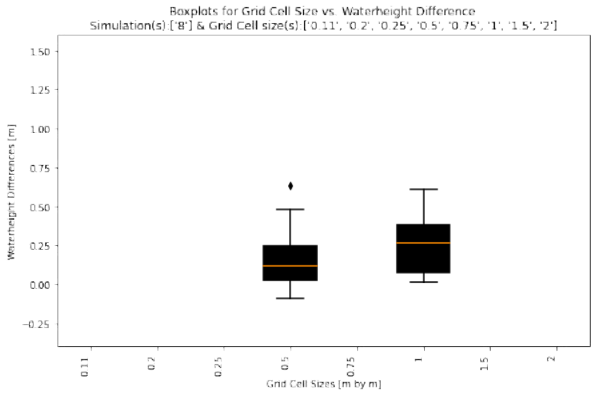

Figure C.16: Boxplot all grid cell size for Scenario 8

C.3. Boxplots divided per channel with all scenarios and divided for grid cell size

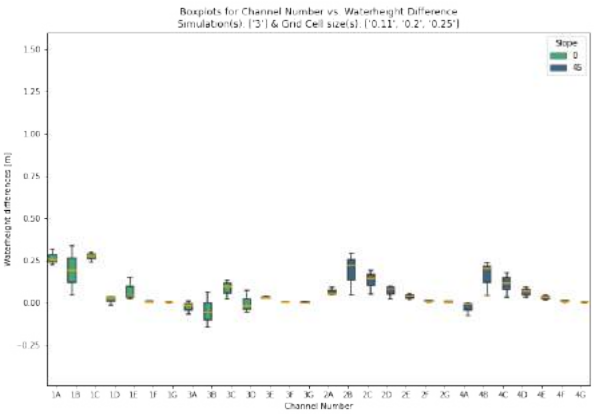

Figure C.17: Boxplot for grid placement results divided per channel and angle. Small grid cell sizes (0.11 to 0.25 meters)

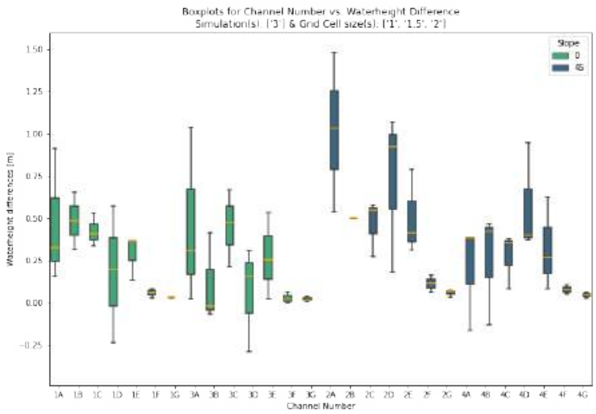

Figure C.18: Boxplot for grid placement results divided per channel and angle. Big grid cell sizes (1 to 2 meters)

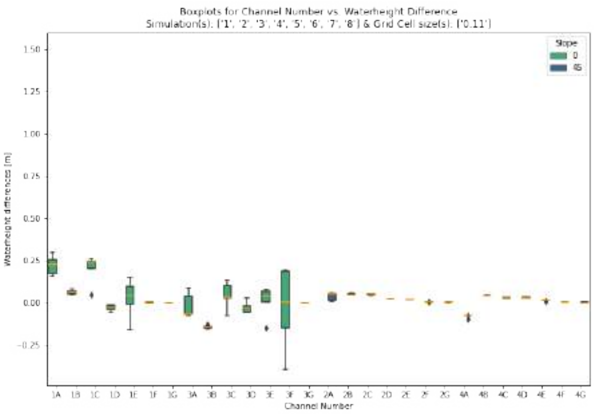

Figure C.19: Boxplot for grid placement results divided per channel and angle. Grid cell size: 0.11 meter

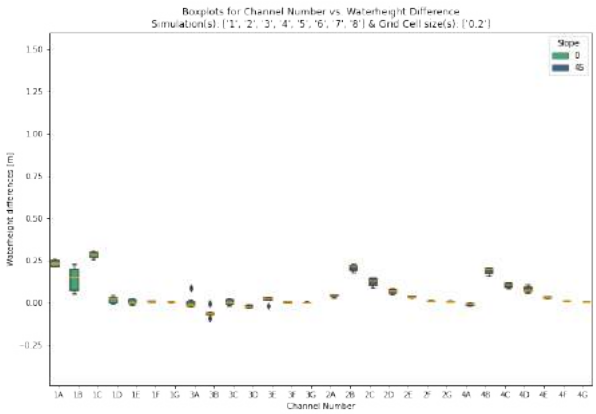

Figure C.20: Boxplot for grid placement results divided per channel and angle. Grid cell size: 0.2 meter

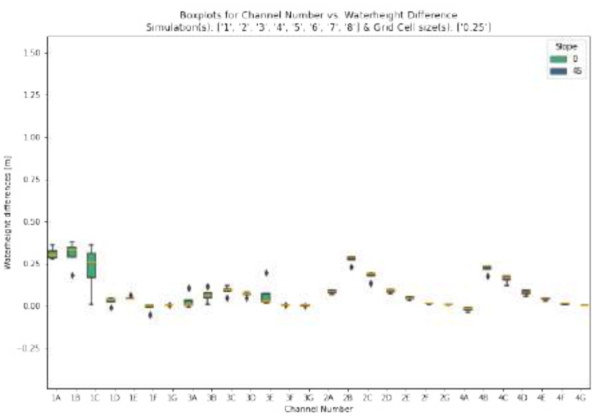

Figure C.21: Boxplot for grid placement results divided per channel and angle. Grid cell size: 0.25 meter

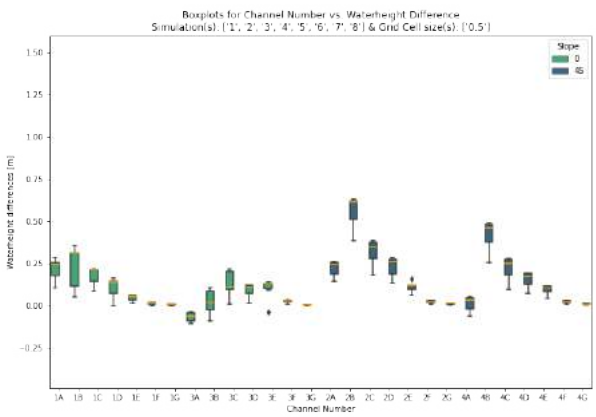

Figure C.22: Boxplot for grid placement results divided per channel and angle. Grid cell size: 0.5 meter

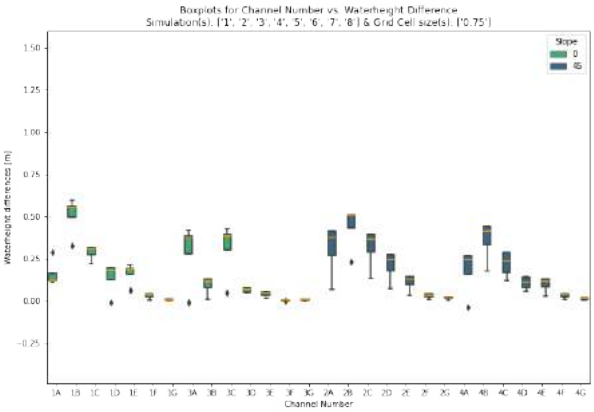

Figure C.23: Boxplot for grid placement results divided per channel and angle. Grid cell size: 0.75 meter

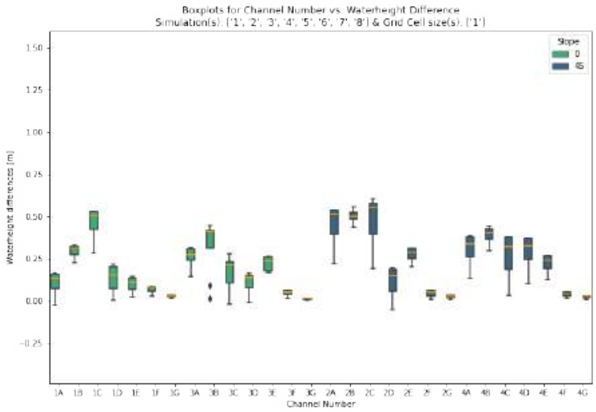

Figure C.24: Boxplot for grid placement results divided per channel and angle. Grid cell size: 1.0 meter

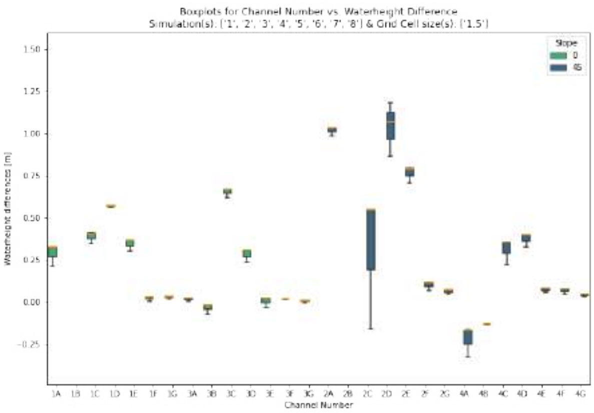

Figure C.25: Boxplot for grid placement results divided per channel and angle. Grid cell size: 1.5 meter

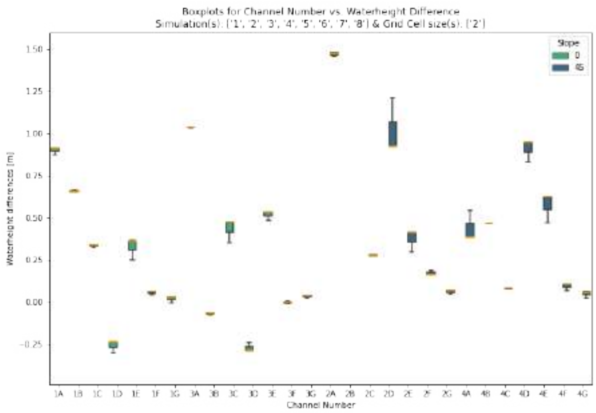

Figure C.26: Boxplot for grid placement results divided per channel and angle. Grid cell size: 2.0 meter

D

Design of cross sections Lage Raam

In this appendix the sesign of the cross sections in the lage raam are shown:

Profielen deelgebied 1-2

Schaal 1:200

Bestaand gemeten profiel

Profiel AHN (indicatief)

Nieuw profiel

Hoogwaterniveau

Waterpeil

Kadastrale grens

Hoogtematen in m NAP

6.0	Aanpassingen profielen na externe review	12-10-2023
5.0	Aanpassingen profielen 0.2, 1.9 en 4.6	15-09-2023
4.0	Aanpassingen profiel 2.4A	23-06-2023
3.0	2e review en aanvullingen	24-05-2023
2.0	Externe review	21-04-2023
1.0	Definitief	29-03-2023

Uitwerking Gebiedsplan de Raam

DO Lage Raam
Profielen Tongelaar- Hoevensedijk - Achter-dijk

Waterschap Aa en Maas

TAUW

Get.:	Formaat:	Afmeting:	Status:	Datum:	Versie:
Johan de Putter	A0	1189x841 mm	Definitief	12-10-2023	6.0

Figure D.1: Information and legend of cross sections Lage raam

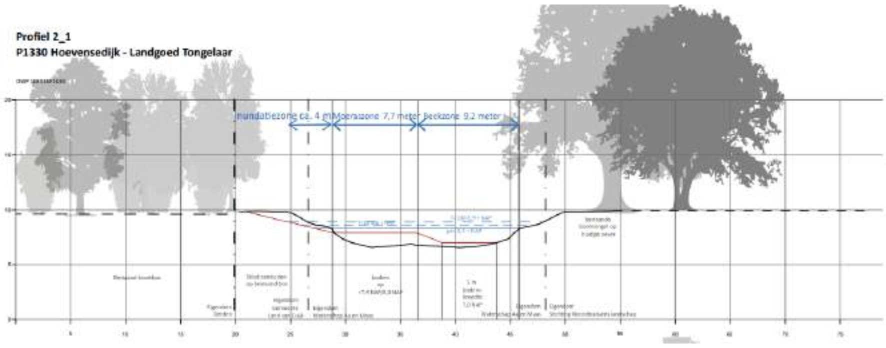

Figure D.2: Cross section Lage raam - Section 1

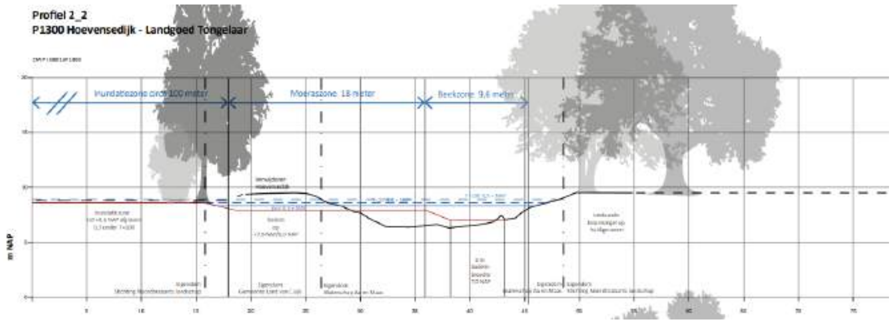

Figure D.3: Cross section Lage raam - Section 2

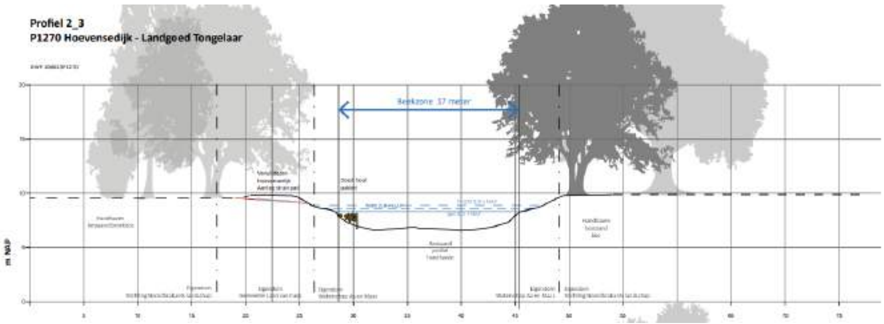

Figure D.4: Cross section Lage raam - Section 3

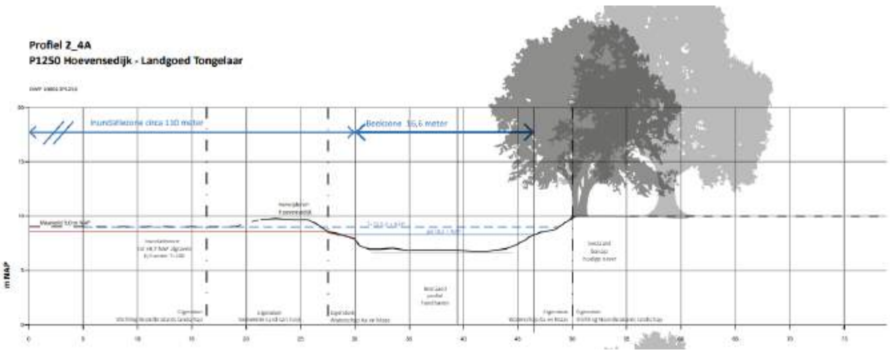

Figure D.5: Cross section Lage raam - Section 4

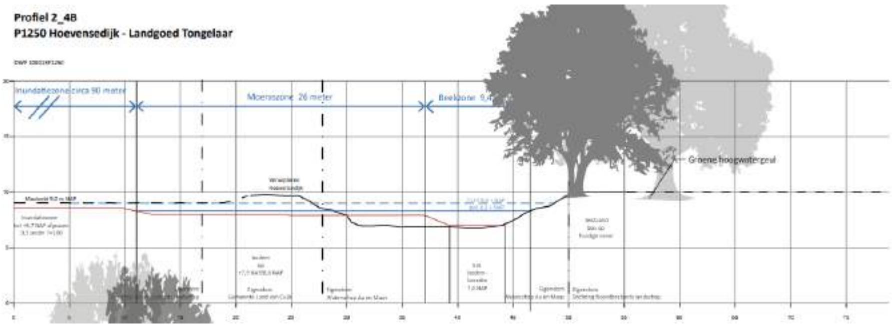

Figure D.6: Cross section Lage raam - Section 4b

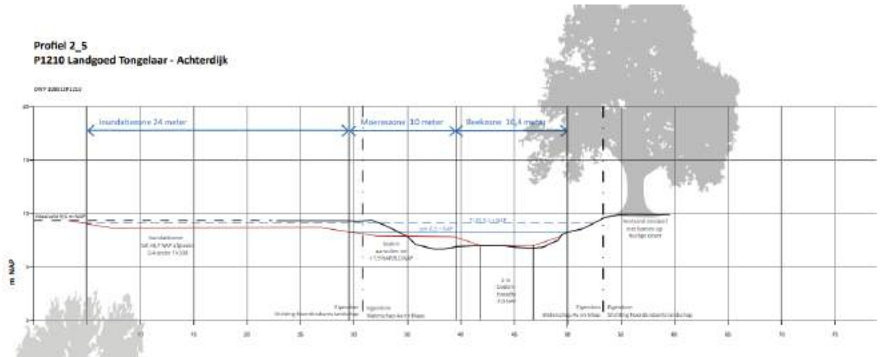

Figure D.7: Cross section Lage raam - Section 5

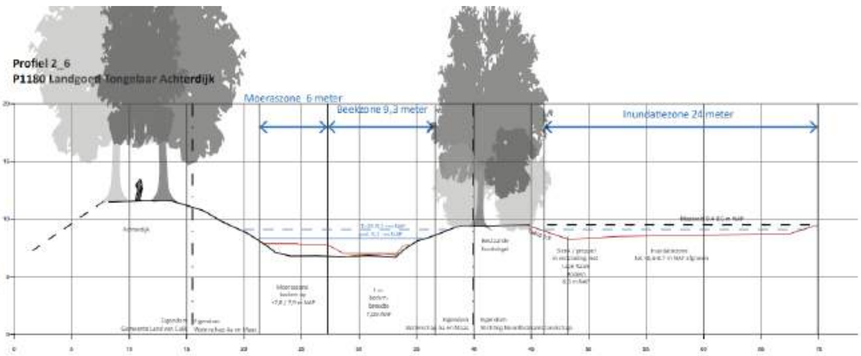

Figure D.8: Cross section Lage raam - Section 6

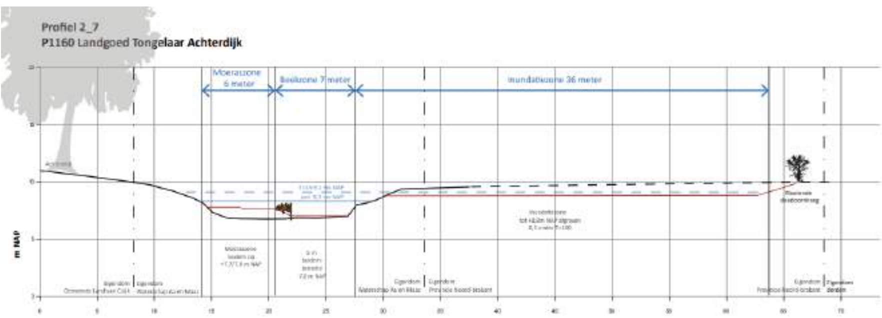

Figure D.9: Cross section Lage raam - Section 7

E
Results Raamvallei Case

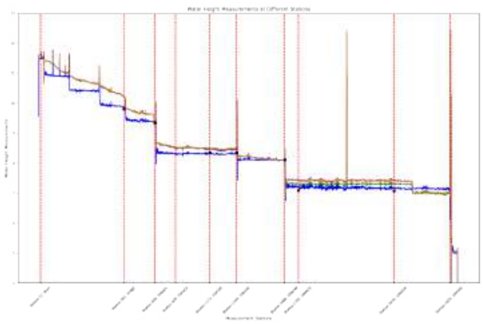

Figure E.1: Tygron Versus MEasured Data Oktober 2019 grid cell size: 1m

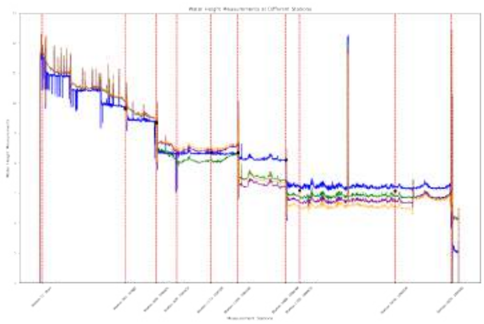

Figure E.2: Tygron Versus MEasured Data Oktober 2019 grid cell size: 2m

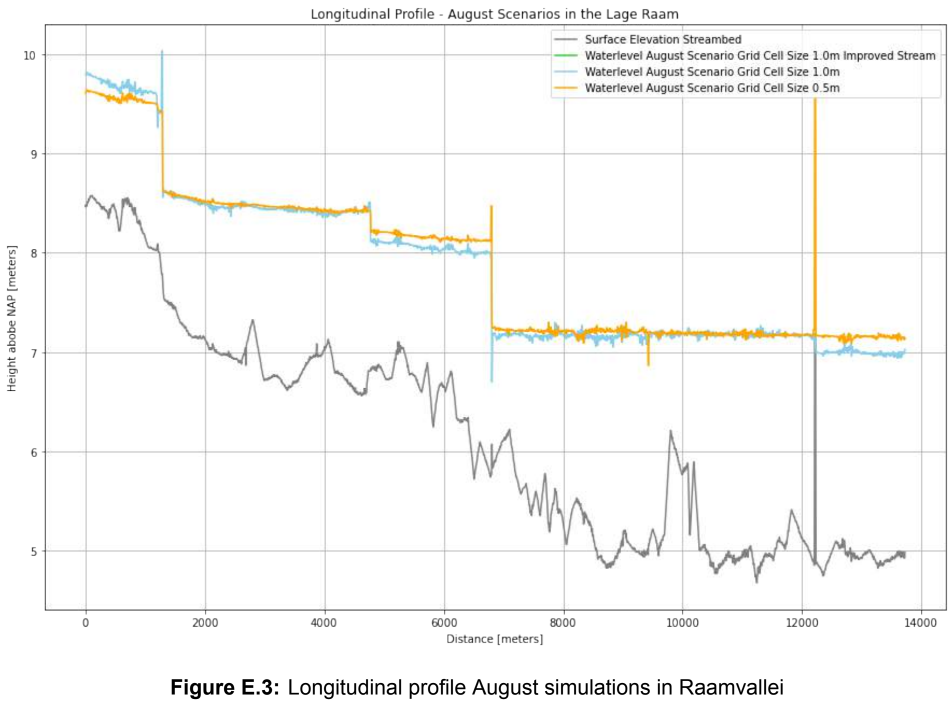

Figure E.3: Longitudinal profile August simulations in Raamvallei

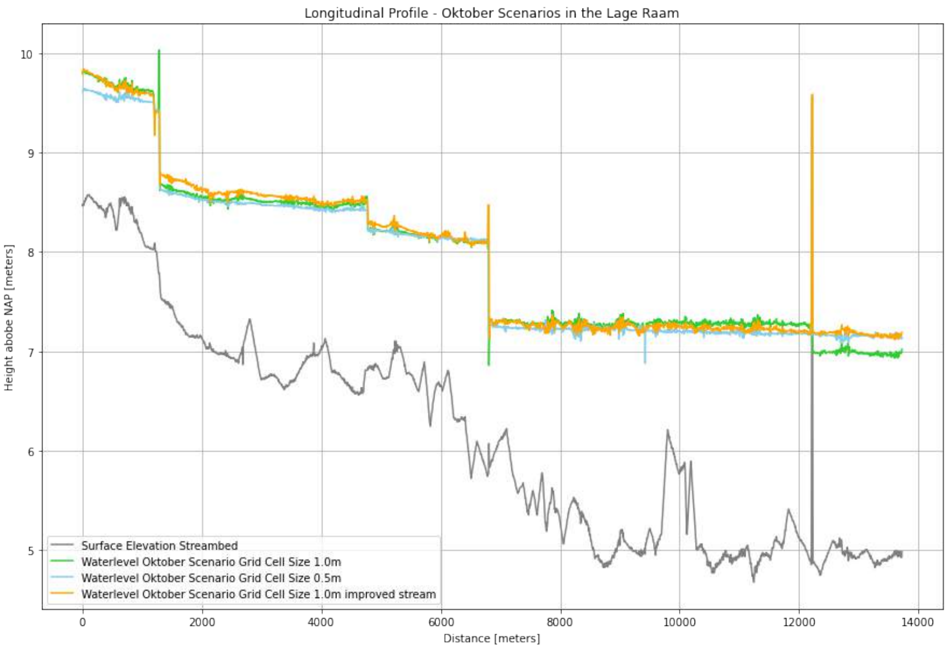

Figure E.4: Longitudinal profile Oktober simulations in Raamvallei

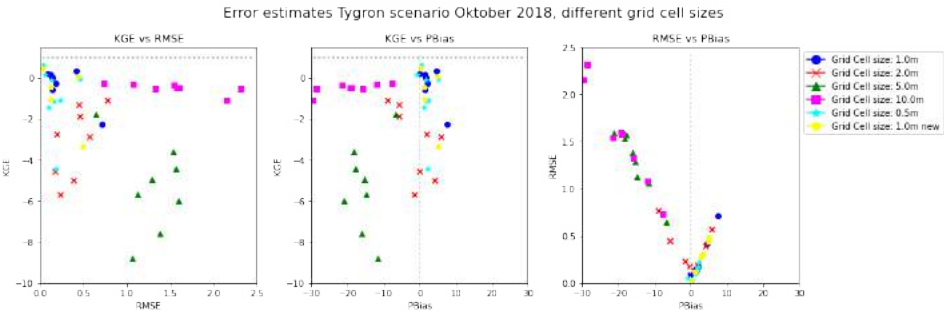

Figure E.5: Estimate error for Oktober 2018 scenario together after validation of the model, each simulation run with different grid cell sizes (gr)

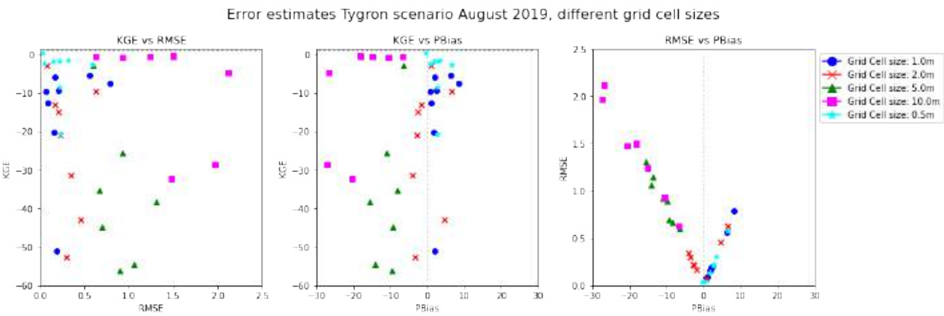

Figure E.6: Estimate error for August 2019 scenario together after validation of the model, each simulation run with different grid cell sizes (gr)

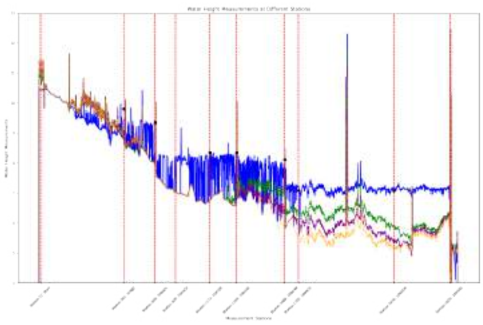

Figure E.7: Tygron Versus MEasured Data Oktober 2019 grid cell size: 5m

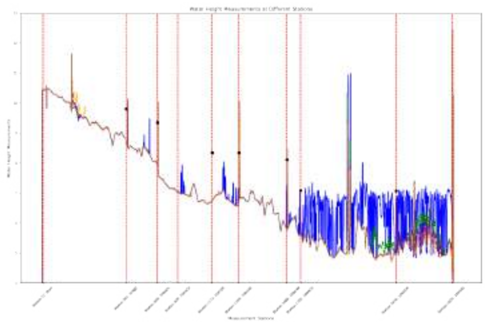

Figure E.8: Tygron Versus MEasured Data Oktober 2019 grid cell size: 10m

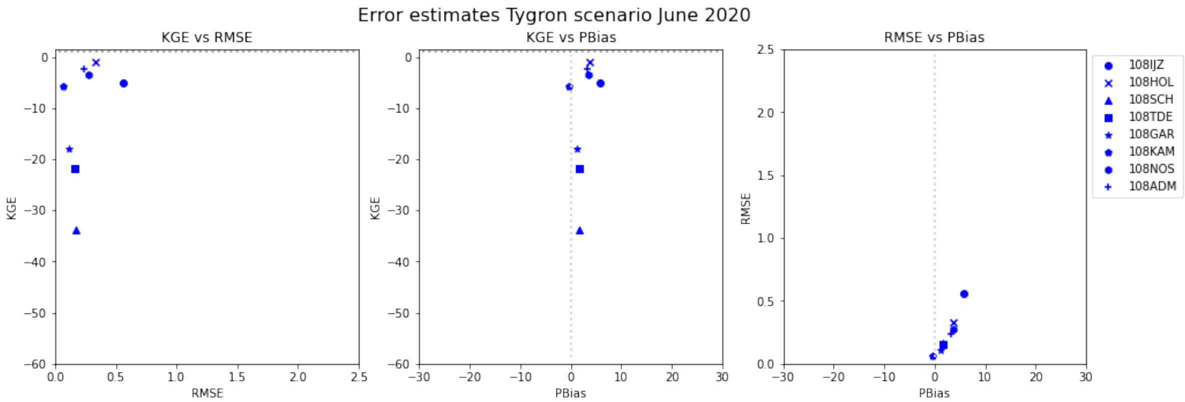

Figure E.9: Error estimates June grid cell size 1m

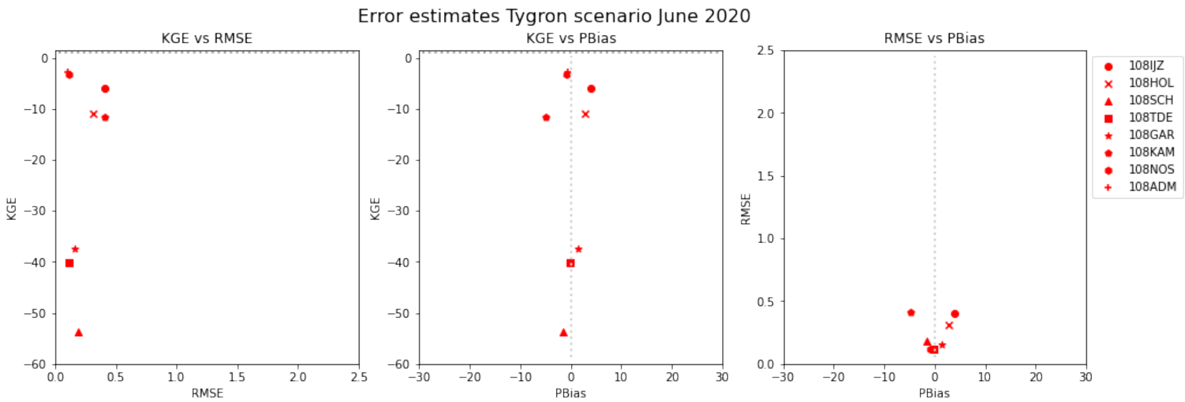

Figure E.10: Error estimates June grid cell size 2m

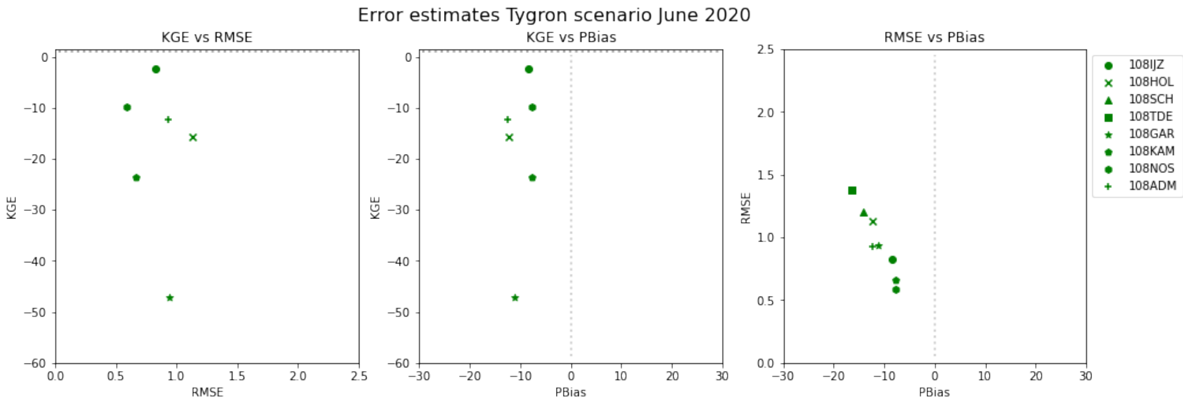

Figure E.11: Error estimates June grid cell size 5m

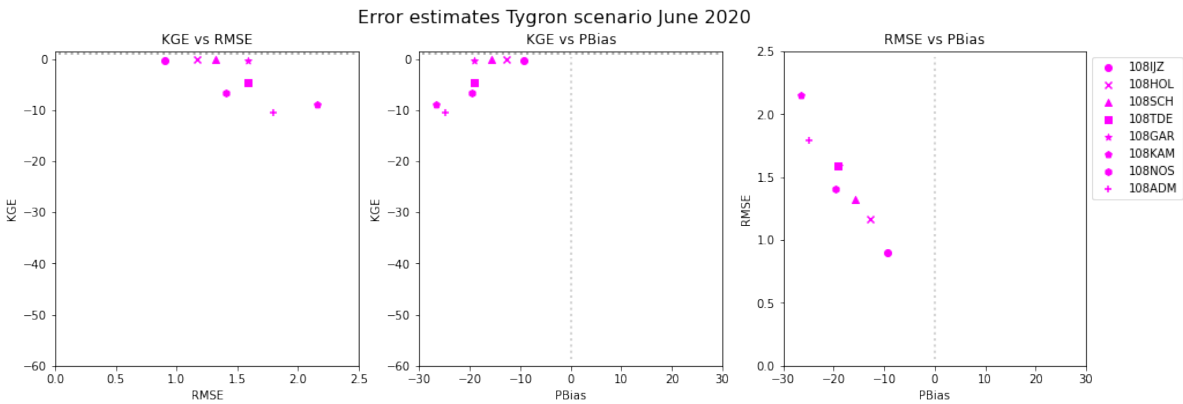

Figure E.12: Error estimates June grid cell size 10m

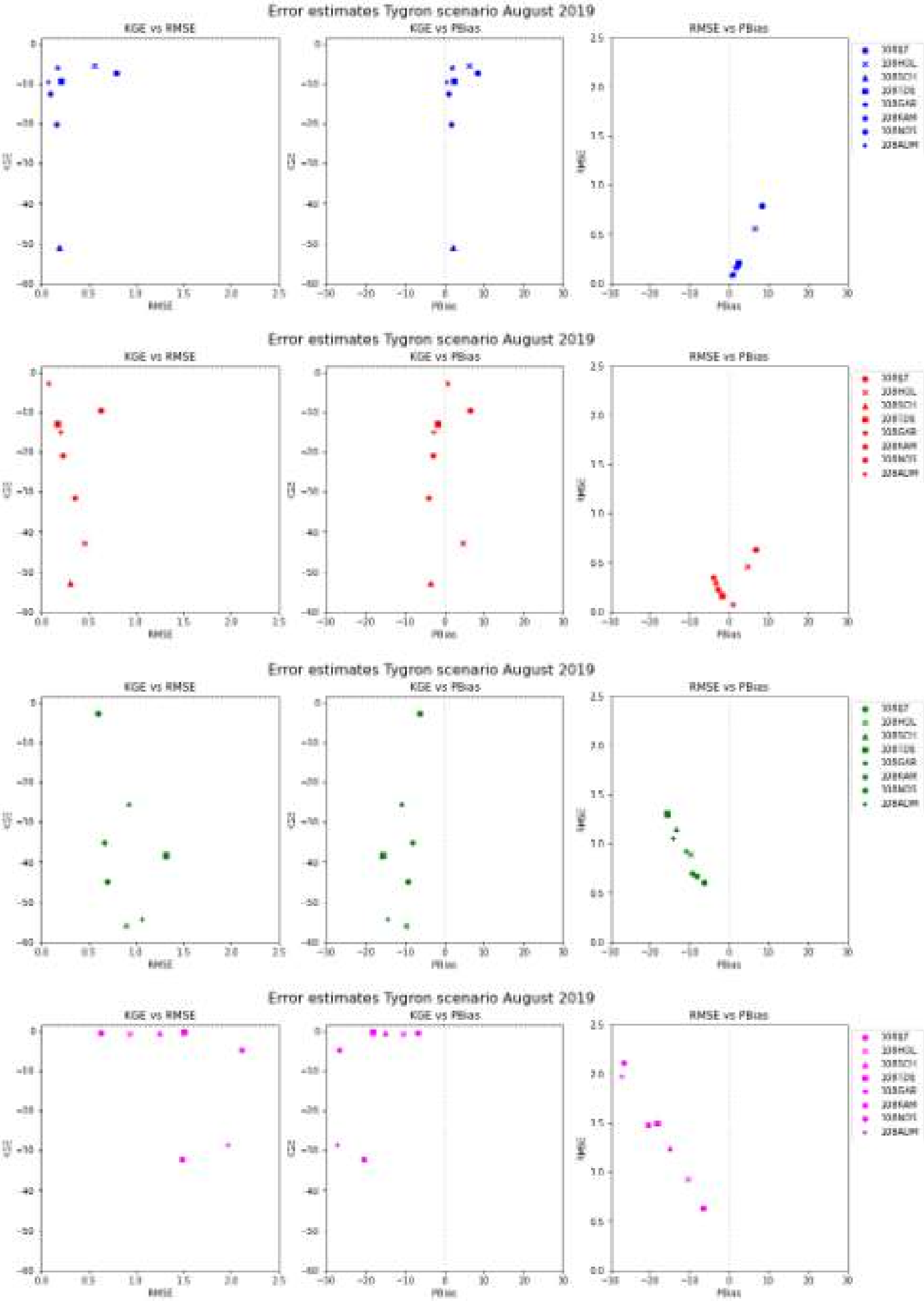

Figure E.13: CLoud subplots augustus 2019

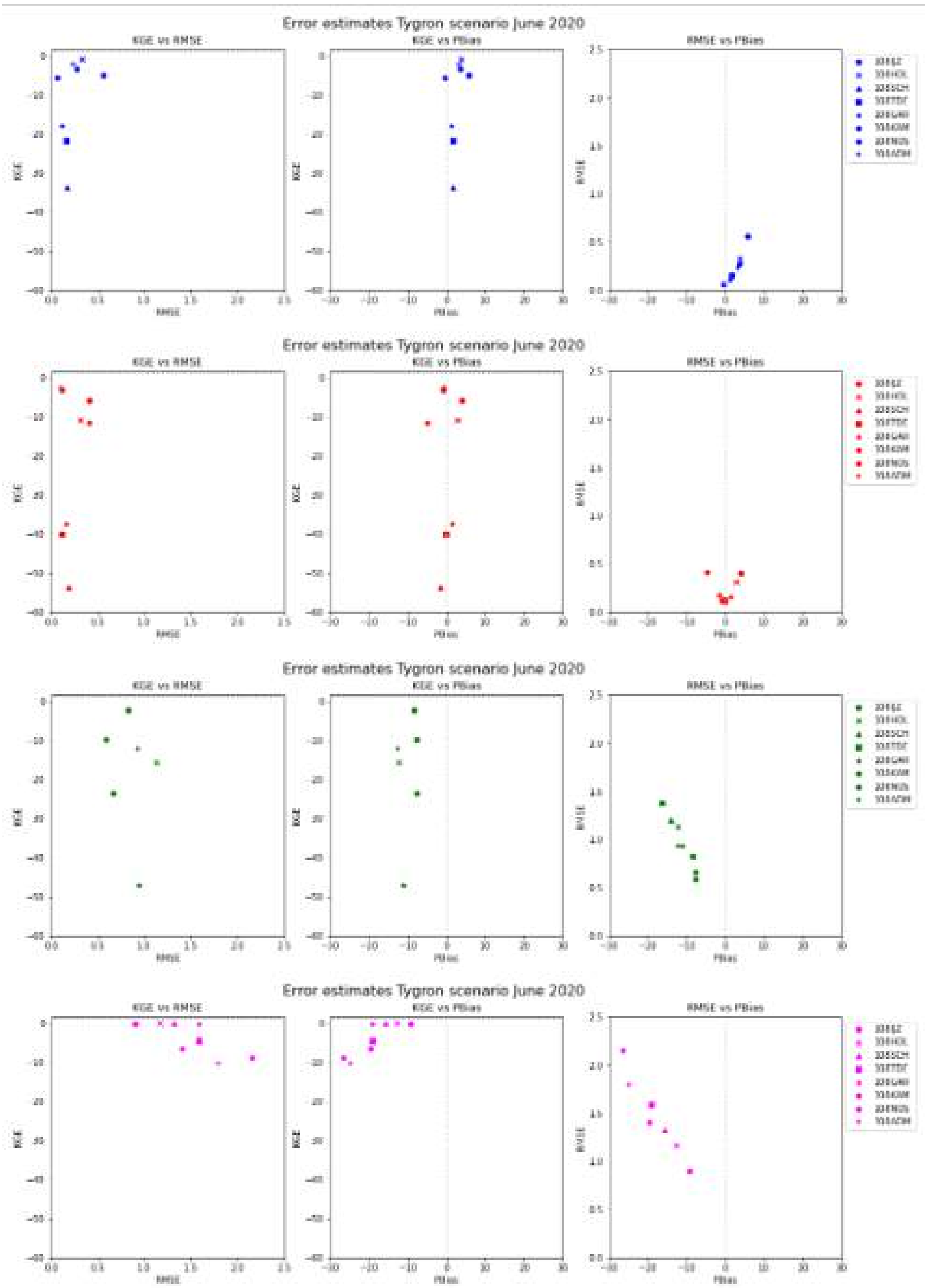

Figure E.14: CLoud subplots june 2020

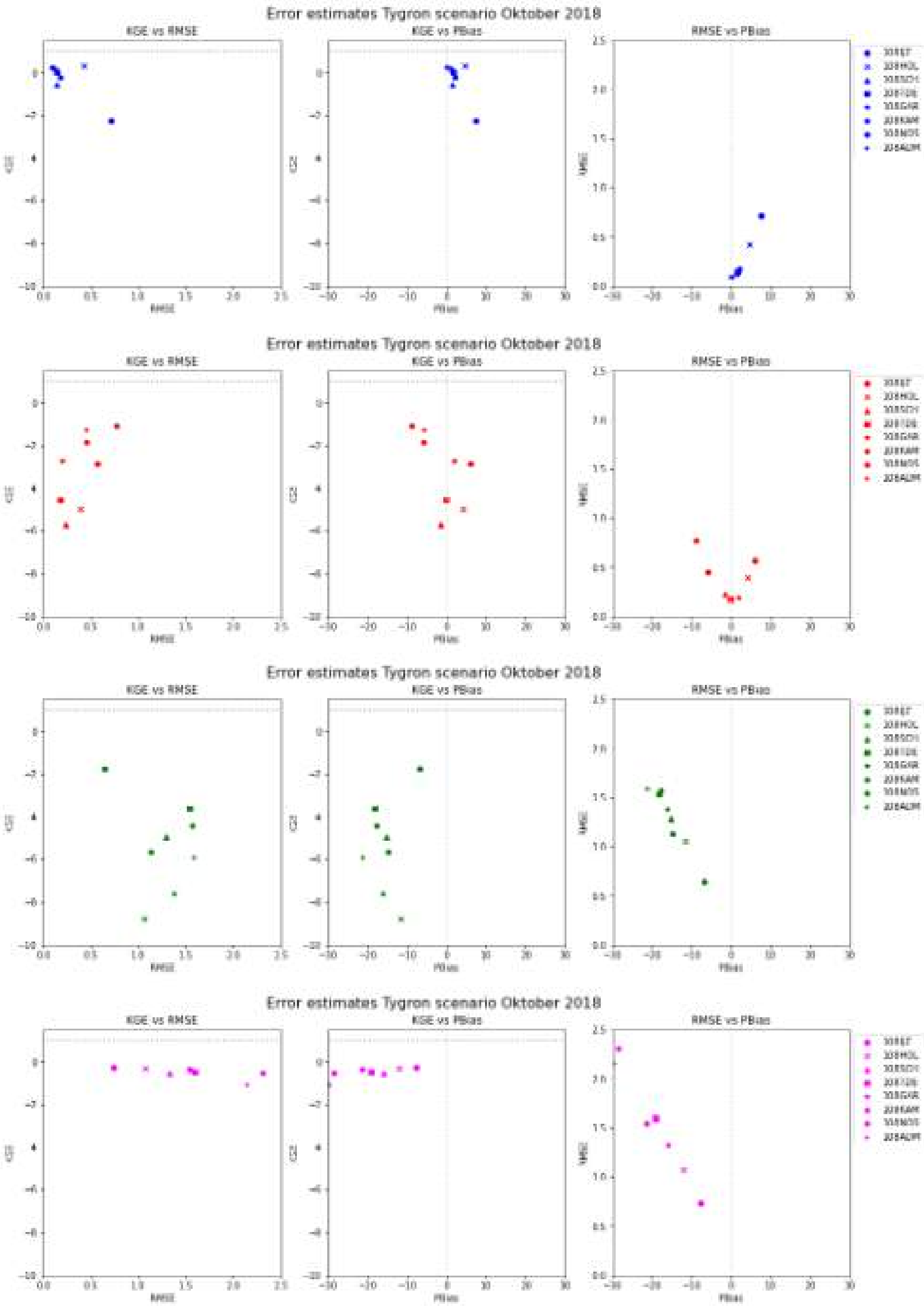

Figure E.15: CLoud subplots oktober 2018

F

Results Stream Restoration Case

As explained in chapter 10.2, the results for each cross section of the Stream Restoration case are presented in this appendix. Below all results of each section. On the left is the old situation, and on the right is the new situation after stream restoration design is implemented. Each row is a different scenario are shown with the corresponding scenarios from chapter 9.3.

- Standard situation, with upstream boundary conditions and no rainfall
- discharge situation with upstream rainfall event of T>1X25 years
- T => 1x1 year event using a uniform rainfall pattern and using a 1 peak pattern.
- T => 1x100 year event using a uniform rainfall pattern and using a 1 peak pattern.

F.1. Cross sections for Section 1

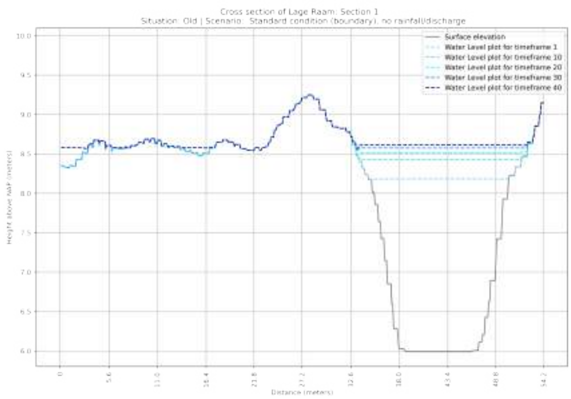

Figure F.1: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: Standard situation

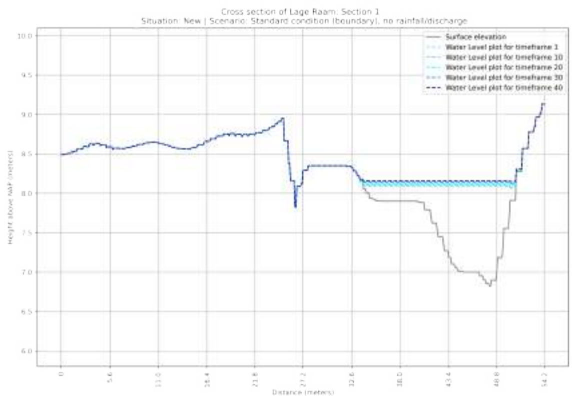

Figure F.2: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: Standard situation

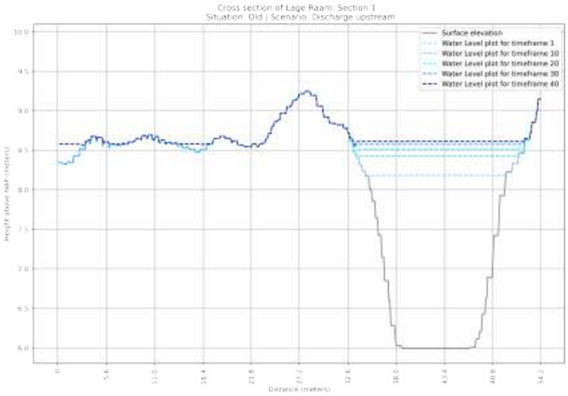

Figure F.3: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: Discharge T > 1X25 year

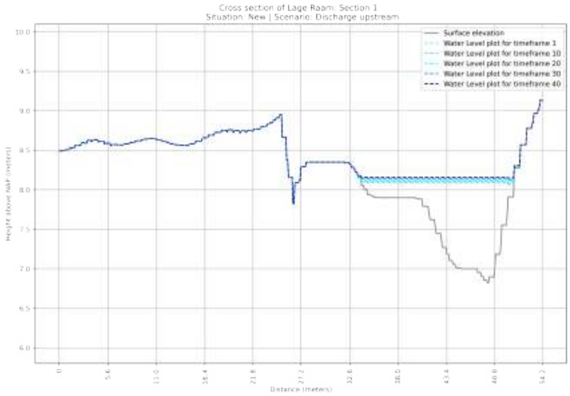

Figure F.4: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: Discharge T > 1X25 year

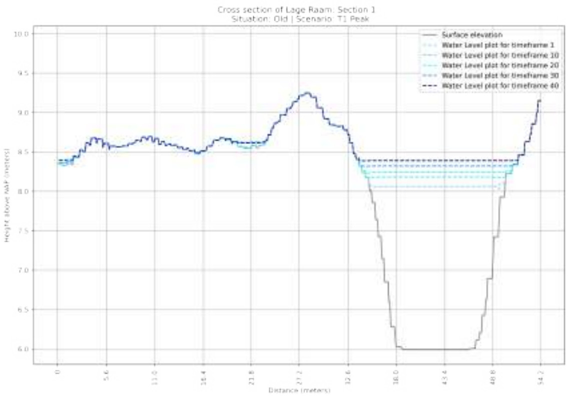

Figure F.5: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

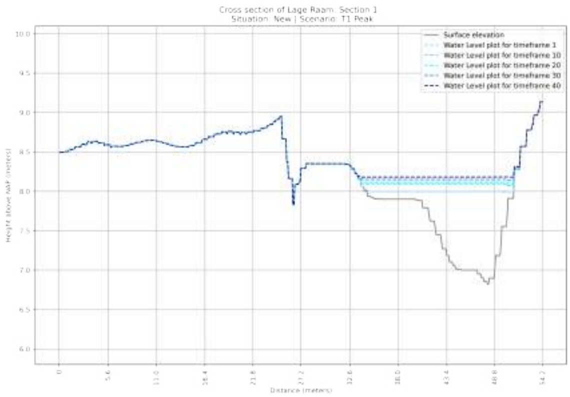

Figure F.6: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

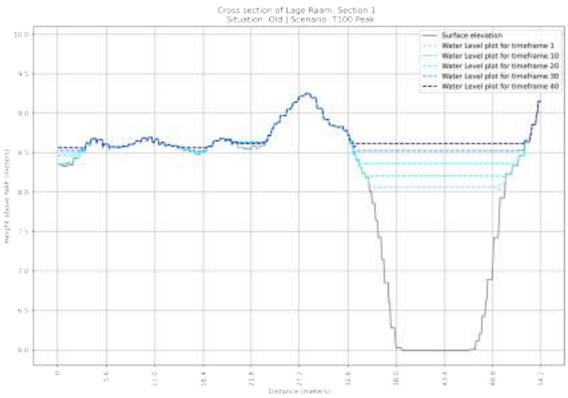

Figure F.7: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

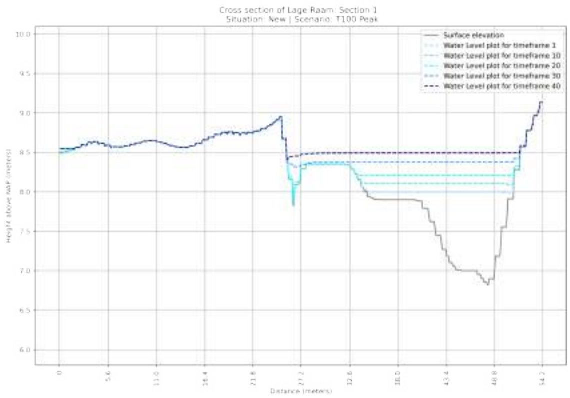

Figure F.8: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

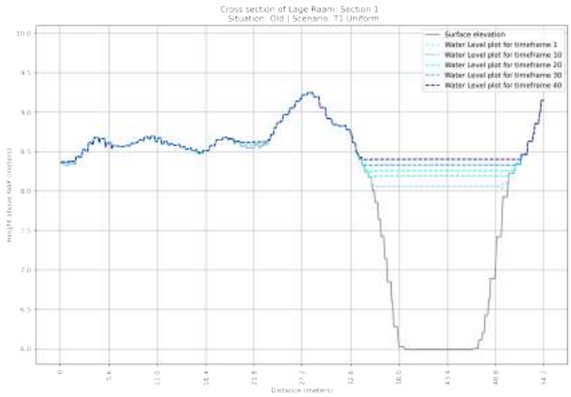

Figure F.9: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

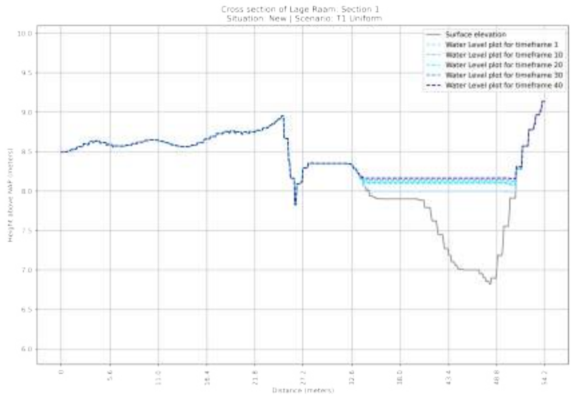

Figure F.10: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

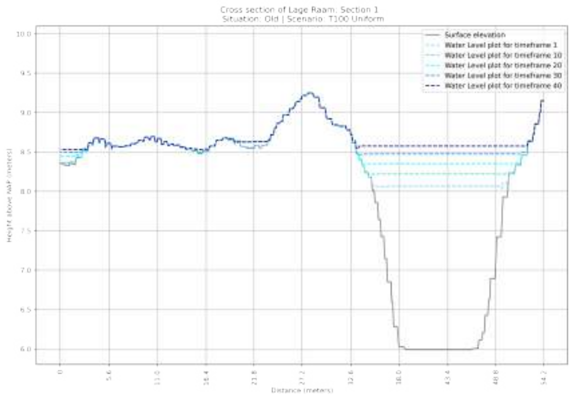

Figure F.11: Cross section of the OLD situation of section 1 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

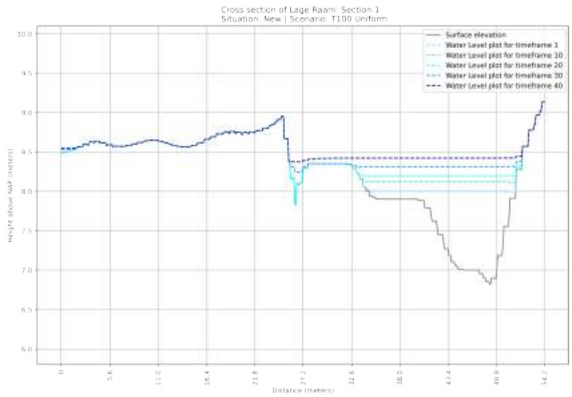

Figure F.12: Cross section of the NEW situation of section 1 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.2. Cross sections for Section 2

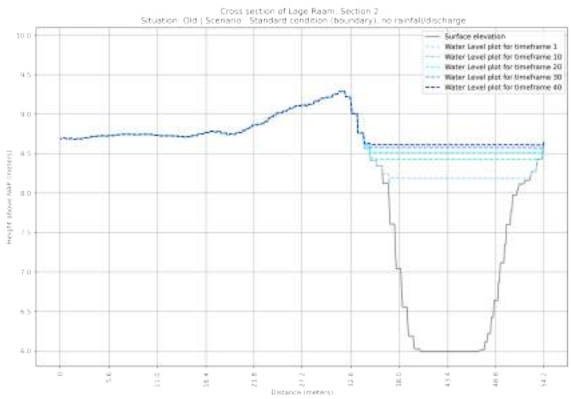

Figure F.13: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: Standard situation

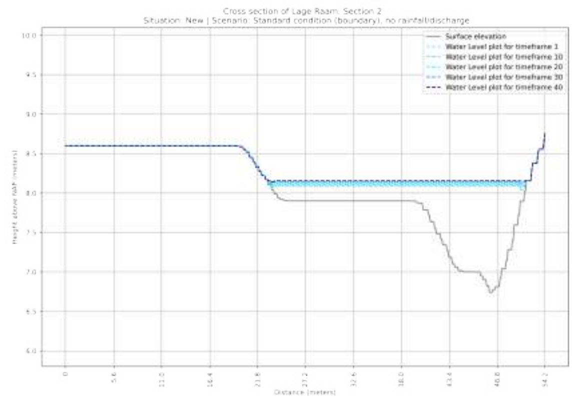

Figure F.14: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: Standard situation

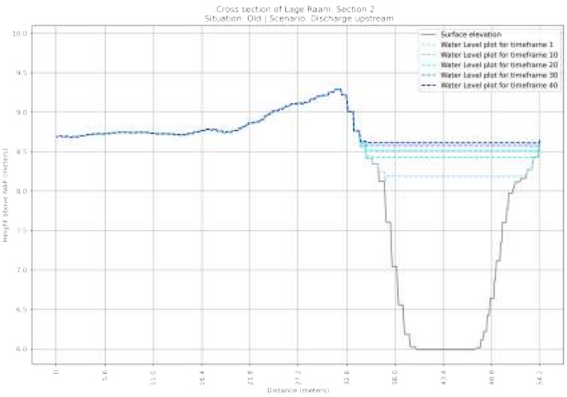

Figure F.15: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: Discharge T > 1X25 year

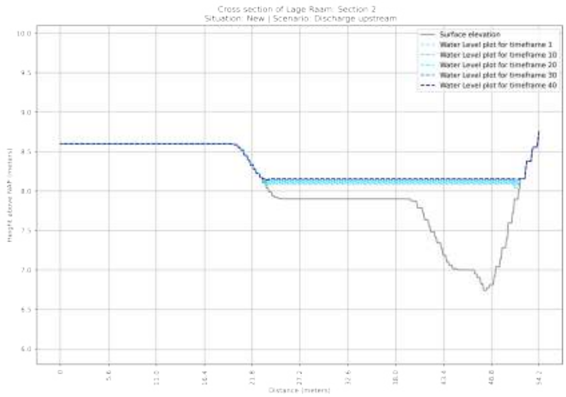

Figure F.16: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: Discharge T > 1X25 year

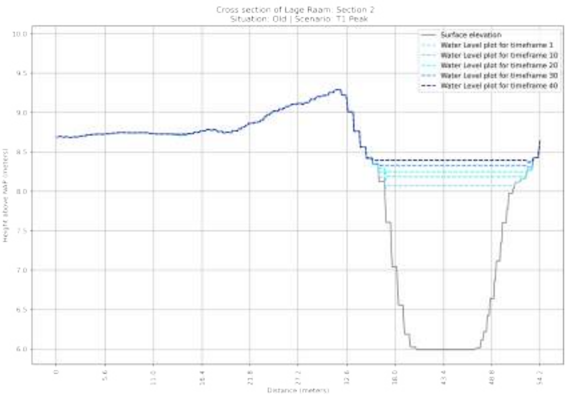

Figure F.17: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

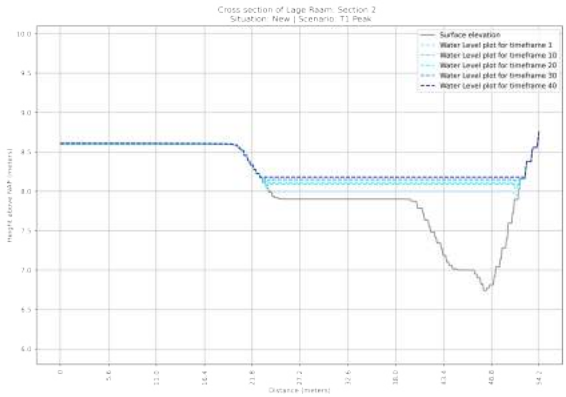

Figure F.18: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

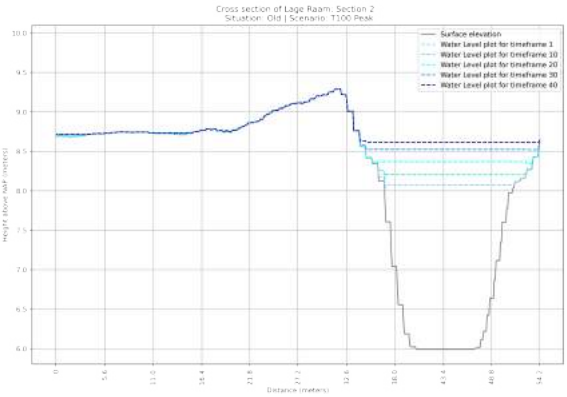

Figure F.19: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

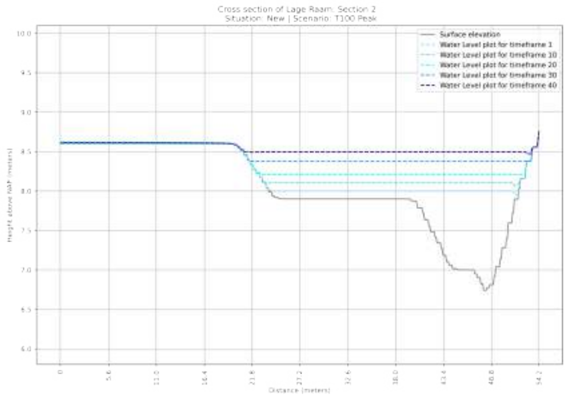

Figure F.20: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

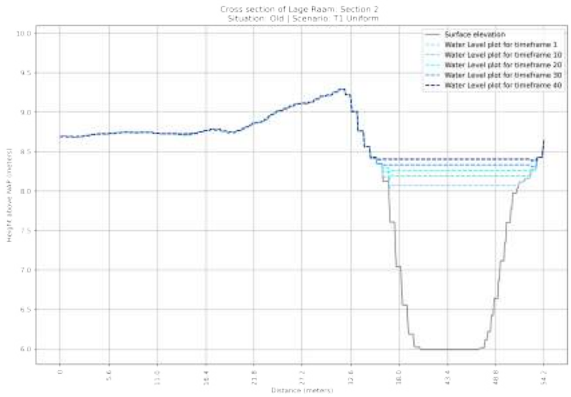

Figure F.21: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

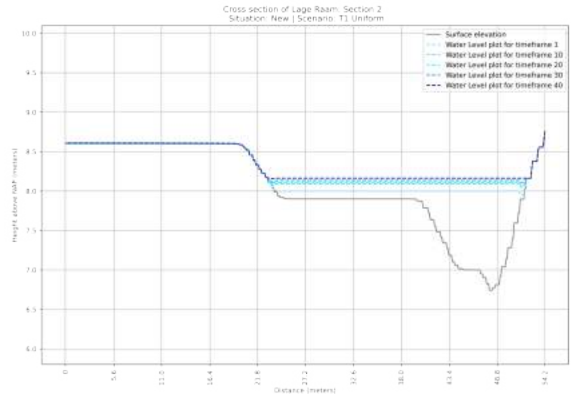

Figure F.22: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

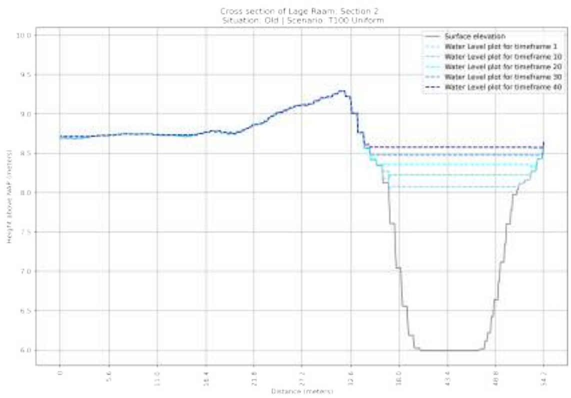

Figure F.23: Cross section of the OLD situation of section 2 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

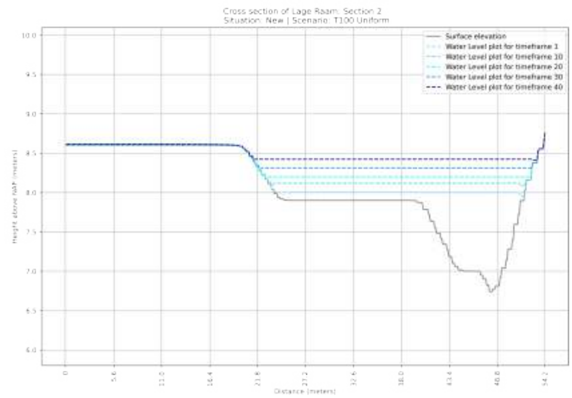

Figure F.24: Cross section of the NEW situation of section 2 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.3. Cross sections for Section 3

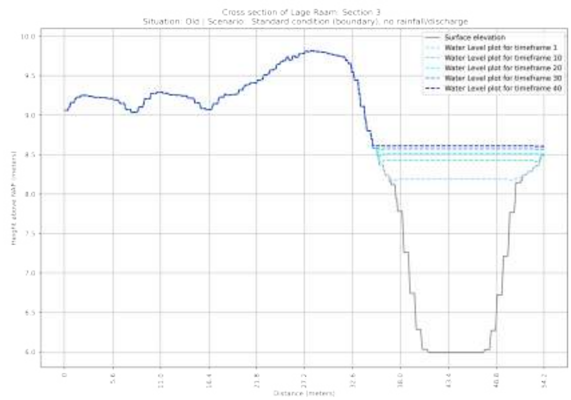

Figure F.25: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: Standard situation

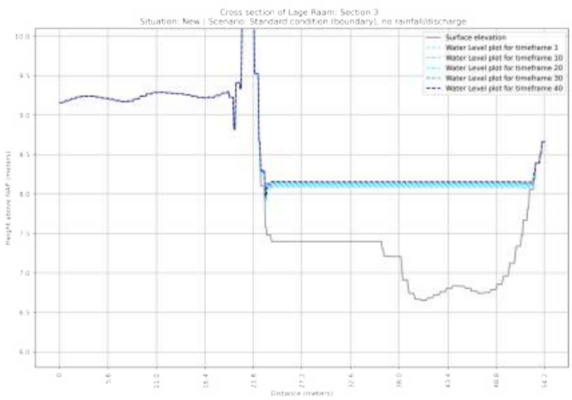

Figure F.26: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: Standard situation

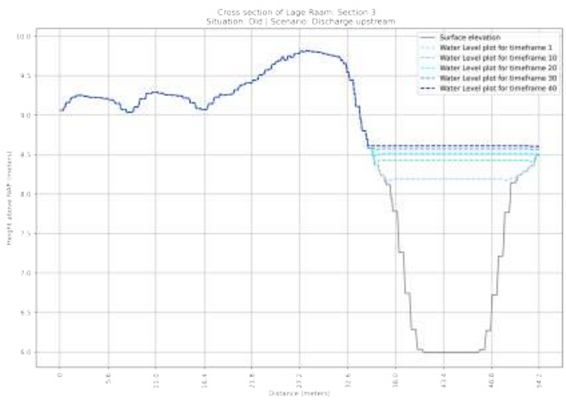

Figure F.27: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: Discharge T > 1X25 year

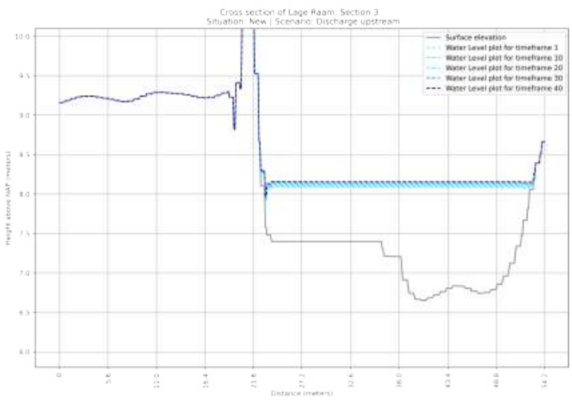

Figure F.28: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: Discharge T > 1X25 year

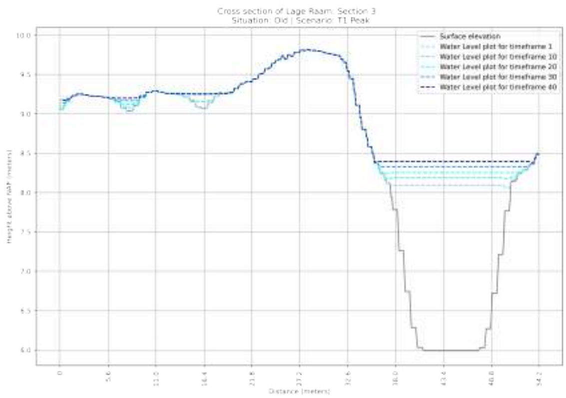

Figure F.29: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

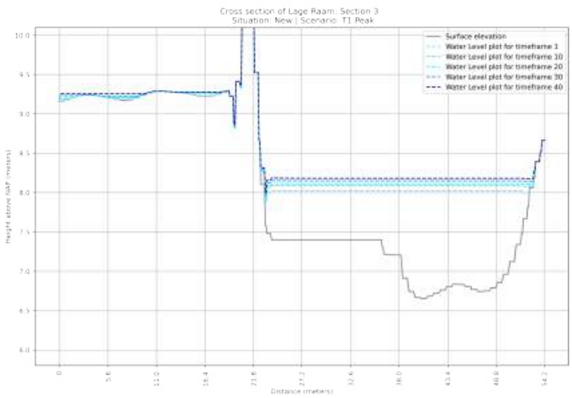

Figure F.30: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

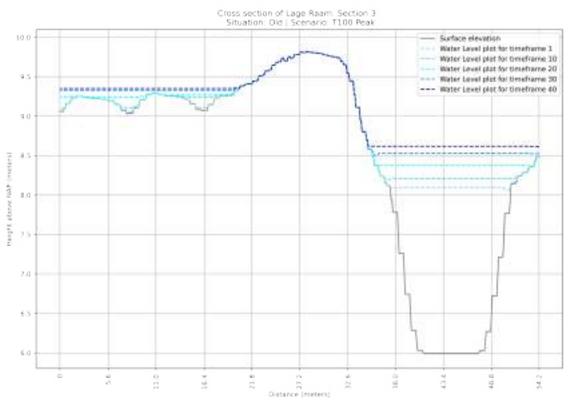

Figure F.31: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

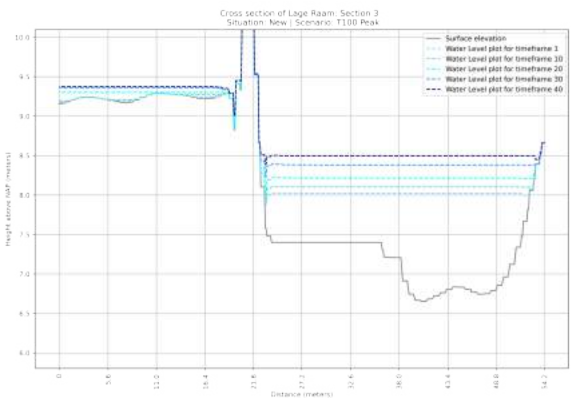

Figure F.32: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

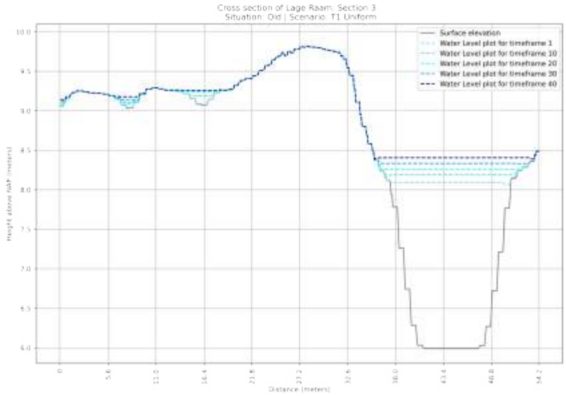

Figure F.33: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

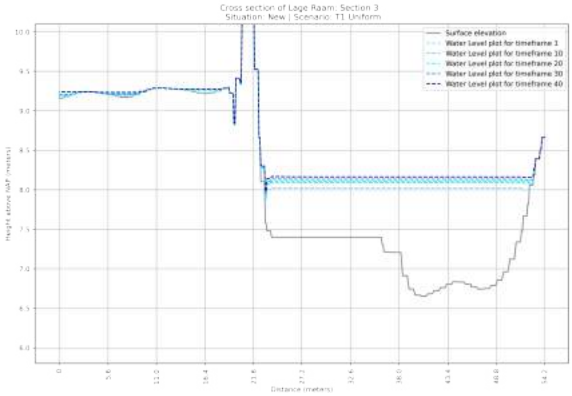

Figure F.34: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

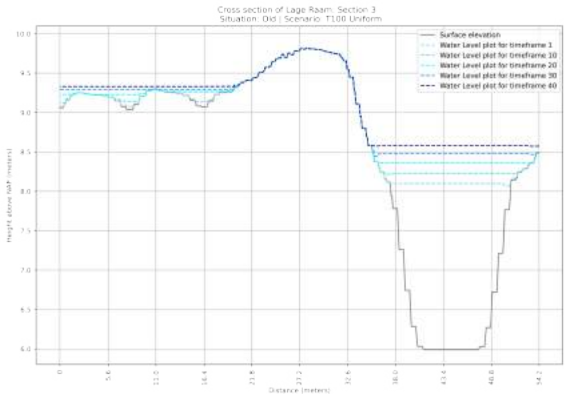

Figure F.35: Cross section of the OLD situation of section 3 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

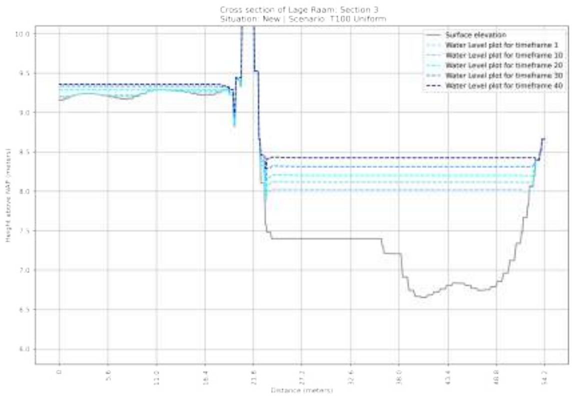

Figure F.36: Cross section of the NEW situation of section 3 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.4. Cross sections for Section 4

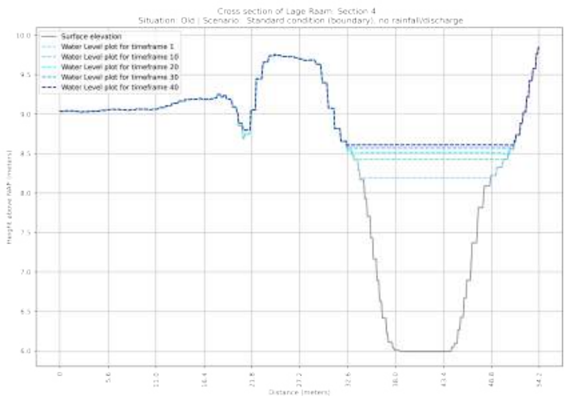

Figure F.37: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: Standard situation

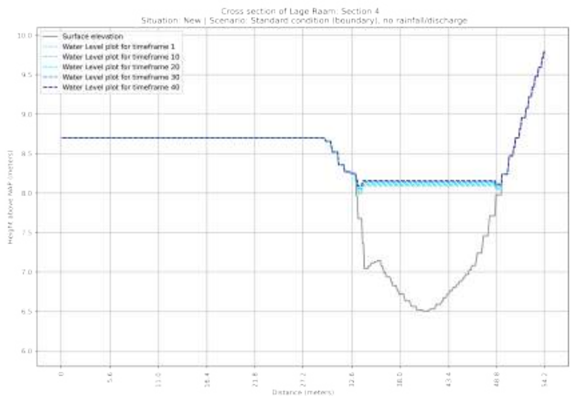

Figure F.38: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: Standard situation

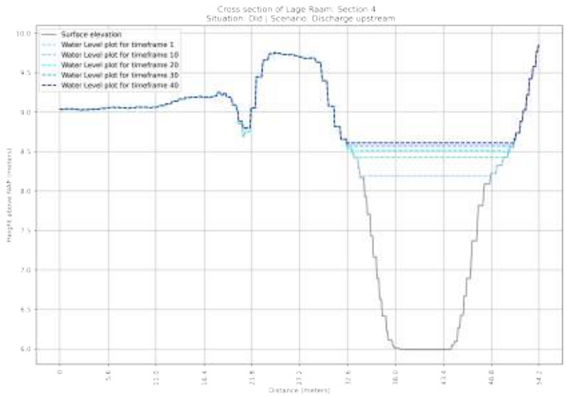

Figure F.39: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: Discharge T > 1X25 year

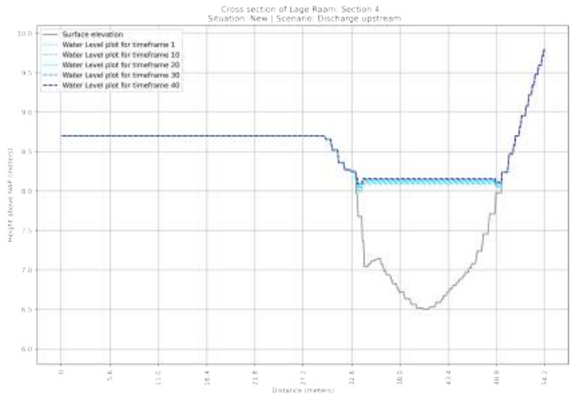

Figure F.40: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: Discharge T > 1X25 year

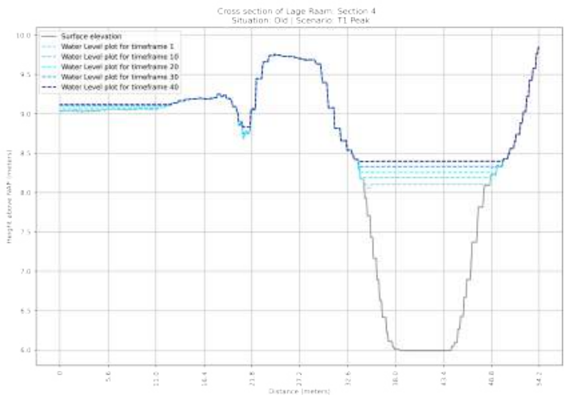

Figure F.41: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

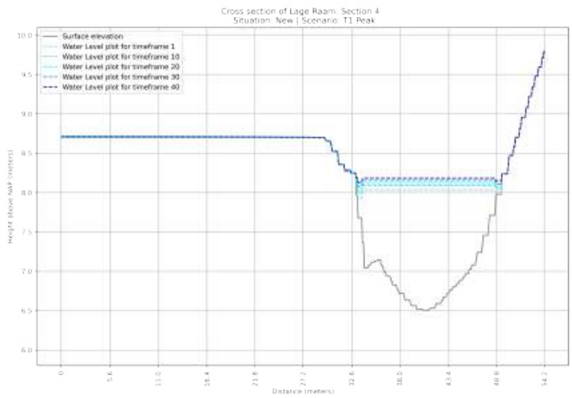

Figure F.42: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

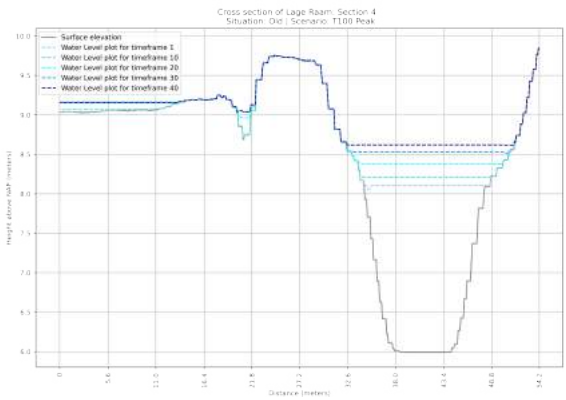

Figure F.43: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

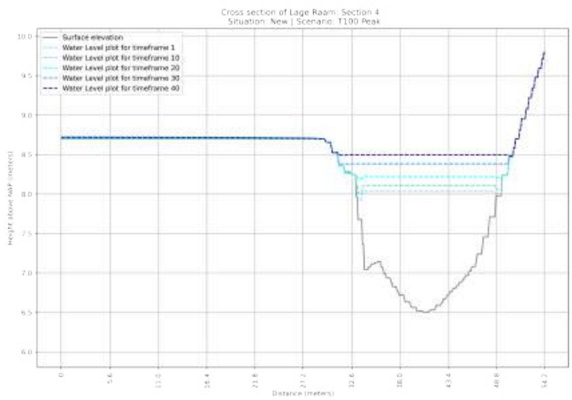

Figure F.44: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

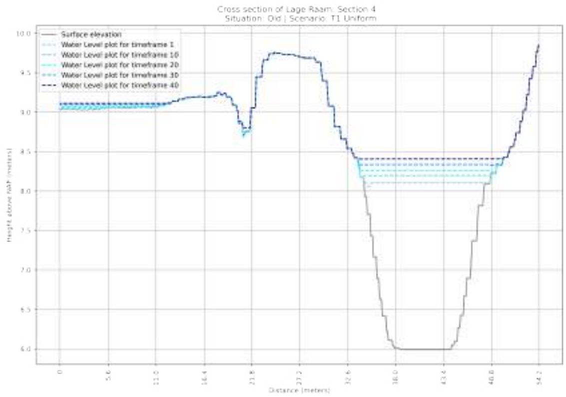

Figure F.45: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

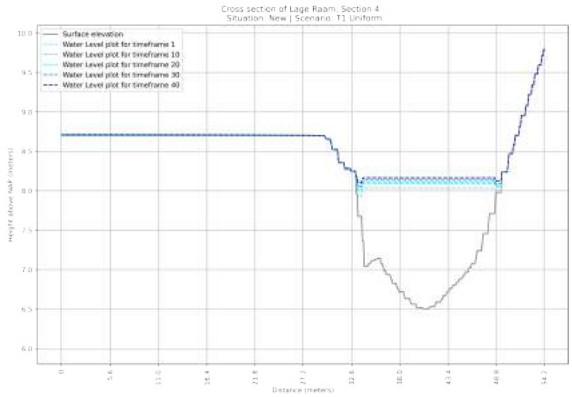

Figure F.46: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

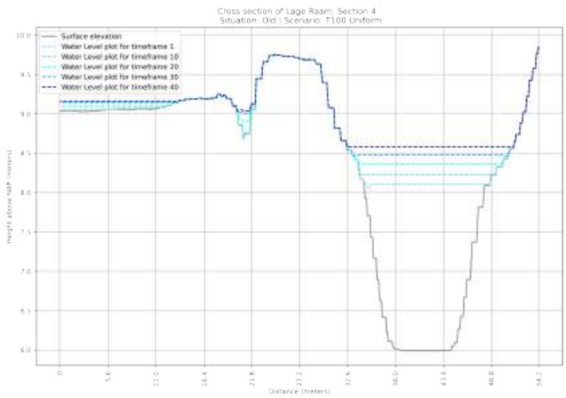

Figure F.47: Cross section of the OLD situation of section 4 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

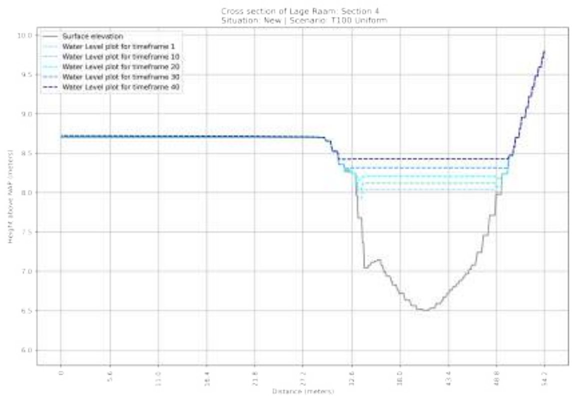

Figure F.48: Cross section of the NEW situation of section 4 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.5. Cross sections for Section 4b

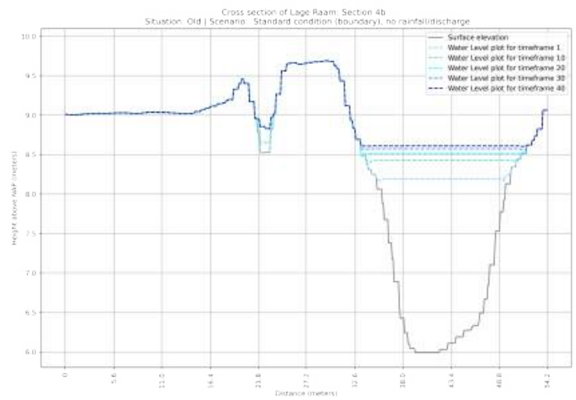

Figure F.49: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: Standard situation

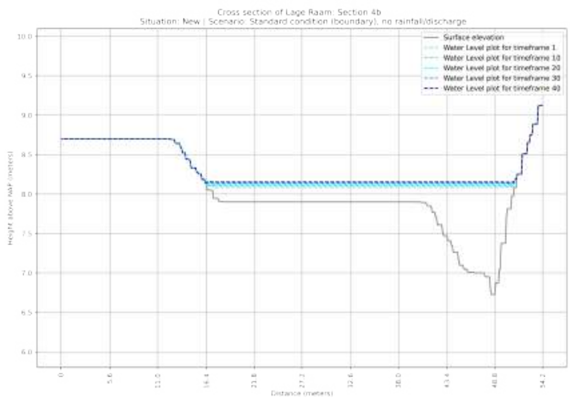

Figure F.50: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: Standard situation

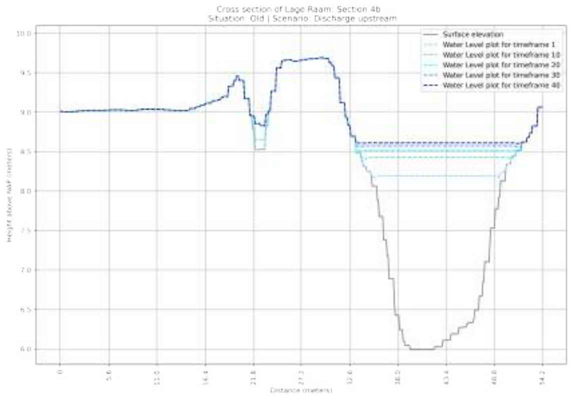

Figure F.51: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: Discharge T > 1X25 year

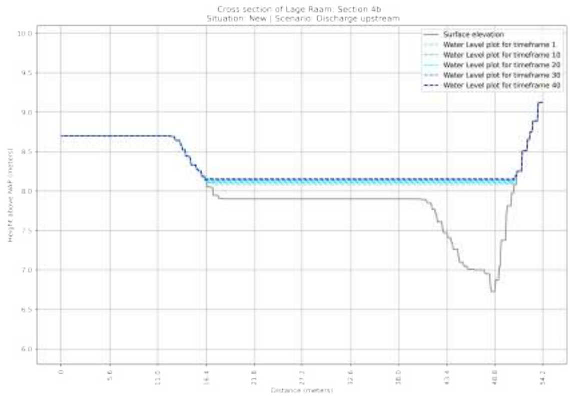

Figure F.52: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: Discharge T > 1X25 year

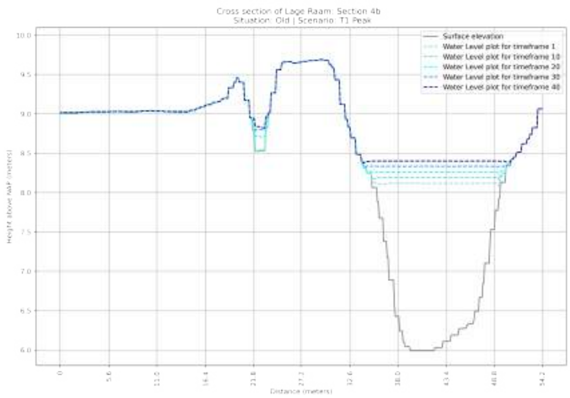

Figure F.53: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

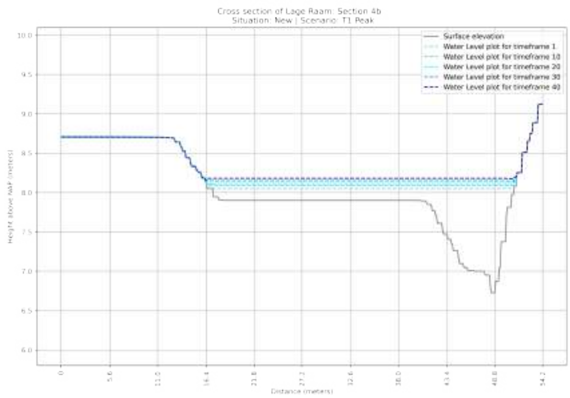

Figure F.54: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

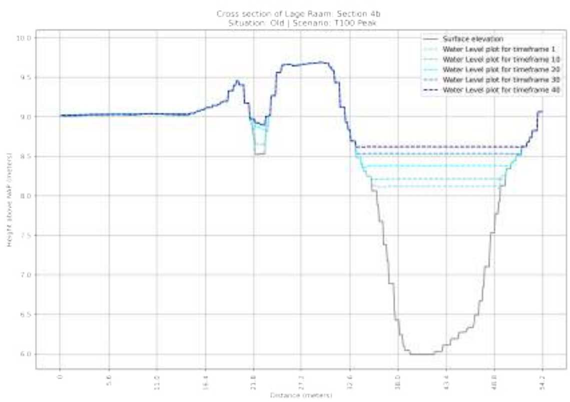

Figure F.55: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

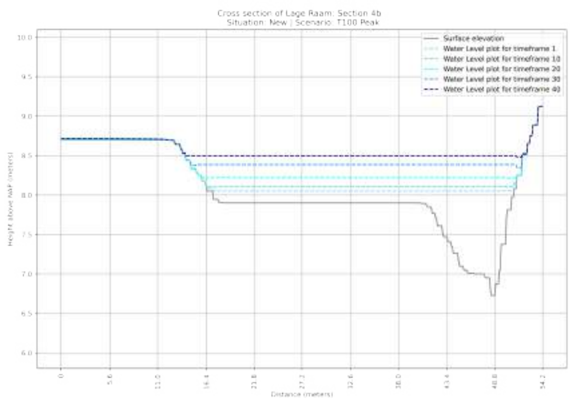

Figure F.56: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

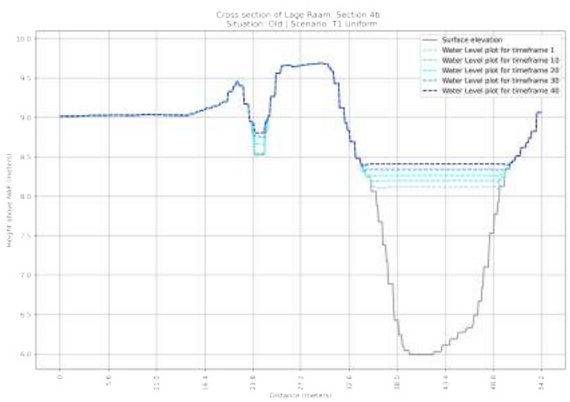

Figure F.57: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

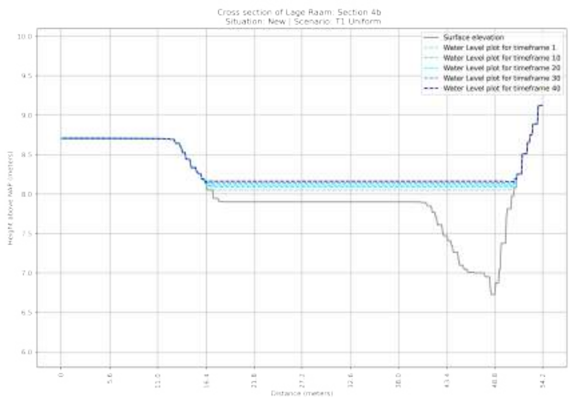

Figure F.58: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

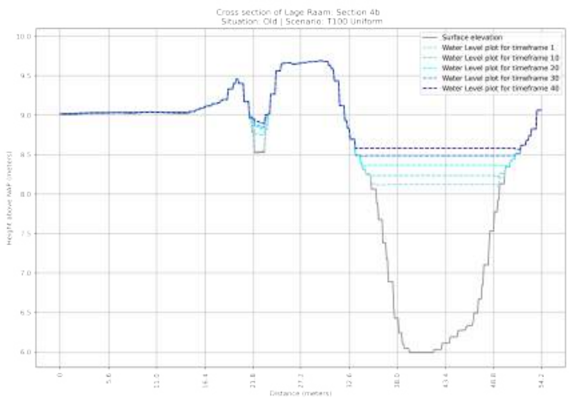

Figure F.59: Cross section of the OLD situation of section 4b in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

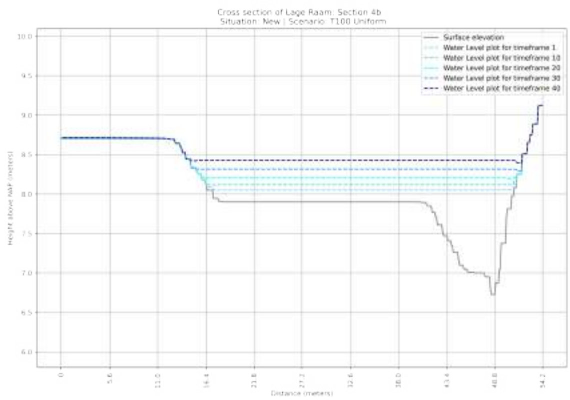

Figure F.60: Cross section of the NEW situation of section 4b in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.6. Cross sections for Section 5

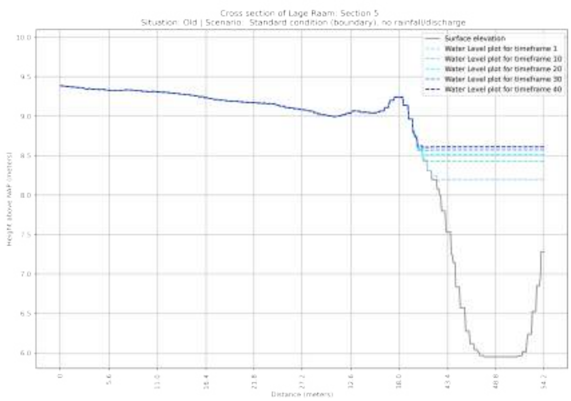

Figure F.61: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: Standard situation

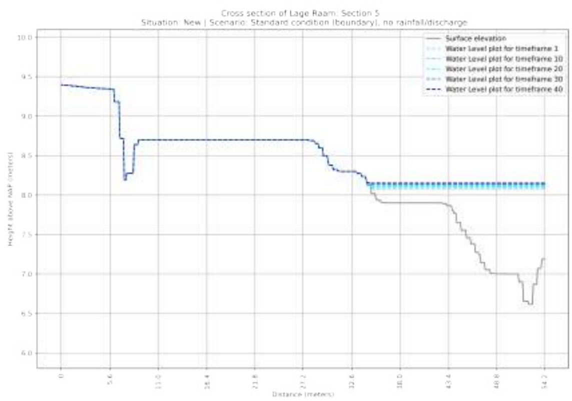

Figure F.62: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: Standard situation

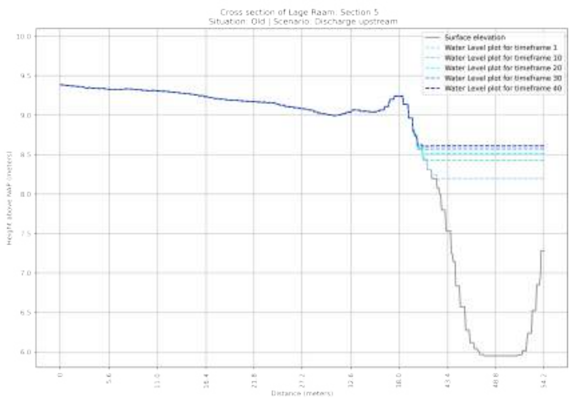

Figure F.63: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: Discharge T > 1X25 year

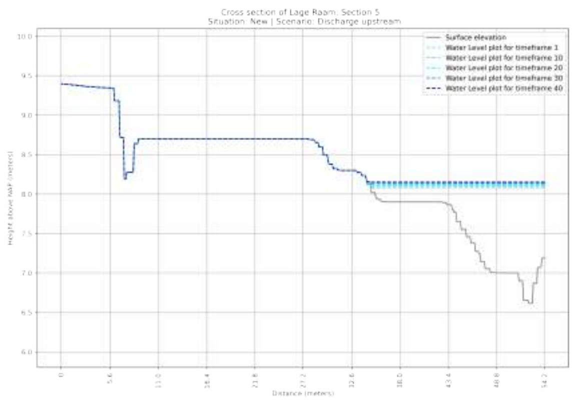

Figure F.64: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: Discharge T > 1X25 year

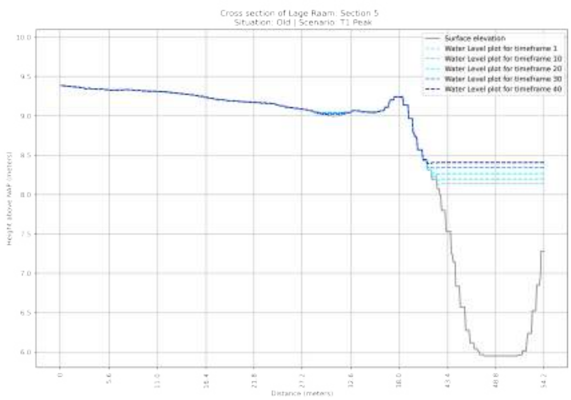

Figure F.65: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

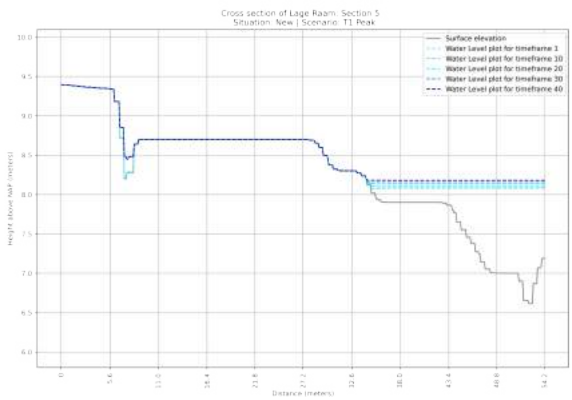

Figure F.66: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

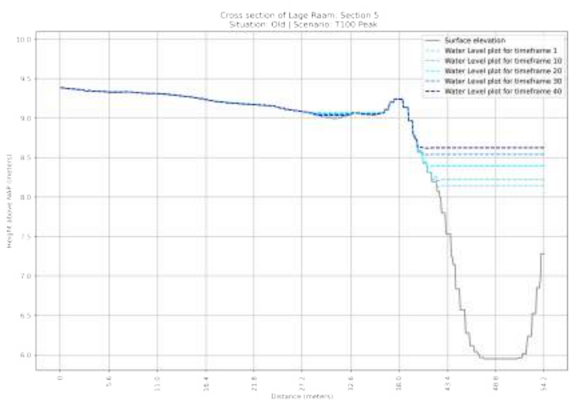

Figure F.67: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

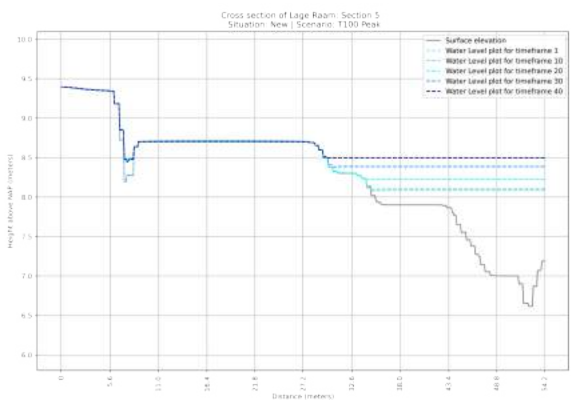

Figure F.68: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

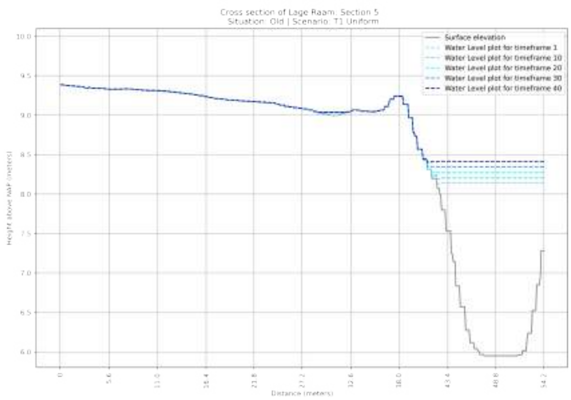

Figure F.69: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

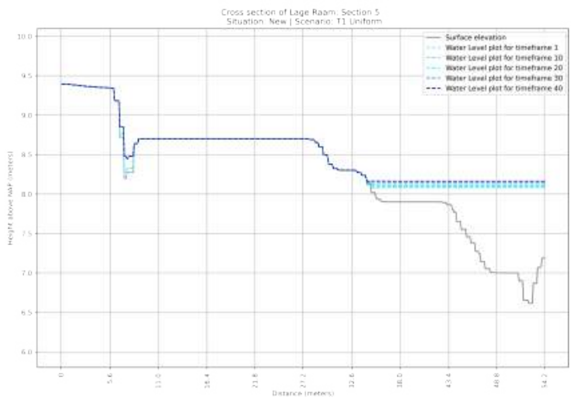

Figure F.70: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

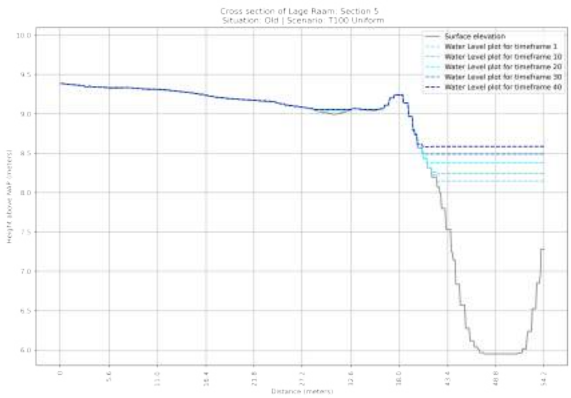

Figure F.71: Cross section of the OLD situation of section 5 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

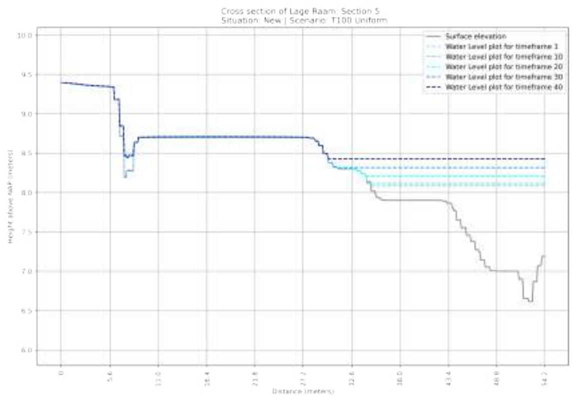

Figure F.72: Cross section of the NEW situation of section 5 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.7. Cross sections for Section 6

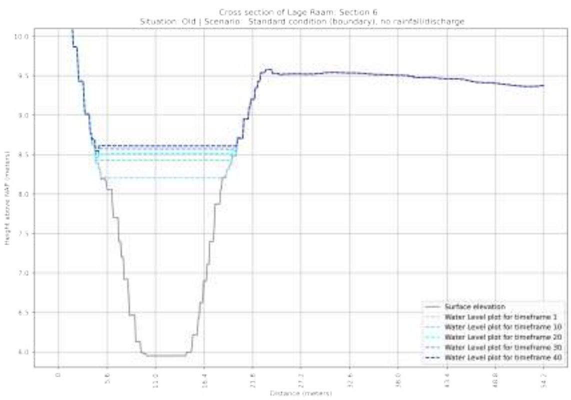

Figure F.73: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: Standard situation

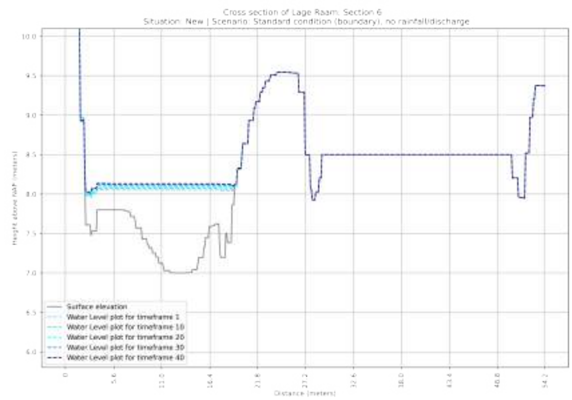

Figure F.74: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: Standard situation

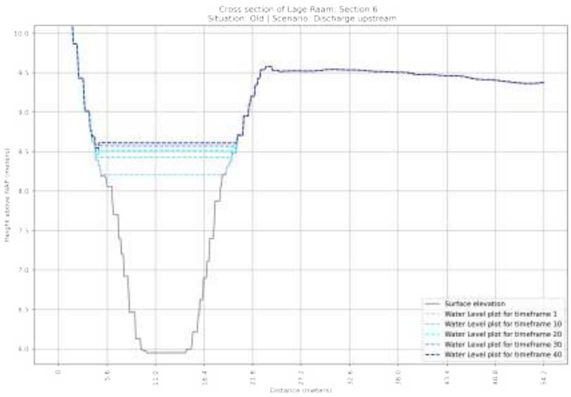

Figure F.75: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: Discharge T > 1X25 year

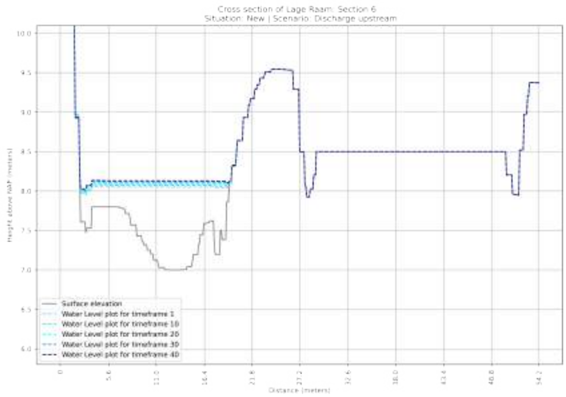

Figure F.76: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: Discharge T > 1X25 year

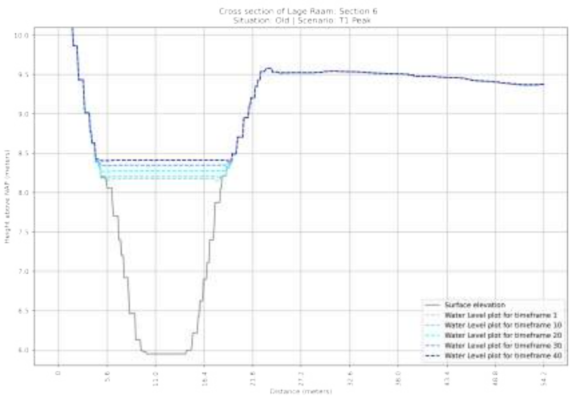

Figure F.77: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

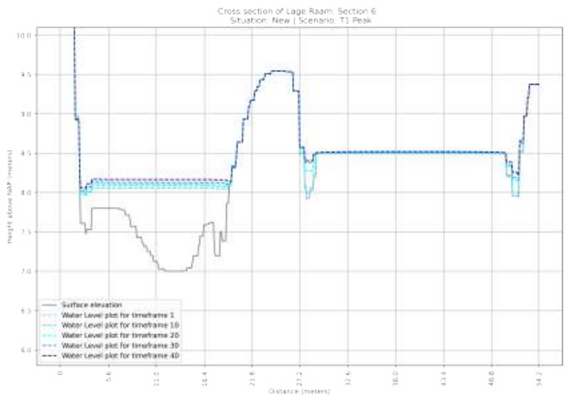

Figure F.78: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

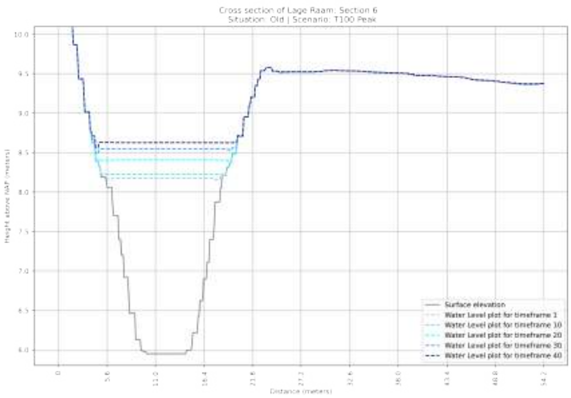

Figure F.79: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

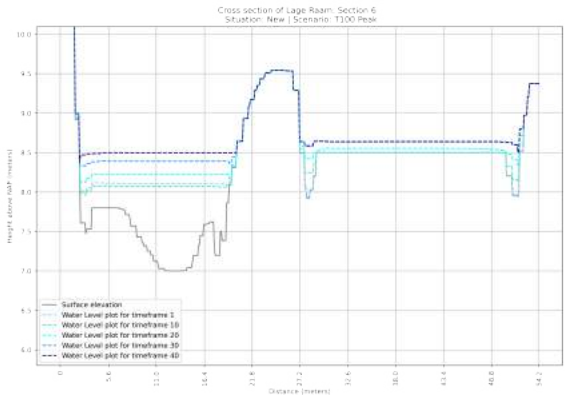

Figure F.80: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

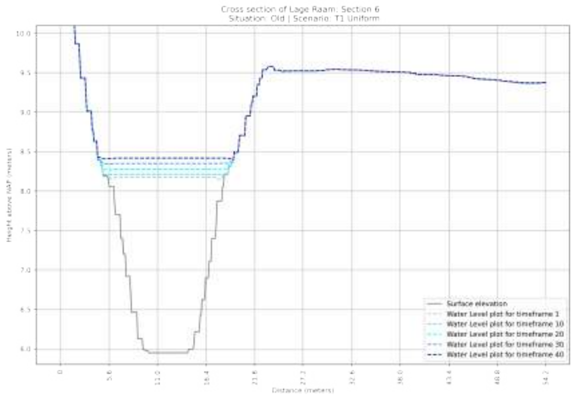

Figure F.81: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

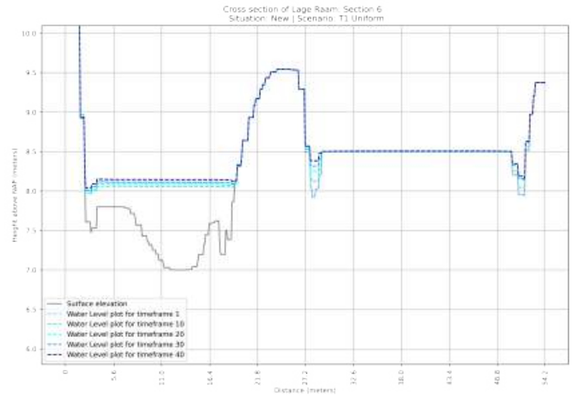

Figure F.82: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

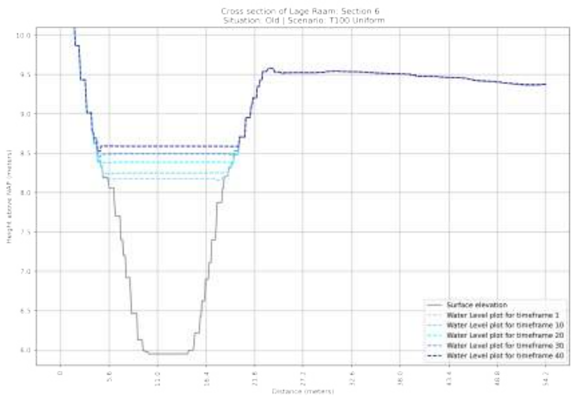

Figure F.83: Cross section of the OLD situation of section 6 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

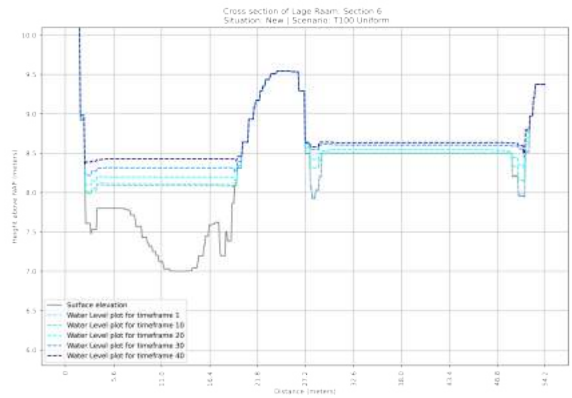

Figure F.84: Cross section of the NEW situation of section 6 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

F.8. Cross sections for Section 7

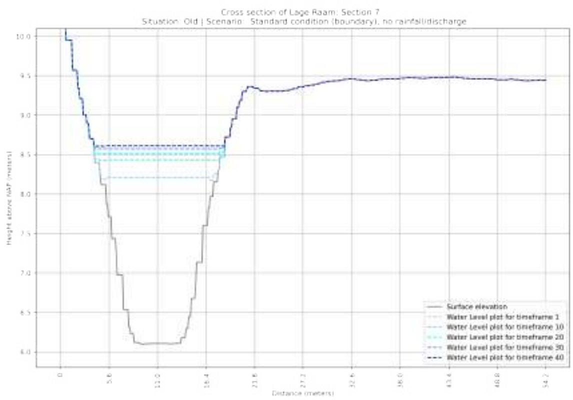

Figure F.85: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: Standard situation

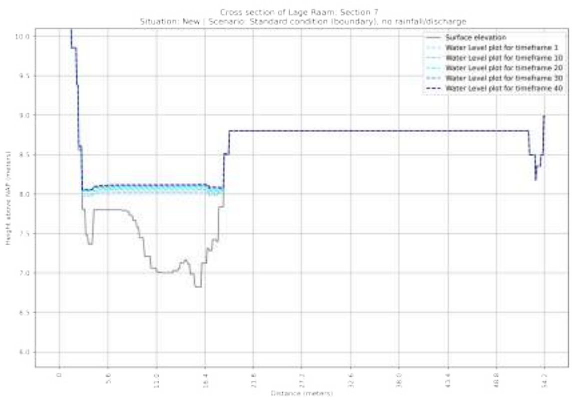

Figure F.86: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: Standard situation

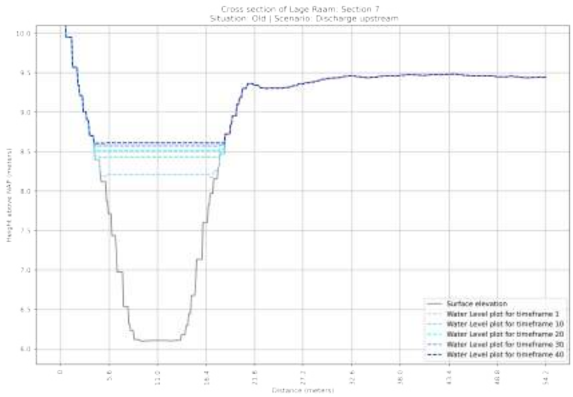

Figure F.87: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: Discharge T > 1X25 year

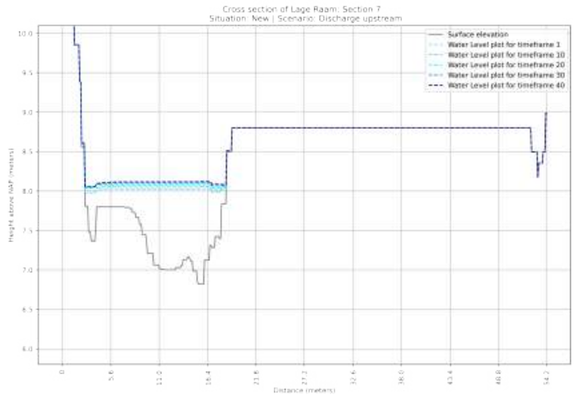

Figure F.88: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: Discharge T > 1X25 year

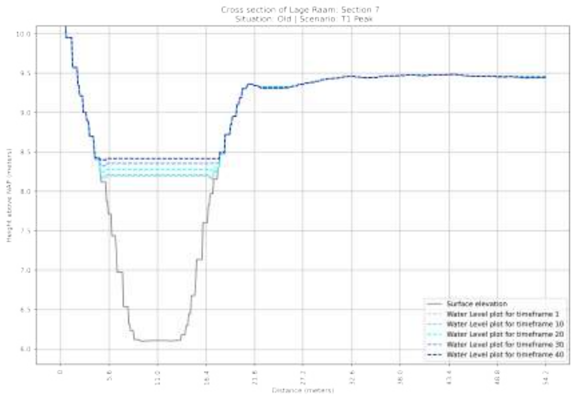

Figure F.89: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

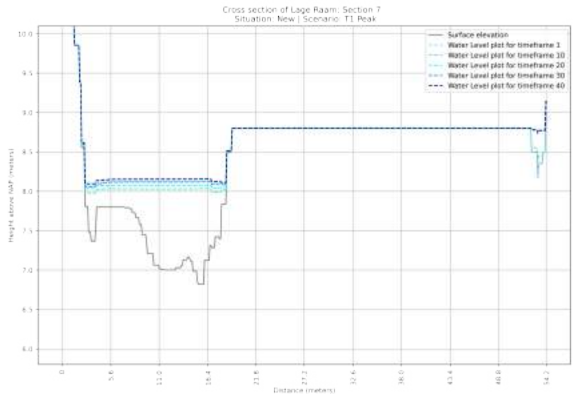

Figure F.90: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: T=1x1 year Peak Rainfall event

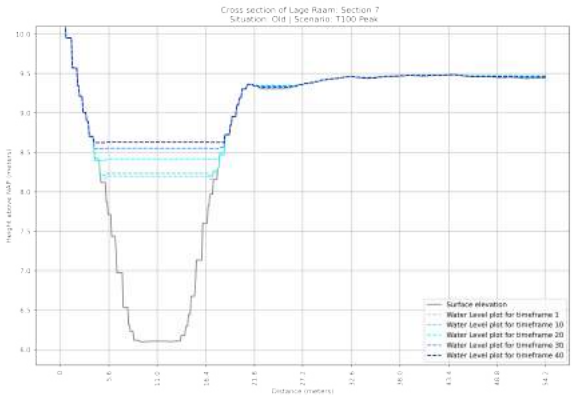

Figure F.91: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

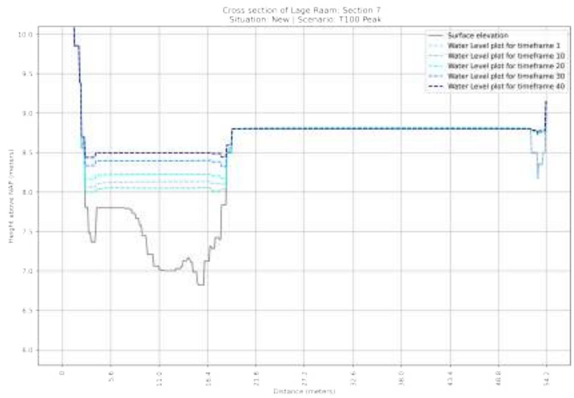

Figure F.92: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: T=1x100 year Peak Rainfall event

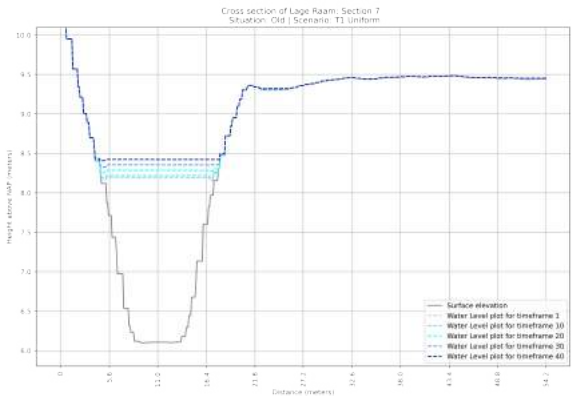

Figure F.93: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

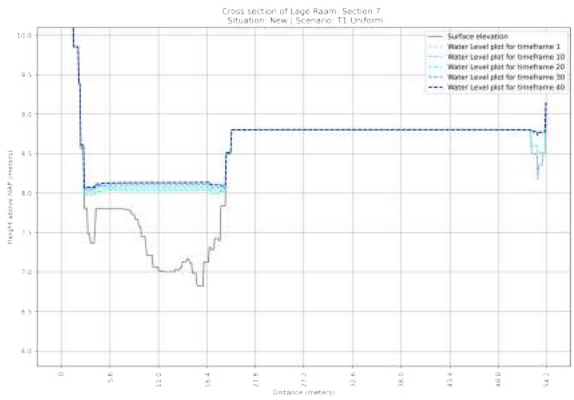

Figure F.94: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: T=1x1 year Uniform Rainfall event

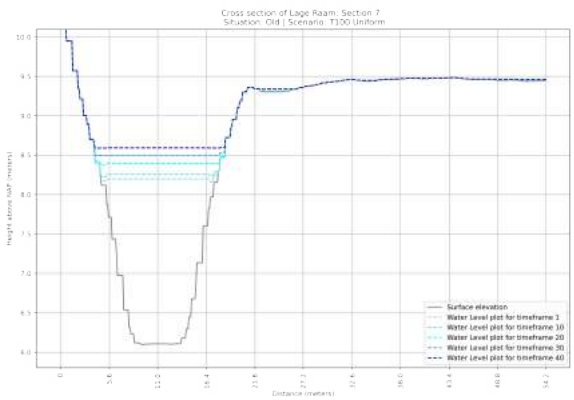

Figure F.95: Cross section of the OLD situation of section 7 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event

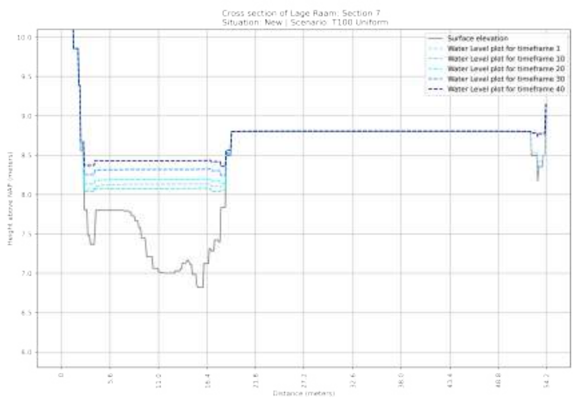

Figure F.96: Cross section of the NEW situation of section 7 in the Lage Raam | Scenario: T=1x100 year Uniform Rainfall event