20-10-2016

Master thesis

Hydraulic models in stream restoration

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MSc thesis
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Abstract

Water boards perform stream restoration projects mainly to restore ecology. Hydrodynamic modelling is an important part of those restoration projects, mainly to forecast future water levels and flood risk. In Dutch stream restoration projects, it is very common to use one-dimensional Sobek software for hydrodynamic modelling. Still, though monitoring of stream restoration projects is scarcely performed, it is a common belief that hydraulic forecasts are not always optimal. The general assumption is that multi-dimensional models can improve upon the predictions made with the one-dimensional model.

This research makes a comparison between modelling stream restoration projects in their design phase with one-dimensional Sobek software compared to two-dimensional Delft3D FM software. The Delft3D FM software was specifically selected out of the two-dimensional models available, because of its flexible grid. This means both spacing and shape of the grid can vary, which is especially useful in modelling meandering streams.

The objective of the research was: *to determine if modelling stream restoration projects, in their design phase, with a two-dimensional (Delft3D FM) compared to a one-dimensional (Sobek) model has advantages in forecasting water levels and developments in morphology and vegetation.* To investigate this, two restoration projects were modelled, one in the Lunterse beek and one in the Tungelroyse beek. Both projects were traditional stream restoration projects (re-meandering projects).

For the stream restoration project analysed in the Lunterse beek two models were set-up, a Sobek model and a Delft3D FM model. Both models were set-up for the period shortly after restoration and stationary discharge scenarios were used as model forcing. A comparison between simulated water levels and observed water levels showed that the one-dimensional model performed better than the two-dimensional model for this particular situation. It was also found that the water level simulations with the Delft3D FM model could improve if lower roughness values were selected or if the bed level interpolation method was changed though, which was not the case for the Sobek model. It was found that differences in output between the models were likely caused by differences in bathymetry and experience in working with the models.

For the stream restoration project performed in the Tungelroyse beek, a Delft3D FM model was set-up. Again, the period shortly after restoration was modelled using stationary discharge scenarios as forcing for the model. Performance of water level forecasts improved compared to the Delft3D FM model of the Lunterse beek. However, it was concluded that advantages of a two-dimensional model over a one-dimensional model will likely not come from water level forecasts since the water levels simulated with the Sobek model are already accurate. It is expected that the two-dimensional model can list equally good results though if more experience is gained with two-dimensional modelling in stream restoration projects.

Forecasts in morphological developments were made based upon output of the Delft3D FM models. First the locations where transport can be expected were determined using the Shields parameter and the critical Shields parameter. After that flow velocity and flow direction maps were made for the most important discharge scenarios. For the Lunterse beek these maps were qualitatively compared to monitored quantitative developments in bed level. The maps created with the high uniform discharge scenarios (T100, T10 and T1) showed good correspondence to monitored developments, while the lower discharge scenarios (T0.05 and T0.005) showed some correspondence looking into bed erosion and sedimentation. It was found that the monitored discharge for the given period was between the discharge used as forcing for the T0.05 and T0.005 scenarios. The bank erosion that was monitored in the field could not be explained by these scenarios. An explanation for this can be that water levels are overestimated in the model, wherefore flow velocities are underestimated for equal discharges.

The flow velocity and flow direction maps made for the Tungelroyse beek agreed with qualitative developments monitored with respect to morphology. However, no quantitative measurements were performed of bed level developments. Therefore, agreement between forecasts made with the models and developments encountered in reality could not be proven. In the end it was concluded that there might be benefits of a two-dimensional model with respect to forecasting morphological developments after stream restoration in its design phase, but this could not be proven in this research.

To make forecasts about expected developments in vegetation, flow velocity output of the Delft3D FM models was used. In the literature it was found that more vegetation can be expected for locations with low flow velocities and less vegetation if flow velocities are high. Though developments in vegetation depend on many other factors, it was found that forecasts corresponded quite well to monitored developments in vegetation for some scenarios. Validation was performed for the Lunterse beek by using a high resolution aerial image and for the Tungelroyse beek using a Normalized Difference Vegetation Index (NDVI) map. It has to be noted though that in-stream vegetation developments could not be validated, while these are often very important for water boards.

Finally it was concluded that using a two-dimensional Delft3D FM model in the design phase of stream restoration projects to make forecasts in vegetation development might be beneficial. Using flow velocity output of the two-dimensional model to base these forecasts upon gave good results for a few discharge scenarios for both streams. There might also be a benefit in two-dimensional modelling with respect to making forecasts in morphological

developments, however this is only partly supported by this research. Finally, it became clear that advantages of a two-dimensional model compared to one-dimensional model are likely not present in water level forecasts since the one-dimensional model already performs very well. It is expected though, that the water level forecasts made with the two-dimensional model can be improved by gathering more experience. This should eventually lead to water level forecasts that are just as accurate for the two-dimensional model as for the one-dimensional model.

Preface

With this documentation I (hope to) finish my Master study Water Engineering and Management at the University of Twente. It is the same University where I started my Bachelor Civil Engineering a little over five years ago. This period has been of invaluable importance for me to develop myself into an engineer and to grow as a person. For this, I would like to thank everyone that contributed.

This graduation project started at the 1st of February 2016 and was performed mainly at HKV Lijn in Water in Lelystad. I would like to thank the company and all its employees for giving me the possibility to perform my thesis here and for creating a positive environment to do so. A special thanks goes out to my external supervisors Andries Paarlberg and Hermjan Barneveld from HKV for their help during the assignment.

Besides that, I would like to thank my supervisors Erik Raaijmakers and Christian Huising from Water board Peel & Maasvallei and Water board Vallei & Veluwe respectively. They helped to collect all the data needed for this research and provided tons of site-specific information. A thanks also goes out to Arthur van Dam from Deltares for helping out with questions about the Delft3D FM software. For the high resolution aerial photo of the Lunterse beek I would like to thank the Unmanned Aerial Remote Sensing Facility of the Wageningen University (WUR-UARSF) and the Section of Environmental Fluid Mechanics from the Delft University of Technology, and in particular Andrés Vargas Luna for letting me use this photo.

Finally, I would like to thank Denie Augustijn and Pepijn van Denderen from the University of Twente for their supervision and feedback during the Master thesis.

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1. Introduction

This chapter introduces the subject of this Master thesis. Section 1.1 gives a general background and explains why this research is of importance. In section 1.2 the problem is given, while the objective and research questions are presented in section 1.3. Finally, section 1.4 provides a reading guide.

1.1 General background

Water systems in the Netherlands are under constant control and manipulation in order to serve water-related interests (Rijkswaterstaat, 2011). In the 20th century a lot of work was done to normalize streams and rivers in order to increase discharge capacities and decrease flooding (STOWA, 2015). The normalisation has shown to be effective in this, but downsides to these changes were underestimated. Normalization made discharging of streams too fast in many cases. Besides that, streams are deeper than before which caused decreases in groundwater levels. Finally, and most importantly, aquatic ecology is seriously affected by the normalization of streams and rivers, since variations in flow conditions are of vital importance for the survival of many organisms (Verdonschot et al., 2012).

To counteract the negative effects of normalization, stream restoration projects are carried out. In these projects the focus is often on improving ecology and water quality (Didderen et al., 2009; Kail & Angelopoulos, 2014; Palmer & Allan, 2006). The stream restoration measure that is most often applied in the Netherlands is re-meandering, while in the rest of Europe the development of natural riparian vegetation is most popular (Didderen et al., 2009; Kail & Angelopoulos, 2014).

When river or stream restoration projects are designed, setting up a hydrodynamic model is usually an integral and very valuable part of the project (Schwartz & Neff, 2011). Predicting future water levels and flood risks would be hardly possible without these models. Currently, one-dimensional hydrodynamic models are often preferred over multi-dimensional models due to the fact that multi-dimensional models are more resource intensive (Volkwein, 2011). Looking at water boards in particular, organisations that are often responsible for stream restoration, a lack of experience in working with multi-dimensional models further stimulates the choice for one-dimensional models in those projects. At the same time though, the general assumption is that multi-dimensional hydrodynamic models can give better hydraulic predictions than one-dimensional models (Jowett & Duncan, 2012).

The use of multi-dimensional models is increasing though. The large rivers in the Netherlands are standardly modelled two- and sometimes even three-dimensionally nowadays (Sloff et al., 2012). In stream restoration projects however, one-dimensional flow models are still used most of the time. There is some research that has focussed on using two-dimensional models in these projects though. An example is the research of Zantvoort et al. (2008) that was targeted on investigating the added value of two-dimensional flow models in flood calculations. The research showed that two-dimensional modelling had many advantages over one-dimensional modelling when performing flood calculations. Regarding hydraulic modelling though, no studies were performed on comparing multi-dimensional with one-dimensional models. Stream restoration projects are an excellent opportunity for such an investigation.

Since 2009, Deltares has been working on a new hydro software package. As a first step, they extended the Delft3D model with a flexible grid: Delft3D Flexible Mesh (Delft3D FM). The main advantage of this software is the possibility to generate a flexible grid in which both spacing and shape can vary (Deltares, 2013). This makes it possible to model the flow while using grids that do not conform to the matrix shape needed in curvilinear grids. Therefore the model software is more suited to capture important details. Especially in modelling meandering streams, where dimensions are often small and sinuosity can become large, the flexibility in the grid might be useful. This raises the question whether it is possible to better predict hydraulic effects of stream restoration measures using the relatively new two-dimensional Delft3D FM software compared to using a more traditional one-dimensional Sobek model as often done nowadays.

1.2 Problem definition

Water boards are often responsible for stream restoration projects in the Netherlands. During the design phase of these projects, hydrodynamic modelling is performed to support decision making processes regarding stream dimensions after restoration. In most cases one-dimensional Sobek software is used for hydrodynamic modelling. The Sobek software with its hydraulic output is also used to obtain insights in plausible morphological developments of the stream and developments in vegetation. The accuracy of the model therefore largely determines if stream restoration objectives will be met. The importance of hydrodynamic modelling in stream restoration projects can therefore hardly be underestimated.

Though monitoring of stream restoration projects is scarcely performed, it is a common belief that the one-dimensional Sobek software is not always able to forecast the new hydraulic situation of a stream correctly. This also means that more uncertainty is introduced in the forecasts of morphological developments and evolutions in vegetation cover. It is not yet clear what causes the Sobek model forecasts to deviate from the situation as monitored after stream restoration, except for the simple fact that the model is just an approximation of reality.

It is possible that the two-dimensional Delft3D FM software gives more accurate results in forecasting the hydraulic situation of a stream after restoration, because less assumptions need to be made to set-up a two-dimensional model compared to a one-dimensional model. Spatial roughness can be captured as well as the streams bathymetry. Besides that, spatially varying output of water depths and flow velocities might contribute to better forecasts of developments in morphology and vegetation after stream restoration. Therefore this study will analyse the performance of a two-dimensional Delft3D FM model compared to a one-dimensional Sobek model in forecasting stream developments after restoration. Predictions will be targeted on water levels and developments in morphology and vegetation.

1.3 Objective and research questions

The objective of this graduation assignment is to determine if modelling stream restoration projects, in their design phase, with a two-dimensional (Delft3D FM) compared to a one-dimensional (Sobek) model has advantages in forecasting water levels and developments in morphology and vegetation. This will be done by comparing the water level output of the Sobek and Delft3D FM model to each other and to measurements. Besides that, forecasts of developments in vegetation and morphology will be made based upon the hydraulic model output and a comparison will be performed with in-field developments. The assignment will be carried out for stream restoration projects in the Lunterse beek and the Tungelroyse beek. The main research question is:

Are there advantages in using a two-dimensional (Delft3D FM) model compared to a one-dimensional (Sobek) model in the design phase of stream restoration projects to forecast water levels after stream restoration and is there an added benefit of the two-dimensional (Delft3D FM) model with respect to forecasting developments in vegetation and morphology based on hydraulic model output if the model forecasts are compared to monitored developments in vegetation and morphology?

Dividing this into sub questions gives:

1. What are the differences in water level between the output of the one-dimensional Sobek model and the monitored data and between the two-dimensional Delft3D FM model and monitored data for the Lunterse beek and the Tungelroyse beek after stream restoration and how do the model results compare to each other?

2. What are expected morphological developments for both streams based on the hydraulic model output of the Delft3D FM model and how do these expected developments correspond to monitored developments?

3. What are expected developments in vegetation for both streams based on the hydraulic model output of the Delft3D FM model and how do these expected developments correspond to monitored developments?

1.4 Reading guide

In this report, chapter 2 provides background information regarding stream restoration and introduces the case studies that are of importance for this research; the Lunterse beek and the Tungelroyse beek. Chapter 3 gives a description of the aspects that are important for the set-up of the models and also explains how the models were set-up. A description of how the developments in morphology and vegetation were forecasted is provided in chapter 4. The results for the Lunterse beek are presented in chapter 5 and in chapter 6 the results for the Tungelroyse beek are shown. A discussion is given in chapter 7. Finally, chapter 8 gives the conclusions and chapter 9 provides the recommendations.

2. Stream restoration and case studies

This chapter starts with the description of different objectives for stream restoration in section 2.1. In section 2.2 a description of the Lunterse beek case study is given. For the Tungelroyse beek case study information is provided in section 2.3.

2.1 Stream restoration

A study of literature showed that objectives in river and stream restoration throughout Europe and the United States of America (USA) are often quite similar. Ecological improvement is the most important objective in both continents (Kail & Angelopoulos, 2014; Palmer & Allan, 2006). After that water quality improvements, often as a prerequisite for better ecological conditions, are the most mentioned objective. Looking at the Dutch situation between 1993 and 2003, the most mentioned objective for stream restoration was also improving ecology (Didderen et al., 2009). Between 2004 and 2008, attention has shifted to more specific objectives like improving morphology, flow conditions, living circumstances of certain species and physiochemical water quality.

An important driving factor behind the stream restoration projects in the European Union (EU) is the Water Framework Directive (WFD), that was adopted in 2000. The WFD was adopted in the EU to improve upon ecological status of water bodies. All countries committed to this WFD, which means certain water quality requirements have to be met before the year 2020. Stream restoration is a great opportunity for water boards to improve the ecological status in streams while satisfying other objectives as well.

Measures that are often applied in stream restoration and the reasons underlying those measures can be found in a separate literature study performed as preparation on this thesis (Boom, 2016).

2.2 The Lunterse beek

The Lunterse beek is part of the water system managed by water board Vallei and Veluwe. This water board manages almost all secondary water systems located in the Gelderland province and besides that all secondary water systems located in the eastern part of the Utrecht province. The Lunterse beek is located in the Gelderse Vallei, an area in the central part of the Netherlands, which is shown in Figure 1.

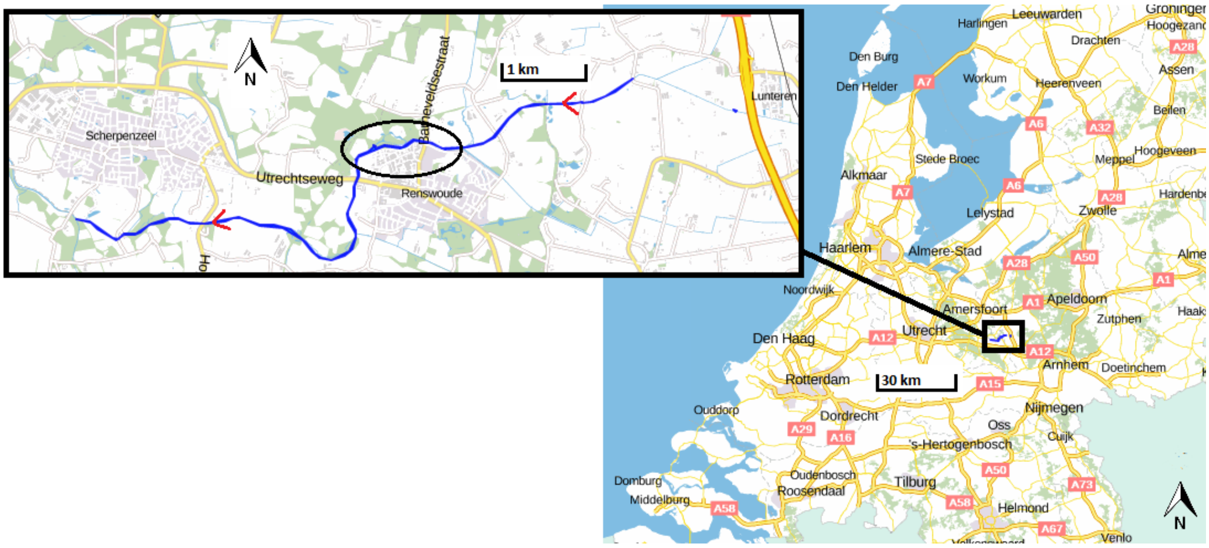

Figure 1: Location of the Lunterse beek (HKV Lijn in Water B.V., 2016), with the black oval indicating the case study area and the red arrows the flow direction

The Lunterse beek has a total length of 11 km, starting at the west of Lunteren (Huising, 2012). The stream then flows westward via the north of Renswoude and south of Scherpenzeel to discharge into the Valleikanaal. Normalisation of the stream was performed in the 1950s (Boer et al., 2013). In recent years, multiple stream restoration projects have been performed in the Lunterse beek. The stream restoration project that will be modelled in this study is called “Herinrichting Lunterse beek Wittenoord-Beekweide” and was carried out between August and November 2011 (Huising, 2012). In this period around 900 m of the 11 km long stream was restored. The case study area is marked with a black oval in Figure 1.

The objective of this stream restoration project in the Lunterse beek was to change the water system at the Wittenoord-Beekweide course in such a way, that goals specified in “inrichtingsbeelden 2015” for the stream basin were met (Smit, 2011). The “inrichtingsbeelden 2015” specifies the following objective for the Lunterse beek: *the stream gets a more winding planform shape with possibilities for meandering processes. Where possible, the old course of the stream is restored and weirs are removed. At the locations where the stream maintains its straight* *shape, variations in water depth and bed material are created while taking the necessary discharge capacity into account*.

Restoration of the Lunterse beek for the Wittenoord-Beekweide project was a traditional stream restoration project, also named re-meandering project (STOWA, 2012). The design dimensions for the Lunterse beek are presented in Table 1 and shown in Figure 2. Take note that these are average dimensions in which natural and artificial variations are present along the stream. The term inundation zone is used here for the lowered and often broad and gently sloping floodplains that are frequently constructed in a "Tweefasenprofiel". In a "Tweefasenprofiel", the floodplain is often deeper while the main channel is more shallow than in a typical stream (Boekel & Weeren, 2010).

Table 1: Design dimensions for the Lunterse beek (STOWA, 2012)

Bank full width (m)	Width at the bed (m)	Depth (m)	Slope (m/km)	Bank slope (1:x)	Slope inundation zone (1:x)
6.0	3.6	0.4	0.94	3	380

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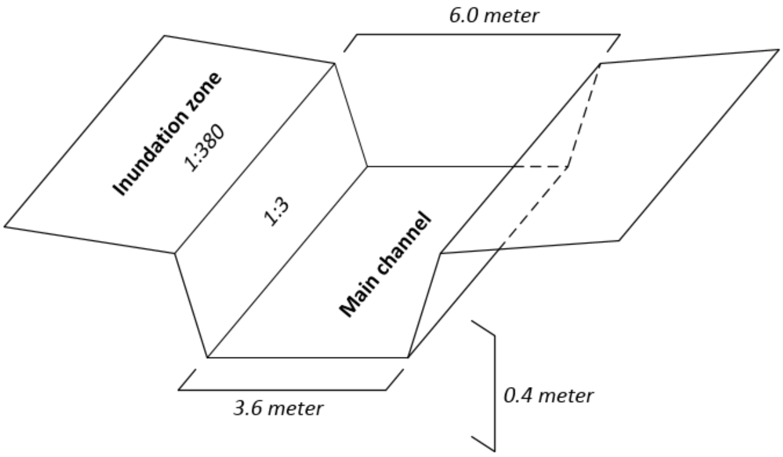

Figure 2: Design dimensions for the Lunterse beek

The discharge and water level characteristics for the Lunterse beek after stream restoration are listed in Table 2. Water level measurements were performed with pressure sensors between January and July 2012, while discharge was based upon a theoretical relationship between water level and discharge (STOWA, 2012).

Table 2: Discharge and water level characteristics Lunterse beek after stream restoration (STOWA, 2012)

Average discharge (m^3/s)	Daily average yearly peak discharge (m^3/s)	Exceedance frequency inundation zone (days/year)	Design inundation time (days/year)
0.33	5.54	206	160

As can be seen from Table 2, the average and peak daily averaged discharge of the Lunterse beek are small. This is in line with what would be expected based on the stream dimensions. It can also be seen that the Lunterse beek has an exceedance frequency of the inundation zone that is higher than designed, which means that the inundation zone is inundating more often than designed.

During restoration of the Lunterse beek multiple measures were taken. An overview of these measures for the project "Herinrichting Lunterse Beek Wittenoord-Beekweide" is listed below (Smit, 2011):

- Profiles were adjusted to a "Tweefasenprofiel" over significant length of the stream
- Re-meandering was applied over a significant length of the stream (this was done actively by digging the new course)
- The weir Barneveldsestraat was lowered to minimal level
- The weir between the Fliertse beek and Lunterse beek was replaced
- The fish passage, located next to the weir Barneveldsestraat, was removed
- Removal of the boat ramp located immediately downstream of the weir Barneveldsestraat
- Pools were constructed
- Removal and planting of trees and bank vegetation
- Creation of a fauna passage
- Large Woody Debris (LWD) was brought into the stream
- The stream was made more shallow over the entire course Wittenoord-Beekweide

Figure 3 gives an overview of the measures that are of importance for hydraulic model performance.

Figure 3: Plan view showing the stream restoration measures performed for the course Wittenoord-Beekweide in the Lunterse beek (background photo gives the 2010 situation)

In Figure 3, the course of the stream after re-meandering is shown in blue. The old straight course, as present in 2010, is shown in the background photo. It becomes clear that the course has changed significantly in the upstream section and little in the downstream section. Re-profiling, not shown in Figure 3, was performed at the same locations where re-meandering was applied. The four brown squares mark the locations where LWD is brought into the stream. The five pools that were constructed in the stream are marked by a blue circle. The two red hexagons mark the locations where the fish passage (right hexagon) and the boat ramp (left hexagon) were removed. Finally the green triangle on the very right marks the location where the weir between the Fliertse and Lunterse beek was replaced, while the green triangle in the middle marks the location where the weir Barneveldsestraat was set to a minimum level.

2.3 The Tungelroyse beek

The Tungelroyse beek is part of the water system that is managed by water board Peel and Maasvallei. This is a water board that manages the secondary water systems in the Northern and central parts of the Limburg province, the most Southern province in the Netherlands. The location of the Tungelroyse beek is shown in Figure 4.

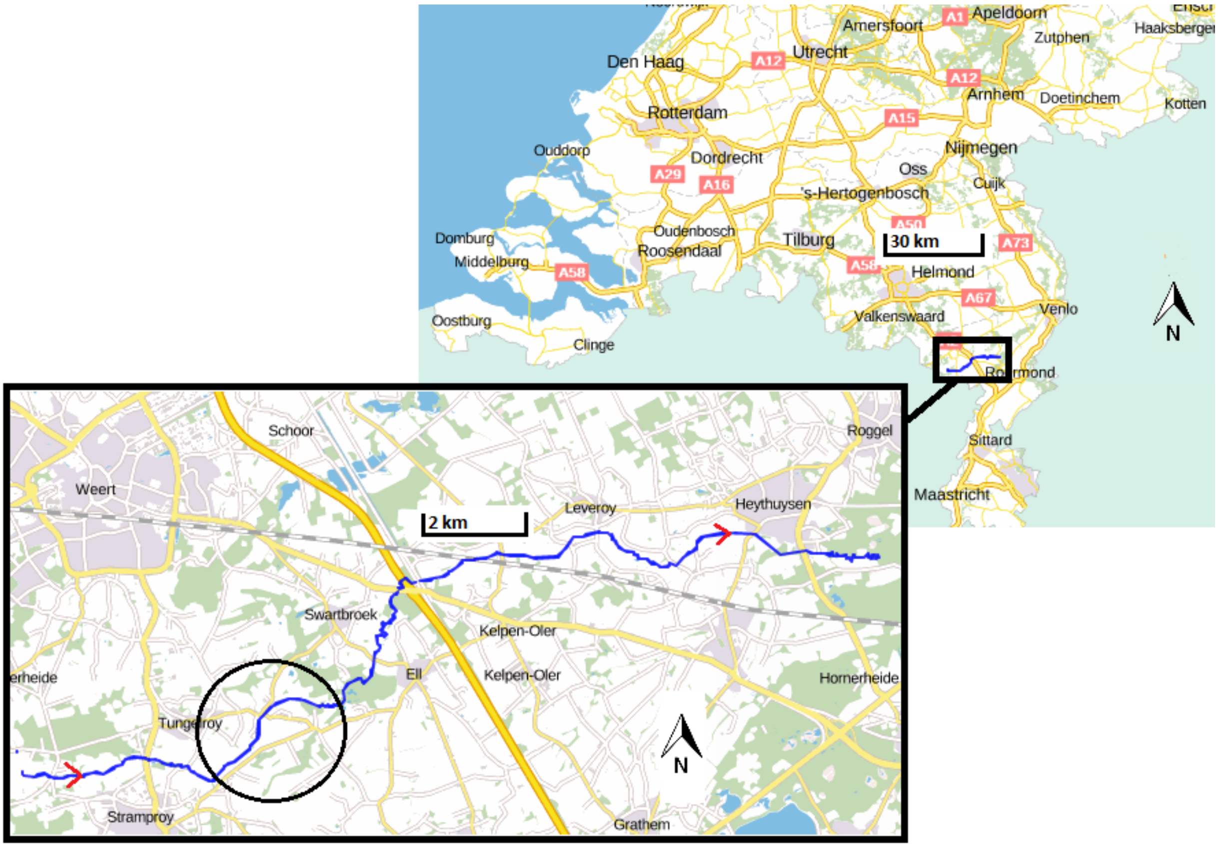

Figure 4: Location of the Tungelroyse beek (HKV Lijn in Water B.V., 2016) with the black circle indicating the case study area and the red arrows the flow direction

Stream restoration in the Tungelroyse beek started in the headwaters of the stream in 1998, while the restoration of the middle and lower reaches started in 2005 (Coenen, 2011). Restoration was finalised in October 2011 (Waterschap Peel en Maasvallei, 2011). During the stream restoration projects, 90% of the 30 km long stream was restored (Coenen, 2011). The restoration that will be modelled in this study is the restoration project named "Tungelroyse beek Traject B", which has a length of around 3.8 km (Pahlplatz & Droesen, 2003).

The reasons for stream restoration of the Tungelroyse beek were twofold. To start with, the stream had a specific ecological function for fish, while water and sediment quality scored insufficient in the WFD. With a part of the stream being "Ecologisch Herstelproject" and an insufficient score on fish and macro fauna in the WFD, restoration was necessary in the vision of the water board. On the other hand, the bad sediment quality and the lack of natural morphology were seen as bottlenecks that had to be restored anyway (Coenen, 2011).

The goal of stream restoration in the Tungelroyse beek was specified as: *coherent development of morphology and ecology such that the system recovers with a focus on stream velocities and the development of possible recreation for residents in the area* (Coenen, 2011). The stream restoration in the Tungelroyse beek was a re-meandering project (STOWA, 2012). The design dimensions of the Tungelroyse beek are presented in Table 3 and shown in Figure 5.

Table 3: Design dimensions for the Tungelroyse beek (STOWA, 2012)

Bank full width (m)	**Width at the bed (m)**	**Depth (m)**	**Slope (m/km)**	**Bank slope (1:x)**	**Slope inundation zone (1:x)**
12.0	6.0	1.4	0.24	2.2	80

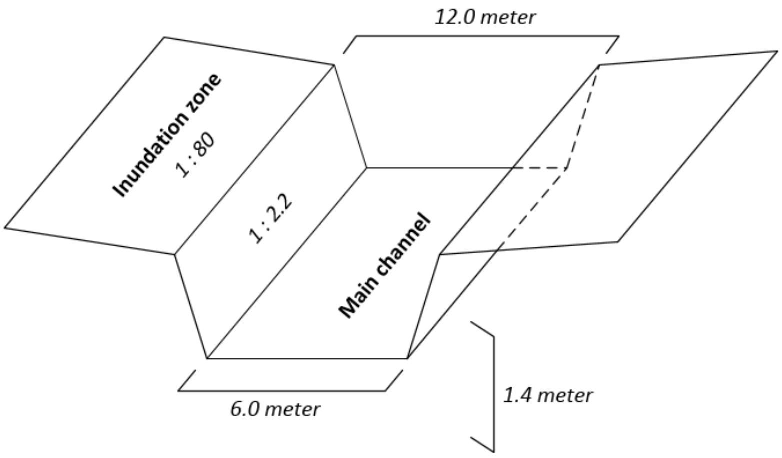

Figure 5: Design dimensions for the Tungelroyse beek

In Table 4 the discharge and water level characteristics for the Tungelroyse beek after restoration are presented. The water levels were measured between May 2011 and May 2012, while the discharge was determined based upon a theoretical relationship between water level and discharge (STOWA, 2012).

Table 4: Discharge and water level characteristics Tungelroyse beek after stream restoration (STOWA, 2012)

Average discharge (m^3/s)	**Daily average yearly peak discharge (m^3/s)**	**Exceedance frequency inundation zone (days/year)**	**Design inundation time (days/year)**
1.01	5.05	6	0

Table 4 shows that the average and peak daily average discharge of the Tungelroyse beek are small. The average discharge is higher than for the Lunterse beek, while the peak daily average discharge is lower. Besides that, the exceedance frequency of the inundation zone is higher than designed, just like for the Lunterse beek.

For the stream restoration project "Tungelroyse beek Traject B", the following measures were implemented (Verlinden, 2007):

- Re-meandering over a large part of the stream (this was done actively by digging the new course)
- Natural redesign of a broad area on both sides of the stream. This was performed for the entire study area, including the removal and planting of trees and bank vegetation
- Re-profiling of the stream in which the bed level is raised between 0 and 45 cm over the entire course and the bottom of the main channel is narrowed from 4 to 3.5 m. Also the slopes of the banks were made more steep at some locations and more gentle at others
- Removal of the weir named "Tun6"

The locations of these measures for the "Tungelroyse beek Traject B" course are shown in Figure 6 for the downstream section (flow from Southwest to Northeast) and in Figure 7 for the upstream section of the study area (flow from Southwest to Northeast).

Figure 6: Measures implemented in the "Tungelroyse beek Traject B" course in the downstream section (background photo shows the 2009 situation)

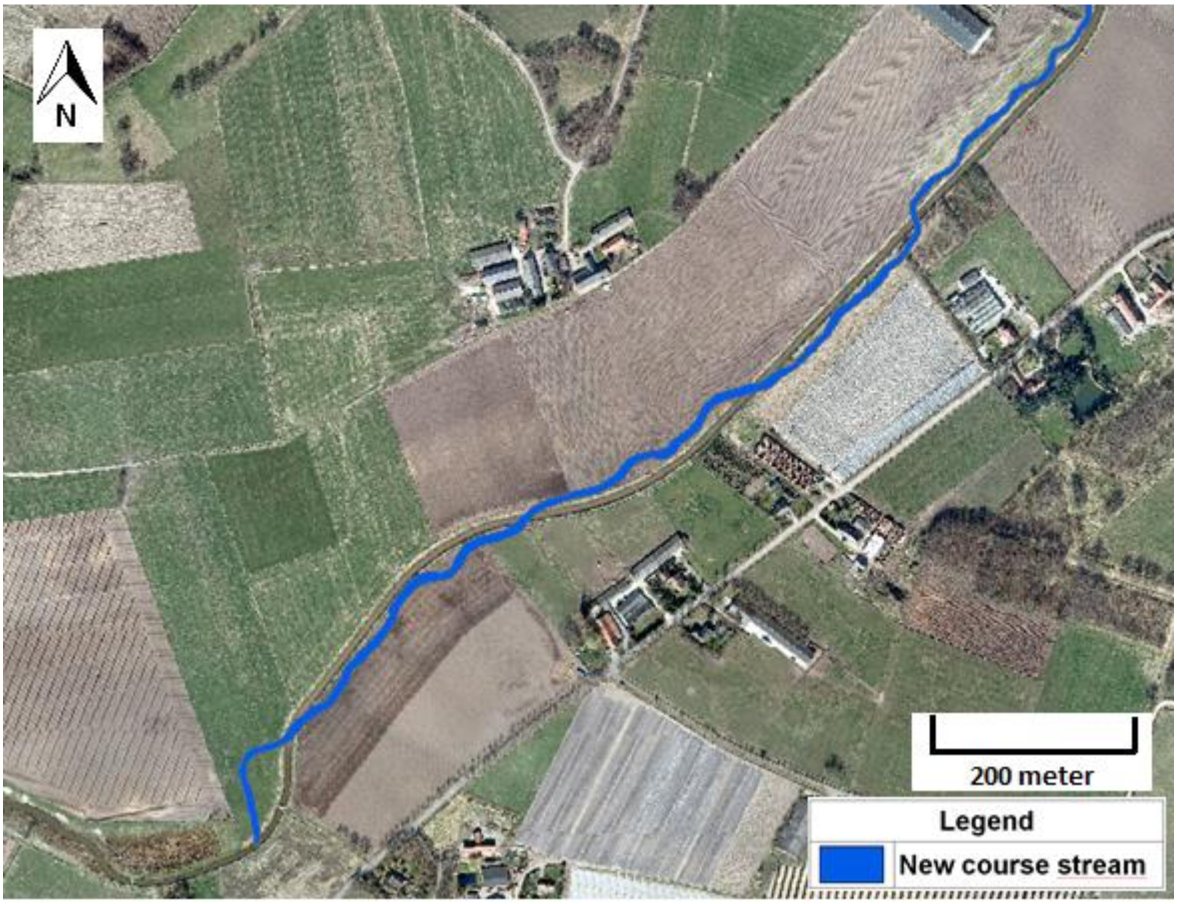

Figure 7: Measures implemented in the "Tungelroyse beek Traject B" course in the upstream section (background photo shows the 2009 situation)

Figure 6 clearly shows the new course for the downstream section of the Tungelroyse beek, with the 2009 situation as background photo. In 2009 the stream was still straight. The green triangle shows the location where the weir named "Tun 6" was removed. The new course of the Tungelroyse beek in the upstream section of Traject B is shown in Figure 7. The background photo shows the nearly straight stream as present in the 2009 situation. As can be seen, the course of the stream changed significantly due to re-meandering.

3. Methodology: model set-up

This chapter explains which methods are used to set-up the models. Section 3.1 explains the general methodology that is used to provide an answer to the research questions. In section 3.2 the different discharge scenarios that will be used for the model simulations are shown. Besides that, the validation locations are presented and the Q-h relationships that are fitted for these locations are shown. Section 3.3 gives a description of the structures that are relevant for the flow characteristics in both study areas. The set-up of the Sobek model for the Lunterse beek is shown in section 3.4. Section 3.5 shows how the Delft3D FM model for the Lunterse beek was set-up, while section 3.6 describes the model set-up of the Delft3D FM model for the Tungelroyse beek. Take note that no Sobek model was set-up for the Tungelroyse beek.

3.1 General

To provide an answer to the research questions, two software packages will be used for the set-up of the models. The first is the Sobek Advanced Version 2.13.002, later referred to as Sobek, that will be used to create a one-dimensional model of the Lunterse beek. The second software package is Delft3D Flexible Mesh 2016 HM, hereafter called Delft3D FM. This software will be used to set-up a two-dimensional model for both the Lunterse beek and the Tungelroyse beek.

For the hydraulic comparison between the Sobek, Delft3D FM model and monitored hydraulics, a case study of the Lunterse beek will be performed. Multiple stationary discharge scenarios will be used as model forcing. The simulations will be used to compare water level output of the models to each other and to monitored water levels. The Sobek model will be based upon an already existing model that is in use with water board Vallei and Veluwe, while the Delft3D FM model will be built from scratch. Water level output of the Delft3D FM model for the Tungelroyse beek will only be compared to monitored water levels. Stationary discharge scenarios will be used as forcing for this model.

The ability of the Delft3D FM model to forecast developments in morphology will be investigated for both the Lunterse and Tungelroyse beek. The main focus will be on the Lunterse beek though, since quantitative validation data is available for this stream. For the Tungelroyse beek, aerial images will be used for validation purposes. Morphological forecasts will be solely based upon hydraulic model output. For both streams locations where transport might occur will be identified using the Shields and critical Shields parameters as indicators. Besides that, flow velocity and flow direction maps will be made. Those will be compared to monitored morphological developments. For the Lunterse beek additional morphological forecasts will be made based upon flow velocity gradients. These forecasts will also be compared to monitored developments in morphology for the Lunterse beek. For the Tungelroyse beek a qualitative comparison will be performed using aerial images that show the planform development between 2012 and 2015. For both streams only a part of the study area will be used for validation of the forecasts, since validation data is lacking for the other locations.

Developments in vegetation will be forecasted for both streams by using hydraulic model output of the Delft3D FM models. The forecasts will be based upon flow velocity and water depth output of the models. More vegetation is expected if flow velocities are low and less vegetation is expected if flow velocities are high (see section 4.2). For the Lunterse beek, these forecasts will be compared with developments in vegetation seen on a high resolution aerial photo. For the Tungelroyse beek the comparison will be performed using the Normalized Difference Vegetation Index (NDVI). The NDVI gives an indication for the amount of vegetation present at certain locations.

3.2 Discharge scenarios, Q-h relations and validation locations

In this section a description is given of the discharge scenarios that will be used in the model runs for both the Lunterse beek in section 3.2.1 and for the Tungelroyse beek in section 3.2.2. Besides that, the fitted Q-h relations and the validation locations for both streams will be shown.

3.2.1 Lunterse beek

For the Lunterse beek the period for which the models will be set-up is immediately after stream restoration. Restoration of the stream was completed in November 2011. Bed level measurements were performed after stream restoration in February 2012 by Meet B.V. (2012). This data will be used to set-up a geometry for both the Sobek and Delft3D FM model. The period for which the model is supposed to be representative is therefore 01-12-2011 till 15-02-2012.

Multiple locations are present in the study area that are important for the set-up and validation of the models. These locations are presented in Figure 8 and their characteristics are shown in Table 5.

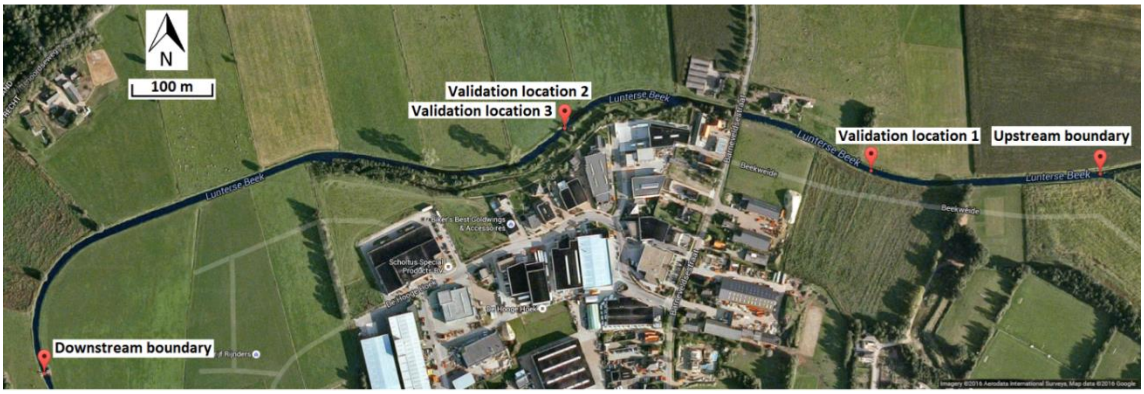

Figure 8:Model boundaries and locations for model validation of the Lunterse beek (Google Maps)

Table 5: Boundaries and validation locations for the Lunterse beek

Location	**Type of measurement**	**Name**
Upstream boundary	Nothing	Groot Abbelaar downstream
Validation location 1	Water levels	WL2
Validation location 2	Water levels and discharge	Barneveldsestraat upstream
Validation location 3	Water levels and discharge	Barneveldsestraat downstream
Downstream boundary	Water levels	Utrechtseweg

As becomes clear from Table 5, no discharge measurements were performed at the upstream boundary. Therefore the discharge measurements performed at the Barneveldsestraat will be used as model forcing. This can be done since inflow between the upstream boundary and the discharge measurement station of the Barneveldsestraat, through run-off and groundwater flow, is minimal compared to the discharge of the stream. Besides that, only stationary discharge scenarios will be used in the simulations and therefore changes in discharge shape between the upstream boundary and the Barneveldsestraat are not important for the model simulations.

At the downstream boundary a weir is present. Therefore, the water level measurements performed just upstream of this weir will be used as boundary condition for the model while the weir will be neglected in the model simulations. For the validation of the model output, the water levels measured at locations 1, 2 and 3 will be used.

For the model simulations, multiple model runs will be performed using stationary discharge scenarios. To start with, 5 discharge scenarios were selected that are important from a hydrological point of view:

- The discharge that is exceeded 0,01 days per year (extreme peak, T100)
- The discharge that is exceeded 0,1 days per year (design norm rural area, T10)
- The discharge that is exceeded 1 day per year (design discharge, T1)
- The discharge that is exceeded 20 days per year (high spring discharge, T0.05)
- The discharge that is exceeded 200 days per year (average summer discharge, T0.005)

To match discharge values to the lower range scenarios (T1, T0.05 and T0.005), a measurement series collected by water board Vallei & Veluwe between 01-12-2011 and 03-03-2016 at the Barneveldsestraat measurement station will be used. The reasoning behind this is that after restoration of the stream, discharge characteristics were altered since the weir Barneveldsestraat was set to a minimum level. Therefore data collected before 01-12-2011 cannot be used. Besides that, discharge measurements at the Barneveldsestraat only started in 2011. For the higher range scenarios (T10 and T100), information from the report: *Hermeandering Lunterse Beek: Effectenberekeningen* (Versteeg et al., 2010) was used. The resulting match between the discharge scenarios and the discharge values is presented in Table 6.

Table 6: Discharges for different scenarios

Discharge scenario	**Discharge (m^3/s)**
Average summer discharge (T0.005)	0.192
High spring discharge (T0.05)	1.264
Design discharge (T1)	3.61
Design norm rural area (T10)	7.40
Extreme peak (T100)	10.06

Beside these important discharge scenarios from a hydrological point of view, 11 other discharge scenarios were selected for validation specifically. Since for these scenarios the period directly after stream restoration was assumed, data collected between 01-12-2011 and 15-02-2012 was analysed to conclude that these 11 scenarios need to range from 0.5 m^3/s up to 5.5 m^3/s, with 0.5 m^3/s increments to describe a range of discharge values that covers the range of the measurements, as can be seen from Figure 9.

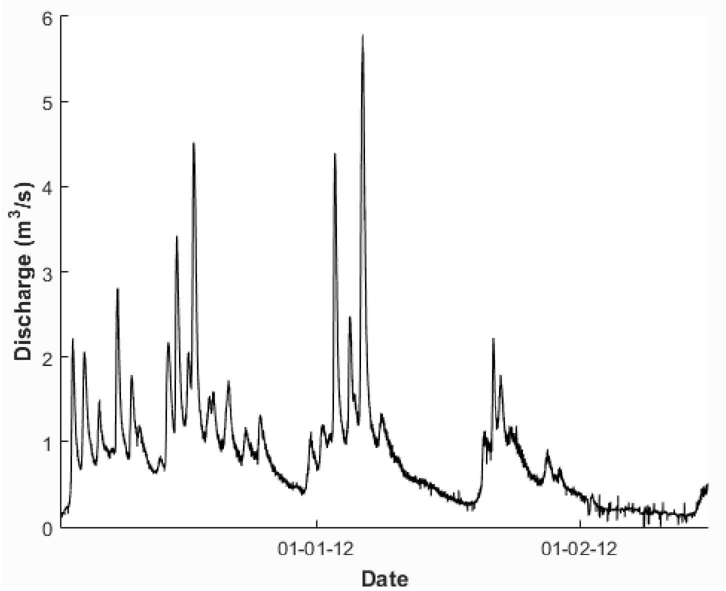

Figure 9: Discharge series for the Lunterse beek, collected at the Barneveldsestraat measurement station between 01-12-2011 and 15-02-2012

Data collected between 01-12-2011 and 15-02-2012 was used to derive Q-h relationships for the validation locations and the downstream boundary. The MatLab curve fitting tool was used to fit the Q-h relationships through the measurements. The decisions made during the fitting process as well as the fit characteristics are shown in Appendix A. The fitted Q-h relationships are presented in Figure 10 including the measured water levels. The boundary conditions based upon the Q-h relation at the Utrechtseweg are shown in Table 7. For the design norm rural area (T10) and peak discharge (T100) events, a different Q-h relation was used than the one presented here. This Q-h relation can be found in Appendix A also.

Table 7: Boundary conditions for the models of the Lunterse beek

Model run	**Upstream discharge (m^3/s)**	**Downstream water level (m)**	**Remarks**
1	0.5	4.91	Model validation
2	1.0	4.96	Model validation
3	1.5	5.04	Model validation
4	2.0	5.12	Model validation
5	2.5	5.22	Model validation
6	3.0	5.32	Model validation
7	3.5	5.42	Model validation
8	4.0	5.50	Model validation
9	4.5	5.57	Model validation
10	5.0	5.62	Model validation
11	5.5	5.65	Model validation
12	0.192	4.91	Average summer discharge (T0.005)
13	1.264	5.00	High spring discharge (T0.05)
14	3.61	5.44	Design discharge (T1)
15	7.40	5.99	Design norm rural area (T10)
16	10.06	6.46	Peak discharge (T100)

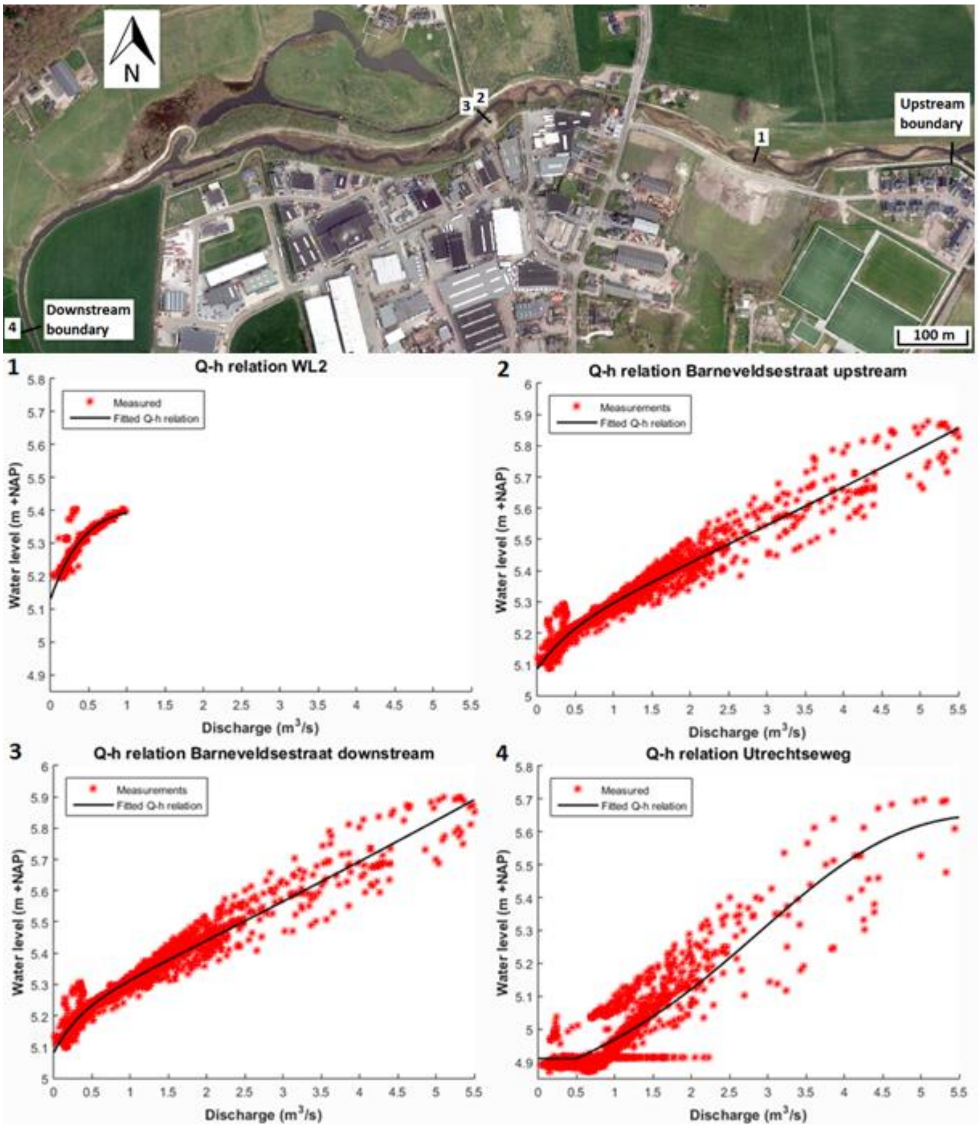

Figure 10: Fitted Q-h relations for the Lunterse beek with their locations

In Figure 10 a hysteresis effect becomes visible. This means that the water levels after the peak are higher than the water levels before the peak for equal discharges, due to a time-lag between changing flow conditions and changing bed roughness (Paarlberg et al., 2010). Since stationary discharge scenarios are used in this study, this effect is not taken into account in the simulations. However, for the fitting of the Q-h relations this effect is accounted for, meaning that uncertainty is introduced for the validation of water levels.

3.2.2 Tungelroyse beek

The period directly after stream restoration is of interest for the model set-up of the Tungelroyse beek. Restoration of the section of interest was finalised in March 2011 (Waterschap Peel en Maasvallei, 2011). However, since the section of interest is quite long, bed level measurements were performed after restoration in the period between 2010 and 2011 (Menten & Strigencz, 2012). These bed level measurements will be used for the set-up of a geometry in the Delft3D FM model. The modelling period will therefore be 2010-2011.

For the Tungelroyse beek, 3 locations are important for model set-up and validation of model results. These locations are shown in Figure 11 and their characteristics are presented in Table 8.

Figure 11: Model boundaries and validation location for the Tungelroyse beek (Google Maps)

Table 8: Boundaries and validation location for the Tungelroyse beek

Location	Type of measurement	Name
Upstream boundary	Nothing	Wisbroek
Validation point	Water level	Castertbrug
Downstream boundary	Water level	OTUNG17

From Table 8 it becomes clear that no discharge measurements were performed at the upstream boundary. Besides that, at the validation location and the downstream boundary no discharge measurements were performed either. Therefore the upstream discharge needs to be derived from measurements performed outside of the study area. A schematic overview of the available data is given in Appendix B. Measurement location OTUNG13, located almost 7.5 km downstream of the upstream boundary Wisbroek, will be used to derive the discharge for the upstream boundary.

To start with, it has to be noted that discharge measurements at location OTUNG13 are affected by inflow from another stream, namely the Leukerbeek. Therefore, the discharge measured at this location will be higher than the discharge expected at Wisbroek, the upstream boundary of the model. The catchment areas of the Tungelroyse beek and Leukerbeek were used, in combination with knowledge from water board Peel and Maasvallei, to determine that the discharge ratio between the Leukerbeek and the Tungelroyse beek is around 1:2 at their confluence.

Besides inflow from the Leukerbeek, the discharge measurement at OTUNG13, further downstream of the study area, will be higher by extra inflow through groundwater flow and run-off. The catchment area of the Tungelroyse beek indicates that the drainage area in-between Wisbroek and OTUNG13 is around 25% of the total catchment area. The normative discharge map, that gives an indication for the peak yearly discharge in the whole stream, shows that the peak yearly discharge in the section Wisbroek is around 80% of the peak yearly discharge just before confluence of the Leukerbeek and Tungelroyse beek. It is therefore assumed that the discharge at Wisbroek will be 20% lower than the discharge measured at OTUNG13 due to run-off and groundwater inflow.

A combination of the 1:2 discharge ratio between the Leukerbeek and Tungelroyse beek and 25% extra inflow through run-off and groundwater flow gives an indication of 8/15 for the discharge measured at OTUNG13 to occur at Wisbroek. Using this factor to relate discharge measurements increases model uncertainty, since variations in discharge between the Leukerbeek and Tungelroyse beek will be present over time that are not accounted for. Besides that, the inflow through run-off and groundwater flow will not be constant over time. However, since other measurements are not available this is the best possible guess that can be used. An advantage is that only stationary discharge scenarios will be used, making that changes in discharge shape can be ignored.

For the Tungelroyse beek 5 important discharge scenarios from a hydrological point of view will be used, just like for the Lunterse beek:

- The discharge that is exceeded 0,01 days per year (extreme peak, T100)
- The discharge that is exceeded 0,1 days per year (design norm rural area, T10)
- The discharge that is exceeded 1 day per year (design discharge, T1)
- The discharge that is exceeded 20 days per year (high spring discharge, T0.05)
- The discharge that is exceeded 200 days per year (average summer discharge, T0.005)

For the study area of the Tungelroyse beek, 3 obviously different periods could be distinguished in the available data. The first period was before stream restoration with data available from 31-03-2009 till 08-03-2011. The second period was after stream restoration with data available from 08-03-2011 till 16-08-2013. The third period was after stream restoration also, but with a large change in catchment area of the Leukerbeek. Data for the third period ranges from 16-08-2013 till 19-06-2016.

To determine the discharge for the lower discharge scenarios (T1, T0.05 and T0.005), data collected in the second period was used. A plot of the daily discharge and water level data collected in the second period for the downstream boundary and validation location is shown in Figure 12. For the higher discharge scenarios (T100 and T10), the discharge belonging to those scenarios was based upon the 10 highest discharge events only. Extrapolation of the fitted curve was performed to determine the discharge for these extreme scenarios.

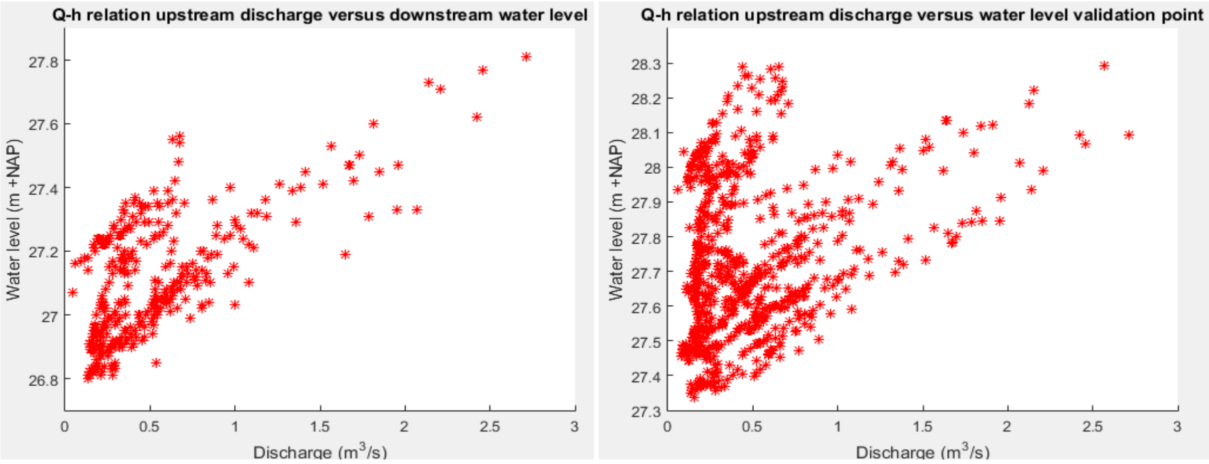

Figure 12: Relation between daily discharge and daily water level measurements at the validation location and downstream boundary for the Tungelroyse beek in the period 08-03-2011 till 16-08-2013

As becomes clear from Figure 12, very clear relations between discharge and water levels are absent. Part of this can be explained by the assumption that the discharge ratio between the Leukerbeek and Tungelroyse beek is fixed at 1:2, which will not be the case in reality. Changes in this discharge ratio will cause a horizontal shift in the measurements. A vertical shift in measurements is likely caused by the delay that occurs in reality between the upstream boundary and the OTUNG13 measurement station 7.5 km downstream. This is not accounted for in this study, but will cause a mismatch between measured discharge and measured water levels, even if daily measurements are used (take note that if the water velocity is 0.2 m/s the delay in discharge will already exceed 10 hours). Another part of the variation might be caused by differences in bed roughness for different periods though. To see how much roughness changes affect the results, data was split for every month. These monthly relationships are presented in Figure 13 for the months December until March.

As becomes clear from Figure 13, when monthly Q-h relations are used instead of yearly ones, much less data is available. However, it also shows that a better relationship is present between monitored discharge and water level. It was therefore chosen to use a monthly Q-h relation for the stationary discharge simulations. The month of December was selected, because the highest range in discharge was present for this month. It can therefore be concluded that the modelled period is December 2011.

From the measurements in December 2011, it becomes clear that 6 other stationary discharge scenarios should be sufficient for validation of the Tungelroyse beek model. These scenarios should range up to 3.0 m^3/s with 0.5 m^3/s increments.

The MatLab curve fitting tool was used to fit the Q-h relationships through the measurements. The decisions made during the fitting process as well as the fit characteristics are shown in Appendix C. The fitted Q-h relationships, including the measured water levels are presented in Figure 14. The boundary conditions based upon the Q-h relation at OTUNG17 are presented in Table 9.

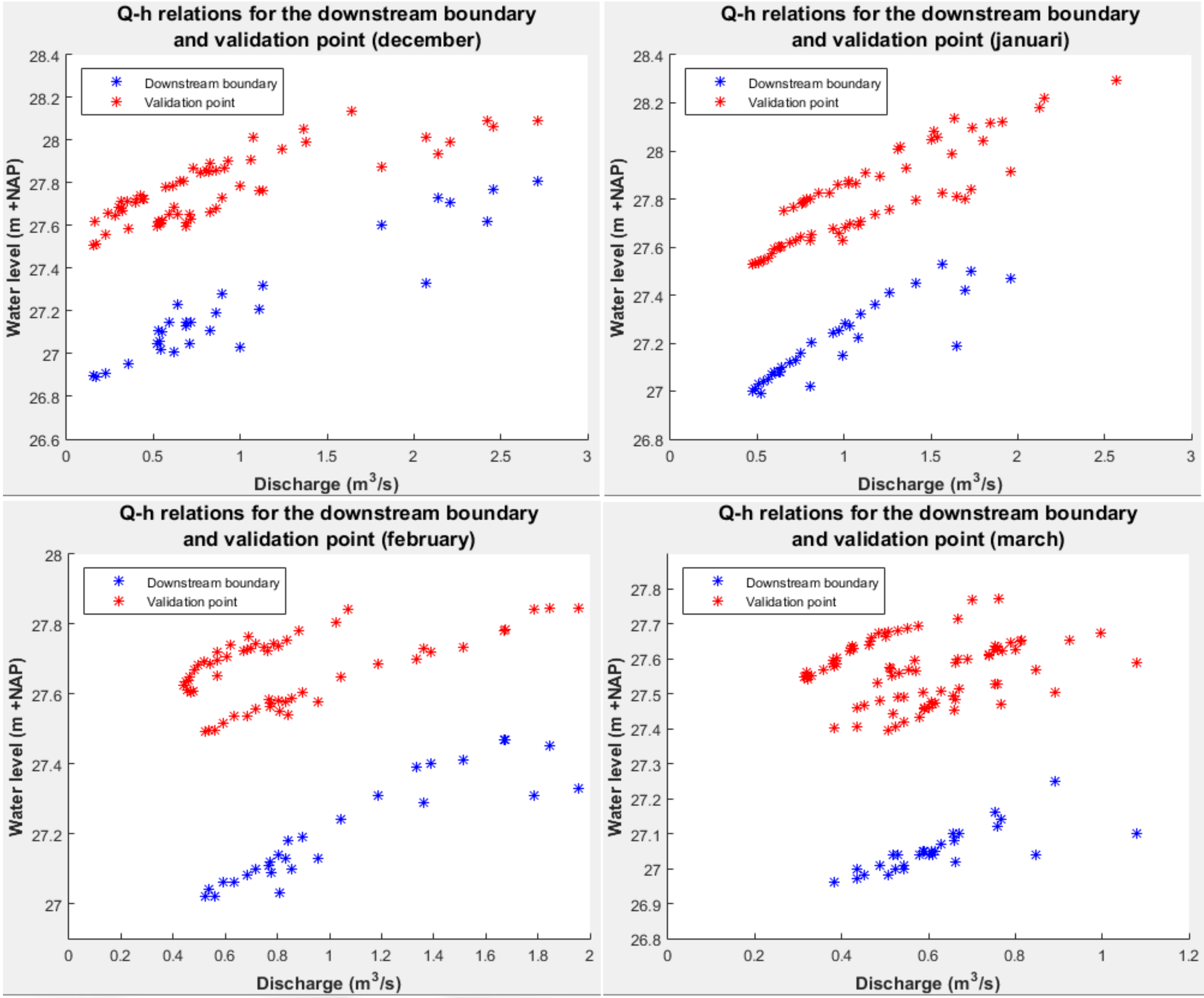

Figure 13: Relations between upstream discharge and water levels for the Tungelroyse beek at the downstream boundary and at validation location Castertbrug for the months December till March

Table 9: Boundary conditions for the Tungelroyse beek models

Model run	Discharge (m^3/s)	Water level (m +NAP)	Remarks
1	0.5	27.04	Model validation
2	1.0	27.22	Model validation
3	1.5	27.40	Model validation
4	2.0	27.56	Model validation
5	2.5	27.72	Model validation
6	3.0	27.88	Model validation
7	0.322	26.98	Average summer discharge (T0.005)
8	1.205	27.29	High spring discharge (T0.05)
9	2.566	27.75	Design discharge (T1)
10	4.2	28.22	Design norm rural area (T10)
11	6.2	28.58	Peak discharge (T100)

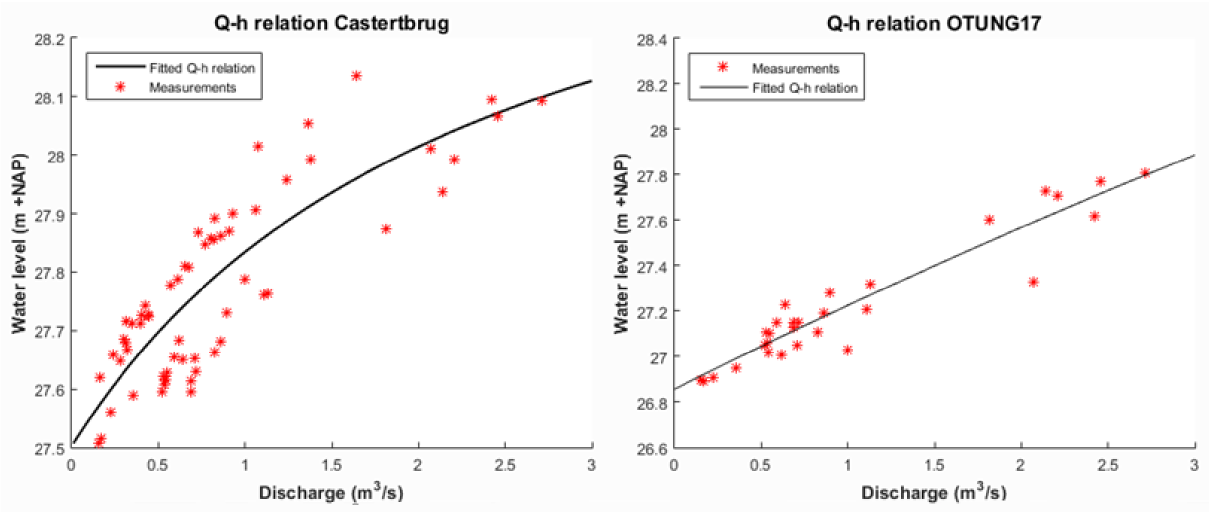

Figure 14: Fitted Q-h relations for the Tungelroyse beek

Uncertainties were introduced in the process performed to obtain boundary conditions and validation data for the models. The main source of uncertainty will likely be caused by the transformation performed to obtain the discharge at the upstream location. This will affect Q-h relations for the downstream boundary and validation location.

3.3 Structures

This section gives a description of the structures that are relevant for the flow characteristics of both the Lunterse and Tungelroyse beek. Section 3.3.1 gives a description for the Lunterse beek and section 3.3.2 for the Tungelroyse beek.

3.3.1 Lunterse beek

In the Lunterse beek multiple structures are present that alter flow characteristics. Both hard structures and soft structures are present in the stream. The hard structures are the bridge “Barneveldsestraat” and the weir “Barneveldsestraat”. The soft structures are 4 packages of LWD that are placed in the Lunterse beek as part of the restoration project. The locations and images of these structures are shown in Figure 15, while the dimensions are presented in Table 10. As noted in section 3.2.1 a weir is also present at the downstream boundary, but since the water levels just upstream of this weir are used, this hard structure is neglected in this analysis.

Table 10: Dimensions of the structures that affect water flow in the Lunterse beek

Name structure	**Bridge “Barneveldsestraat”**	**Weir “Barneveldsestraat”**	**LWD 1**	**LWD 2**	**LWD 3**	**LWD 4**
Width (m)	12.0	7.7	12.0	8.2	10.8	7.8
Height (m)	2.51	(-)	(-)	(-)	(-)	(-)
Crest level (m +NAP)	(-)	4.59	(-)	(-)	(-)	(-)
Length (m)	13	(-)	22.9	16.1	20.6	20.3
Area (m^2)	(-)	(-)	228.0	120.7	175.7	137.5
Thickness bridge deck (m)	0.5	(-)	(-)	(-)	(-)	(-)
Top level bridge (m +NAP)	7.43	(-)	(-)	(-)	(-)	(-)
Manning roughness (s/m$^{1/3}$)	0.01429[1]	(-)	0.1	0.1	0.1	0,1

[1] The Manning roughness was based upon the Sobek model

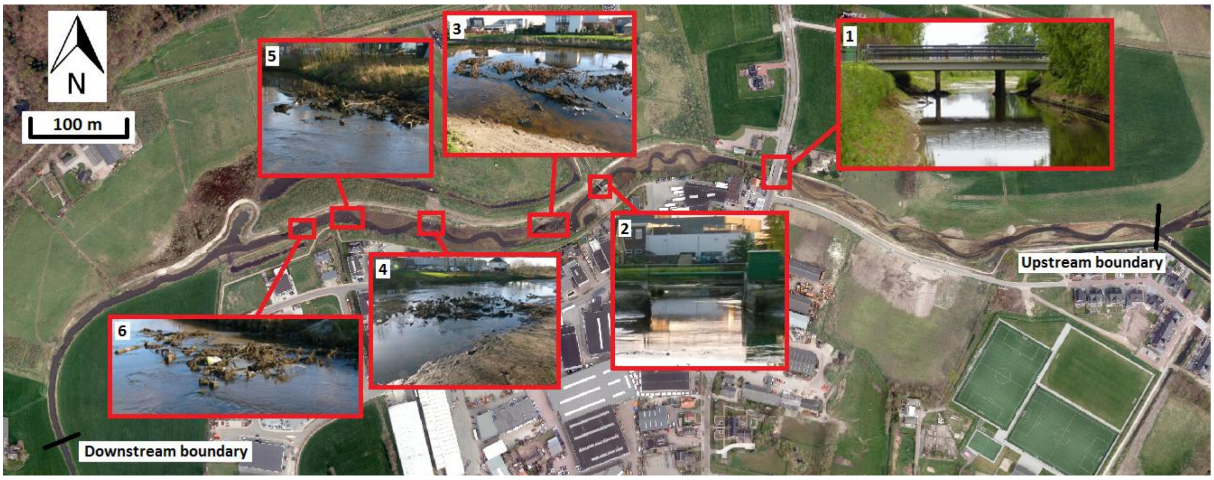

Figure 15: Relevant structures for water flow in the Lunterse beek study area with: 1) Bridge "Barneveldsestraat" 2) Weir "Barneveldsestraat" 3) First LWD package 4) Second LWD package 5) Third LWD package 6) Fourth LWD package

3.3.2 Tungelroyse beek

In the study area of the Tungelroyse beek 2 hard structures are present that affect flow processes. The first structure is the bridge “Wisbroek” and the second structure is the “Castertbrug”. The locations of these bridges along with an image of them is shown in Figure 16. The dimensions are presented in Table 11.

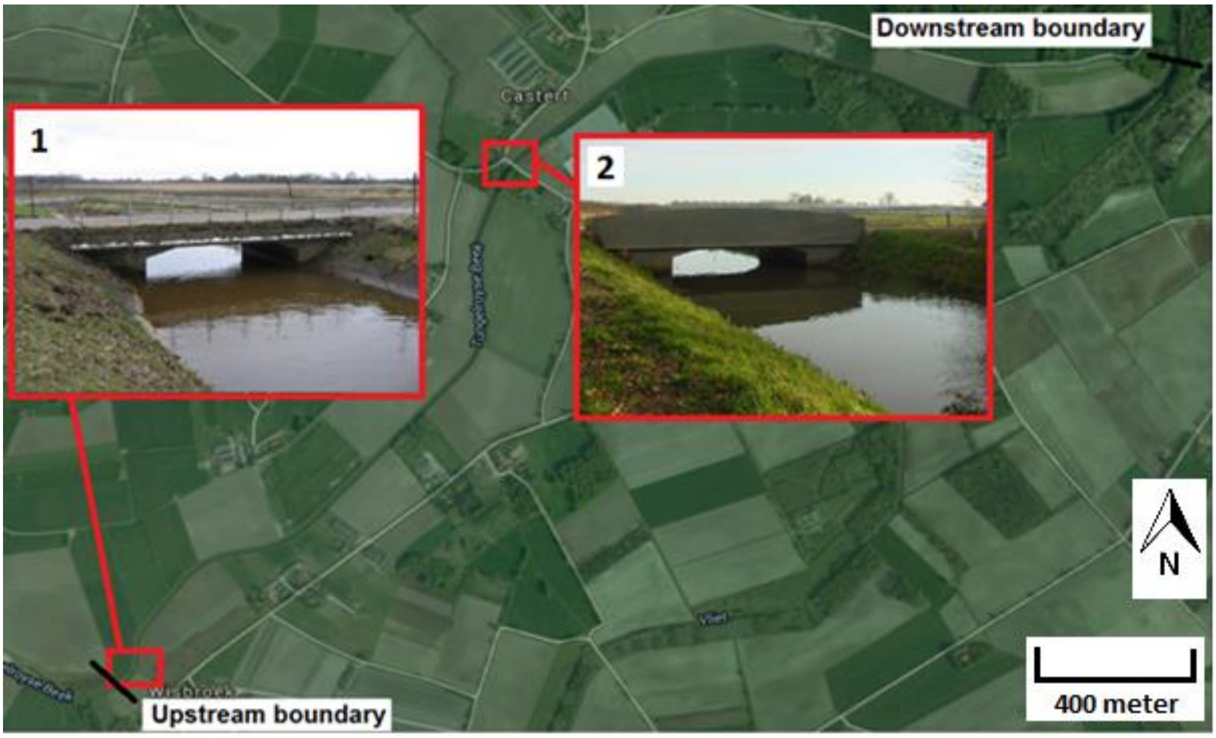

Figure 16: Location of structures that are relevant for water flow in the Tungelroyse beek with: 1) Bridge “Wisbroek” 2) “Castertbrug”

Table 11: Dimensions of the relevant structures for water flow in the Tungelroyse beek

Name structure	Bridge “Wisbroek”	“Casterbrug”
Width (m)	4.4	5.5
Height (m)	1.8	2.0
Length (m)	2.7	5.25
Thickness bridge deck (m)	0.5	0.7
Top level bridge (m +NAP)	29.8	29.3
Manning roughness (s/m$^{1/3}$)	0.01333[2]	0.01333[2]

[2] (Hager, 2010)

3.4 Sobek model Lunterse beek

The Sobek model as used by water board Vallei and Veluwe was used as a starting point for the set-up of a Sobek model for the Lunterse beek. This model was made by HKV Lijn in Water as part of the "Nationaal Bestuursakkoord Water" (NBW) (Graaff & Jungermann, 2014). This model includes all streams that are managed by water board Vallei and Veluwe. For this study it is important to note that the model was set-up without taking into account the stream restoration that took place at the Wittenoord-Beekweide course. This means the model needs to be adjusted to describe the situation after restoration of the stream correctly.

Six adjustments were performed on the initial model. This was done at water board Vallei and Veluwe:

1. All sections, including all the structures outside of the study area (as described in section 2.2) were deleted and flow boundaries were added to the model at the locations of the up- and downstream boundaries of the Wittenoord-Beekweide course.
2. Bed levels of the stream were altered so that those agreed with the period that is modelled for the Lunterse beek (01-12-2011 till 15-02-2012). To alter the geometry, all the cross sections in the initial model were deleted and the measurements performed by Meet B.V. (2012) in February 2012 were imported in the Sobek model using the IRIStoSobek tool obtained from water board Vallei and Veluwe.
3. After modifying the study area extent and the bed levels, the settings of the weir Barneveldsestraat were changed. As explained in section 2.2 the weir was lowered to its minimal level during the restoration project.
4. The length of the flow links was changed in order to represent the new meandering length of the main channel.
5. Monitoring stations were added at the locations where validation of water levels need to take place (see section 3.2.1).
6. Bed roughness values were changed to represent the period directly after stream restoration.

This resulted in a new model geometry that is shown in Figure 17.

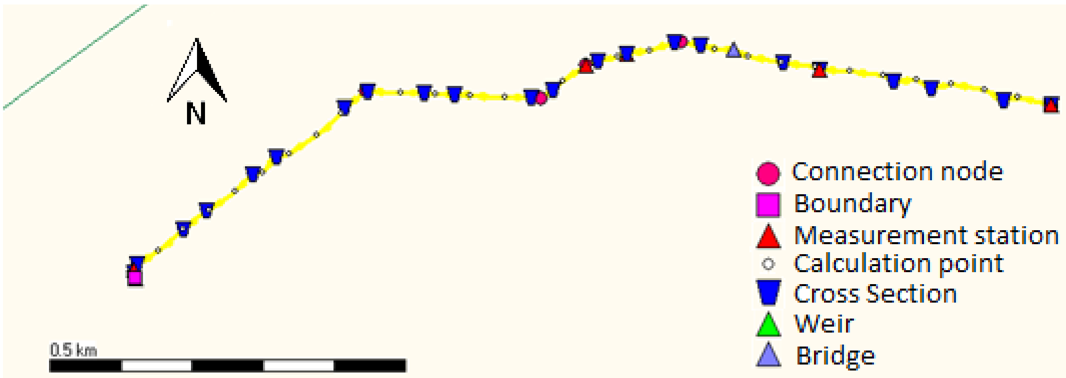

Figure 17: Final model geometry for the Sobek model of the Lunterse beek

The sixth adjustment performed in the model was to determine the bed roughness for the period directly after stream restoration. The bed roughness was specified for the Sobek model using the Manning roughness coefficient. This decision was made, because research showed that the Manning roughness parameter gives good results for vegetation that has a relatively high water depth on top of it (Huthoff, 2014). For the Lunterse beek this is likely to be the case in most of the study area, since a winter situation is modelled in which vegetation will be scarcely present. The locations where this is not likely to be the case are the locations where LWD was placed during restoration. The effect of using the Chézy roughness parameter (that gives better results when vegetation is relatively high compared to water levels (Huthoff, 2014)) instead of Manning in this section will be analysed in Appendix D.

The Manning roughness values for the Sobek simulations were determined using the Cowan method (Cowan, 1956). The Cowan method makes use of the formula listed below to take two-dimensional effects into consideration when setting up a one-dimensional model:

$$Manning's\ n = (n_b + n_1 + n_2 + n_3 + n_4)m$$

The two-dimensional effects described by the different parameters are shown in Table 12. Take note that Cowan (1956) makes a distinction between the main channel and the floodplain when determining the roughness parameters.

Table 12: The two-dimensional effects described by the different parameters in the Cowan method

Parameter	Explanation main channel	Explanation floodplain
n_b	Channel material	Floodplain material
n_1	Degree of irregularity	Degree of irregularity
n_2	Variation in channel cross-section	Variation in floodplain cross-section
n_3	Effect of obstructions	Effect of obstructions
n_4	Amount of vegetation	Amount of vegetation
m	Degree of channel meandering	Floodplain meander

Since the stream shows considerable variations with respect to the different parameters listed in Table 12, three different sections were distinguished. Section one is the most upstream section and has been actively restored by re-meandering. This section is highlighted in Figure 18.

Figure 18: First section for the Sobek schematization regarding bed roughness (photo 2012)

Section two is also a part that was actively restored by re-meandering, however this section is clearly different from the first section since LWD was placed in the stream. Section 2 is presented in Figure 19. The locations where LWD is placed are marked with red circles.

Figure 19: Second section for Sobek schematization regarding bed roughness (photo 2012)

The third and most downstream section that was distinguished is different from the first two sections since it was not actively restored. The straight planform shape of the stream was maintained in section three as can be seen in Figure 20.

Figure 20: Third section for Sobek schematization regarding bed roughness (photo 2012)

Besides differences in the alongshore direction of the stream, cross-shore differences were found. To start with, there is a difference in roughness between the main channel and the floodplains of the stream. This difference is also recognized by Cowan (1956). Both sections use the basic formula, but there is a difference in the parameter values and descriptions, as can be seen in Table 12.

For this study a distinction was also made between the close floodplain and the distant floodplain of the stream. The close floodplain is the part that was actively restored just like the main channel, while the distant floodplain was not. Besides this, the close floodplain is designed to actively participate in discharging water when water levels exceed a certain threshold. The distant floodplains on the other hand are often formed by pasture grounds that might flood during high discharge events, but are not meant to inundate.

As explained in section 3.2.1, 16 uniform discharge scenarios will be used for the model simulations with the modelled period ranging from 01-12-2011 until 15-02-2012. This means that stream restoration was just finished at that time and vegetation was still absent.

The Cowan method gives a range for all parameter values. For all calculations it was chosen to use the average value for the simulations. In Appendix D, the effect of this decision is investigated. In Table 13 the parameter values that will be used in the Sobek simulations are presented. Argumentation for selecting these values is given in Appendix E.

Table 13: Manning roughness values for Sobek simulations with uniform discharge scenarios

Section	Channel type	n_b	n_1	n_2	n_3	n_4	m	n_{Final}
1	Main channel	0.024	0.003	0.003	0.002	0.006	1	0.038
1	Close floodplain	0.024	0.008	0	0.002	0.006	1	0.040
1	Distant floodplain	0.024	0.008	0	0.025	0.0375	1	0.095
2	Main channel	0.024	0.003	0.003	0.025	0.006	1.15	0.070
2	Close floodplain	0.024	0.008	0	0.002	0.006	1	0.040
2	Distant floodplain	0.024	0.003	0	0.01	0.0375	1	0.075
3	Main channel	0.024	0.008	0	0.002	0.006	1	0.040
3	Close floodplain	0.024	0.003	0	0.002	0.006	1	0.035
3	Distant floodplain	0.024	0.003	0	0.01	0.0375	1	0.075

It may appear strange that in section 2 the roughness in the main channel exceeds the close floodplain roughness and is relatively close to the distant floodplain roughness. However, this is solely caused by the LWD that is present in the main channel as can be seen from parameter n_3.

3.5 Delft3D FM model Lunterse beek

In this section a description is given of how the Delft3D FM model for the Lunterse beek was set-up. The study area for the Lunterse beek was presented in section 2.2. For the Delft3D FM model this exact area is used to set-up the model. The lateral extent of the study area was harder to determine, since there is no levee or physical barrier present for the Lunterse beek floodplains. Therefore AHN2 data (Publieke Dienstverlening Op de Kaart, 2015) was used to determine the channel boundaries. An estimate of the maximum water level for the stream was made with an additional height of 0.3 m. This resulted in an extent of the study area as presented in Figure 21. To give more insight in how this corresponds to the study area of the Sobek model, the cross-section measurements (Meet B.V., 2012) that define the extent of the Sobek model are also shown in Figure 21.

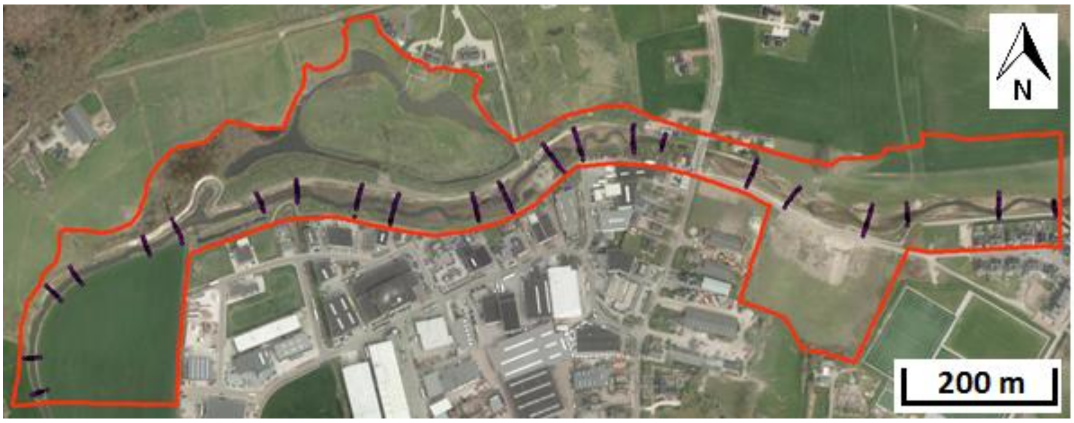

Figure 21: Study area of the Delft3D FM model (red line) for the Lunterse beek with the cross-sectional measurement locations in purple (Meet B.V., 2012) (photo 2012)

Figure 21 shows that the study area of the Delft3D FM model is larger than the study area of the Sobek model. A check for the Delft3D FM model showed that the study area was chosen large enough for the discharge scenarios that are used in this study. Water will remain within the study area specified in Figure 21 for all discharge scenarios. For the Sobek model it was found that the study area was not large enough in the upstream section for discharges exceeding 5.0 m^3/s (for the 1^{st} to 5^{th} cross-section in the study area). In the Sobek model, water will stay within the model since a vertical wall will be assumed at the outer boundaries of each cross-section. It has to be taken into account though that simulated hydraulics will be slightly affected in this section. Simulated water levels will likely be higher as are flow velocities (due to the absence of roughness in this area).

After defining the study area, a grid was set-up for calculations in the Delft3D FM software. For the main channel, a curvilinear grid was set-up with an average cell size around 0.4 by 1.0 m in lateral and flow direction respectively. This makes that the main channel has 18 cells in lateral direction and around 2000 cells along the stream. For the floodplains a triangular grid was created. Close to the main channel cell size lies around 1 x 1 x 1 m. Figure 22 shows part of the grid in which the main channel (curvilinear grid) is already connected to the floodplains (non curvilinear grid).

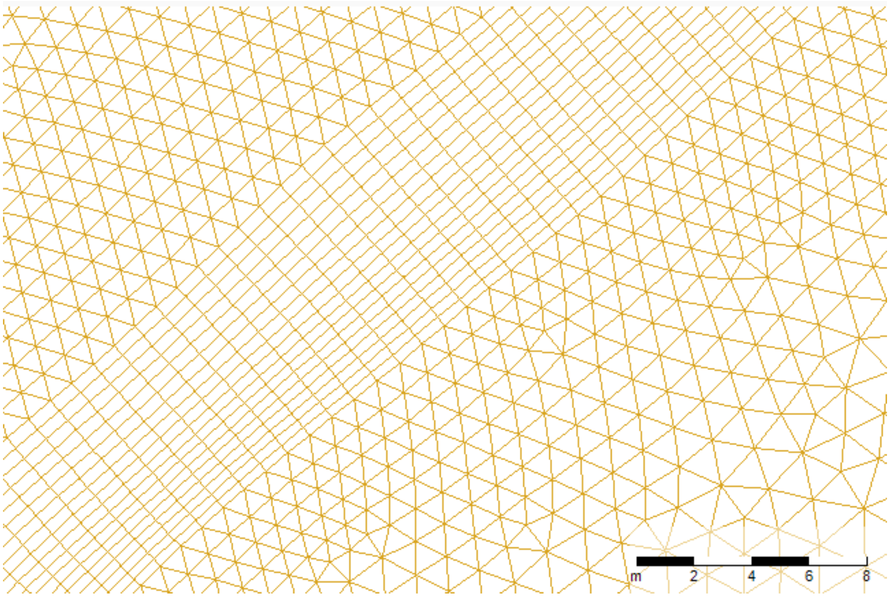

Figure 22: Part of the grid in the Delft3D FM model (Lunterse beek) showing the main channel and the floodplain

Towards the outer edges of the floodplains, the cell size of the grid increases gradually. At the most outward boundaries of the floodplains the cell size varies between 4 x 4 x 4 meter up to 10 x 10 x 10 meter, depending on how far the location is situated from the main channel.

After generating a grid, the bathymetry of the main channel was created. For this, the same cross-sectional measurements were used as for the Sobek model (Meet B.V., 2012). However, since a complete bathymetry is required for the Delft3D FM model an interpolation of the data was needed. For this interpolation, the tool Surfis2D (RIZA Rijkswaterstaat, 2004) was used. This tool was developed by Rijkswaterstaat and is specifically suited to interpolate river cross-section measurements to a complete bathymetry while taking into account the meandering shape of the waterway. The sensitivity for this interpolation tool is tested in Appendix F. It was found that the bathymetry obtained with the Surfis2D interpolation tool is highly dependent upon the amount of cross-sectional bed level measurements used as input. For this specific test is was found that the bathymetry is on average higher if less cross-sectional bed level measurements are used.

The measurements performed by Meet B.V. (2012) were also used to create a bathymetry for the floodplains where possible. At locations where measurements were missing, AHN2 (Publieke Dienstverlening Op de Kaart, 2015) data was used. This made it possible to create a bathymetry that was nearly covering the entire study area. An analyses in differences between AHN2 data and measurements is presented in Appendix G, since AHN2 data was measured in 2010 while the modelling period is the winter of 2011/2012. Comparison between the measured bed levels and AHN2 data showed that on average the bottom level was 0.27 m higher for the AHN2 measurements. This will result in higher simulated water levels if flow occurs in these areas.

For the locations where both AHN2 measurements and measurements performed by Meet B.V. (2012) were missing, the below given assumptions were made:

- Buildings: bed level height 12 m +NAP (means a height of around 7 m for all buildings)
- Waters that are not part of the Lunterse beek: a water depth of 0.5 m relative to surroundings
- Other areas: equal height to surroundings

This resulted in a complete bathymetry for the Delft3D FM model that is presented in Figure 23.

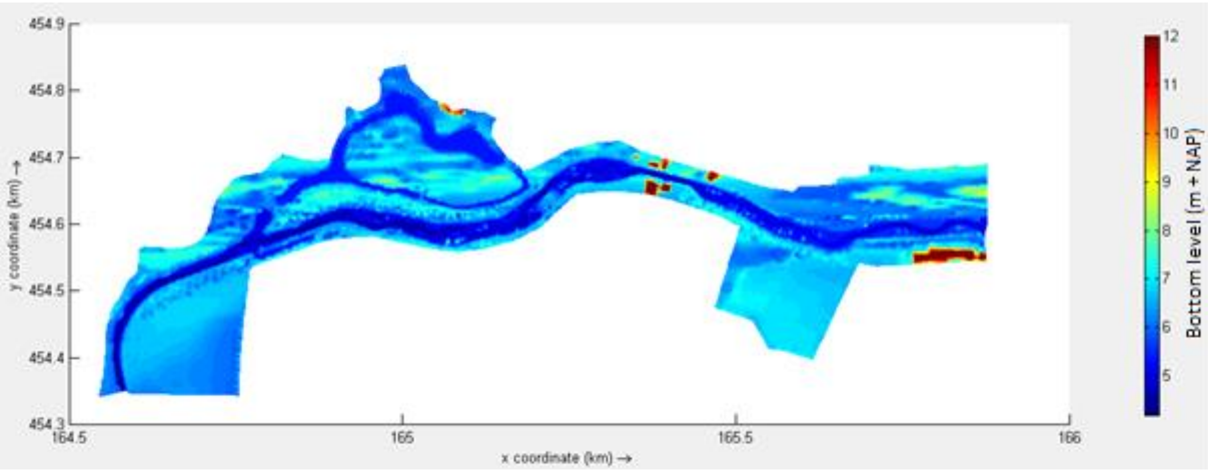

Figure 23: Bathymetry for the Delft3D FM model of the Lunterse beek

To define the bed roughness in Delft3D FM, a spatially varying roughness was used over the entire grid. The roughness was defined using the Manning roughness parameter as was used in the Sobek model. The roughness values were determined based upon typical characteristics of the different parts in the study area. The different types of area that were distinguished for the Lunterse beek are presented in Table 14.

Table 14: Different characteristic areas in the Lunterse beek study area

Type	Characteristics
Main channel	Sandy bottom
Floodplain close to main channel	Sandy bottom
Pasture	Grass
Large Woody Debris	Trees
Roads	Asphalt
Houses	Bricks
Forest	Trees
Garden	Diversified

For the different areas, roughness values were selected using the "Cultuurtechnisch Vademecum", in which a range of k_m roughness values is specified. These values were converted to Manning roughness values using the formula specified below (Ribberink & Hulscher, 2012):

$$C = R^{1/6} * k_m = \frac{R^{1/6}}{n} \quad \text{(Eq. 1)}$$

From this it follows that:

$$n = \frac{1}{k_m} \quad \text{(Eq. 2)}$$

The Manning roughness values that will be used in the simulations with the Delft3D FM model are presented in Table 15 and Figure 24. Besides that, Table 15 specifies the range for these roughness values. The range is determined by the upper and lower limits of the selected roughness categories for the different vegetation types. The motivation for using these values is given in appendix H.

Table 15: Manning roughness values (n) for the different area types in the Delft3D FM model for the Lunterse beek

Type	n_{lower}	n_{upper}	$n_{selected}$
Main channel	0.022	0.05	0.033
Floodplain close to main channel	0.022	0.05	0.033
Pasture	0.05	0.2	0.1
Large Woody Debris	0.075	0.125	0.1
Paved area	0.029	0.067	0.05
Houses	1	1	1
Forest	0.1	0.5	0.2
Garden	0.05	0.2	0.1

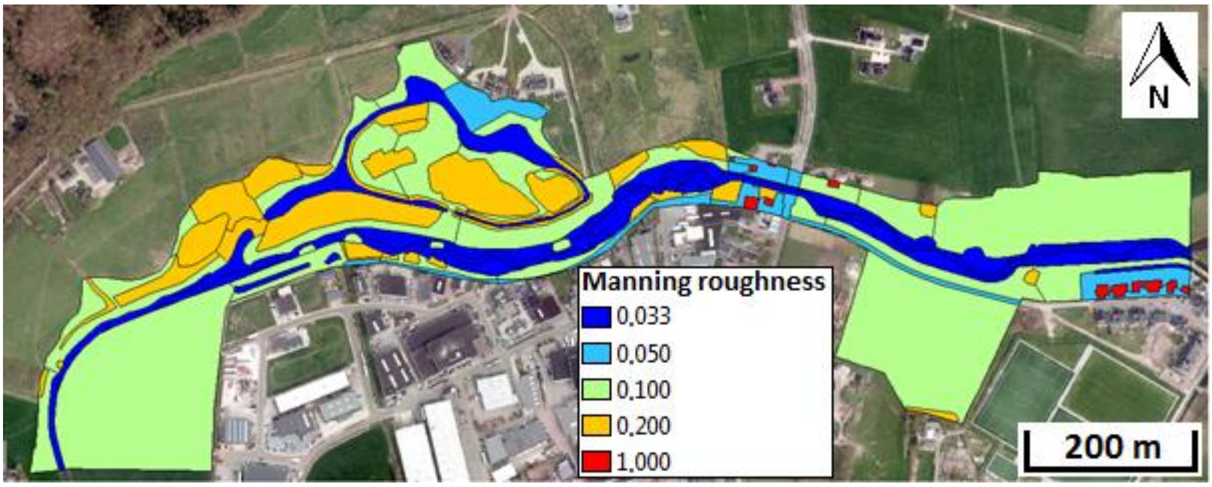

Figure 24: Spatially varying roughness in the Delft3D FM model for the Lunterse beek

3.6 Delft3D FM model Tungelroyse beek

This section describes how the Delft3D FM model for the Tungelroyse beek was set-up. The study area for the Tungelroyse beek was presented in section 2.3. For the Delft3D FM model this exact area is used to set-up the model. The lateral extent of the study area was determined based on AHN2 data (Publieke Dienstverlening Op de Kaart, 2015), since no levee or physical barrier is present for the floodplains of the Tungelroyse beek. By estimating the maximal water level in the study area and a margin of 0.3 m, the extent of the study area as presented in Figure 25 was obtained.

Figure 25: Study area of the Delft3D FM model for the Tungelroyse beek

After defining the study area, a grid was set-up for calculations with the Delft3D FM software. For the main channel, a curvilinear grid was set-up with an average cell size around 1.8 by 2.0 m in lateral and flow direction respectively. A different cell size was chosen compared to the Lunterse beek since dimensions differ between the streams. Besides that, cell size was increased to improve upon calculation times of the model. This resulted in 8 cells in lateral direction for the main channel and around 1900 cells along the stream. For the floodplains a triangular grid was created. Close to the main channel cell size lies around 1.8 x 1.8 x 1.8 m. Figure 26 shows part of the grid in which the main channel (curvilinear grid) is already connected to the floodplains (non curvilinear grid).

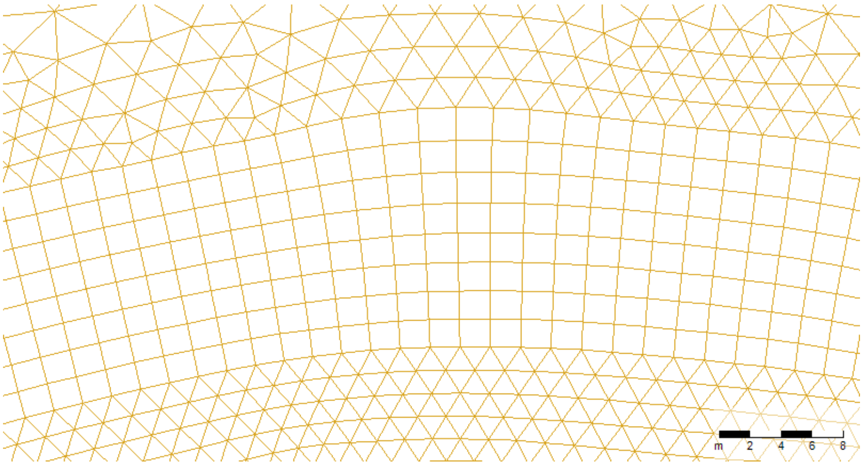

Figure 26: Part of the grid in the Delft3D FM model (Tungelroyse beek) showing the main channel and the floodplain

Towards the outer edges of the floodplains, the cell size of the grid increases gradually. At the most outward boundaries of the floodplain cell size varies. Depending on how far the location is situated from the main channel, cell size can vary between 4 x 4 x 4 meter up to 20 x 20 x 20 meter.

After generating a grid, the bathymetry of the channel was created. Measurements performed by Menten & Strigencz (2012) were used for this. To create a bathymetry that was spatially covering the main channel, the Surfis2D interpolation tool was used (RIZA Rijkswaterstaat, 2004). Since the measurements were not performed for the entire study area, AHN2 data was used in addition to these measurements. The AHN2 data for the area was collected in 2012 (Zon, 2013) while the measurements were performed in 2010/2011 (Menten & Strigencz, 2012). Therefore a comparison between AHN2 data and the measurements was performed, which can be found in Appendix G. The average bottom level was found to be 0.11 m higher in the AHN2 data compared to the measurements performed by Menten & Strigencz (2012), which will result in an overestimation of water levels as flow enters the floodplains.

For the locations where both AHN2 measurements and measurements performed by Menten & Strigencz (2012) were missing, the below given assumptions were made:

- Water that is not part of the Tungelroyse beek has a water depth of 0.5 m compared to its surroundings
- Other areas: equal height to surroundings

The complete bathymetry of the Delft3D FM model is presented in Figure 27.

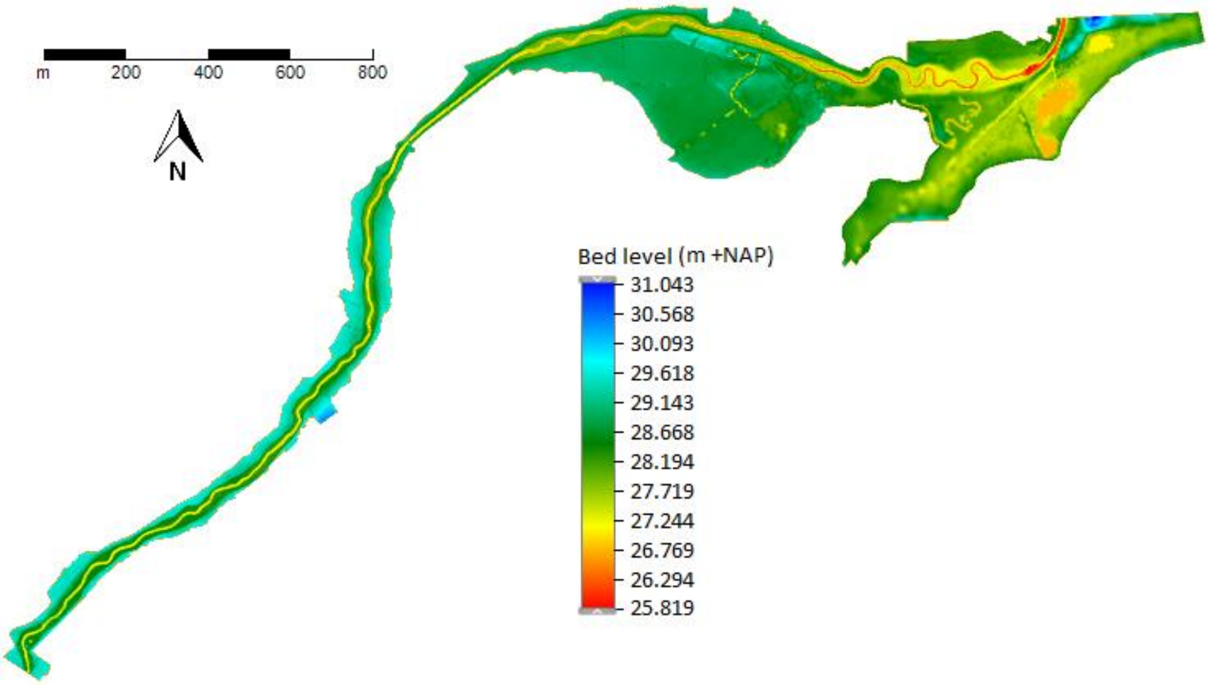

Figure 27: Bathymetry for the Delft3D FM model of the Tungelroyse beek

For the Delft3D FM model of the Tungelroyse beek, spatially varying roughness was used. The Manning roughness parameter was used again to define the bed roughness. The roughness was determined based upon the different types of land use in the study area. The types of area distinguished are presented in Table 16.

Table 16: Different land use types in the study area for the Tungelroyse beek

Type	**Characteristics**
Roads	Asphalt
Water	Main channel/Ponds/Ditches/De Vliet/Floodplains De Vliet
Floodplain close to main channel	Brushy/Sandy
Nature	Moorland
Agriculture	Maize/Onions/Asparagus/Peas/Salsify/Home garden
Houses	Bricks
Pasture	Grass
Forest	Trees

For the different areas, roughness values were selected using the "Cultuurtechnisch Vademecum", in which a range of k_m roughness values is specified. These values were converted to Manning roughness values using Equations 1 and 2 as specified in section 3.5.

The roughness values that were selected are presented in Table 17, together with the maximal and minimal value in the range. A map of the spatial roughness for the study area is shown in Figure 28. The motivation for choosing the values presented here is given in Appendix J.

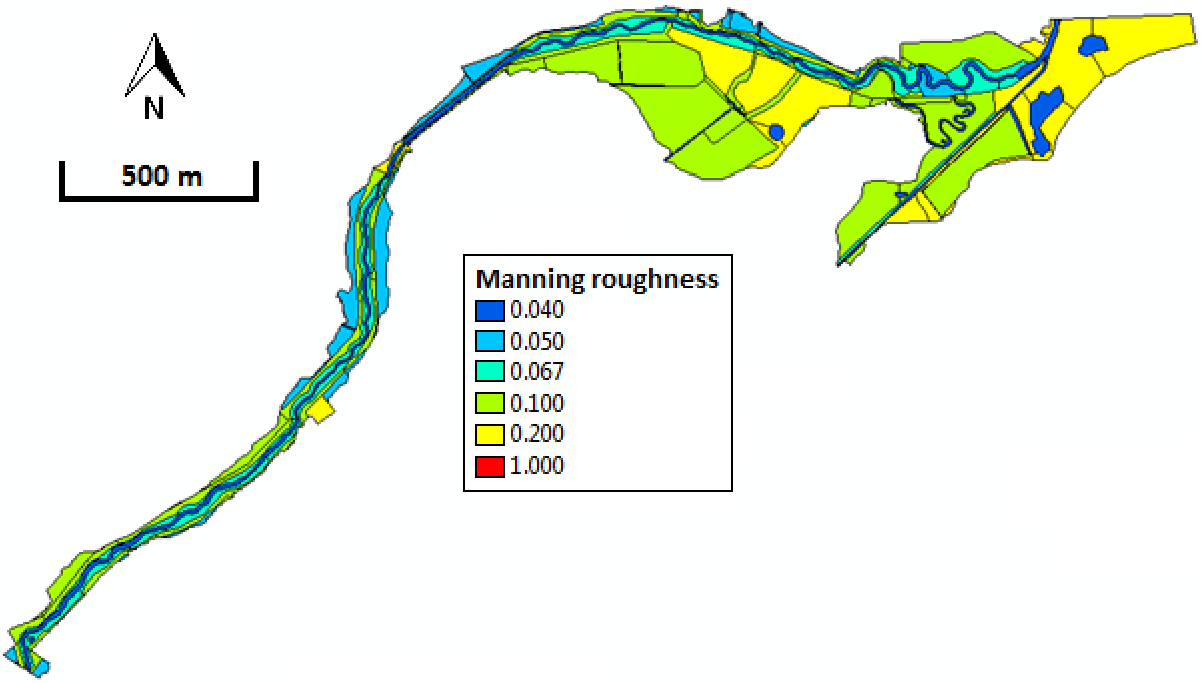

Figure 28: Spatial roughness map for the Delft3D FM model of the Tungelroyse beek

Table 17: Manning roughness values for the different land use types in the Tungelroyse beek study area

Type	Characteristics	n_{lower}	n_{upper}	$n_{selected}$
Roads	Asphalt	0.029	0.067	0.05
Water	Main channel	0.029	0.067	0.04
Water	Ponds	0.029	0.067	0.04
Water	Ditches	0.029	0.067	0.04
Water	De Vliet	0.029	0.067	0.04
Water	Floodplains De Vliet	0.04	0.1	0.067
Floodplains close to main channel	Brushy	0.04	0.1	0.067
Floodplains close to main channel	Sandy	0.029	0.067	0.05
Nature	Moorland	0.05	0.2	0.1
Agriculture	Maize	0.029	0.067	0.05
Agriculture	Onions	0.029	0.067	0.05
Agriculture	Asparagus	0.05	0.2	0.1
Agriculture	Peas	0.029	0.067	0.05
Agriculture	Salsify	0.029	0.067	0.05
Agriculture	Home garden	0.029	0.067	0.05
Houses	Bricks	1	1	1
Pasture	Grass	0.05	0.2	0.1
Forest	Trees	0.1	0.5	0.2

4. Methodology: morphology and vegetation

In this chapter section 4.1 describes the method that will be used to forecast morphological developments and validate those. In section 4.2 the method that will be used to make vegetation development forecasts is explained along with the validation methods that will be used.

4.1 Morphological developments

With respect to morphological developments, two different processes are important: bed erosion/sedimentation (vertical processes) and bank erosion (horizontal processes). To obtain insight in locations where vertical processes might occur for the Lunterse and Tungelroyse beek, maps will be made. The method that will be used for this is explained in section 4.1.1. Besides those maps, other forecasts will be made in which the method differs slightly for the Lunterse and Tungelroyse beek. This mainly has to do with the difference in validation data that is available for both streams. The method for the Lunterse beek will be explained in section 4.1.2 and the method for the Tungelroyse beek in section 4.1.3.

4.1.1 General

The bed of both the Lunterse and Tungelroyse beek consists of grains. With water flowing over the grains, forces are exerted on the grains near the bed as presented in Figure 29 (Ribberink, 2011):

- Flow forces (consisting of a drag and lift force)
- Gravity forces
- Resultant reaction forces from the surrounding grains

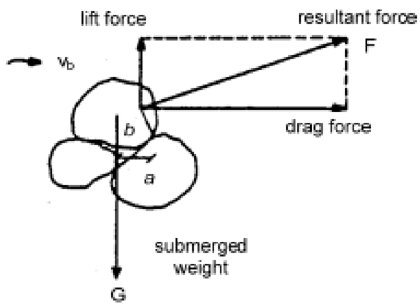

Figure 29: Forces exerted on grains in the stream bed (Ribberink, 2011)

The so called Shields-parameter (θ) is used to define the relation between the forces, giving a measure for the mobility of the sediment (Ribberink, 2011):

$$\theta = \frac{u_*^2}{g\Delta D} \quad \text{(Eq. 3)}$$

With:

$$u_* = u\frac{\sqrt{g}}{C} \quad \text{(Eq. 4)}$$

θ = Shields parameter (-)
u_* = Shear velocity (m/s)
g = Gravitational acceleration (m/s^2)
Δ = Relative density (-)
D = Average grain size diameter (m)
u = Average flow velocity (m/s)
C = Chézy roughness parameter (m$^{1/2}$/s)

Transport will only occur if the Shields parameter exceeds the critical Shields parameter (θ_{cr}), that is dependent upon grain attributes and flow patterns near the bottom (Ribberink, 2011):

$$\begin{aligned}
\theta_{cr} &= \frac{0.24}{D_*} && \text{if } 1 < D_* \leq 4 \\
\theta_{cr} &= \frac{0.14}{D_*^{0.64}} && \text{if } 4 < D_* \leq 10 \\
\theta_{cr} &= \frac{0.04}{D_*^{0.1}} && \text{if } 10 < D_* \leq 20 \qquad \text{(Eq. 5)} \\
\theta_{cr} &= 0.013 D_*^{0.29} && \text{if } 20 < D_* \leq 150 \\
\theta_{cr} &= 0.055 && \text{if } D_* > 150
\end{aligned}$$

With:

$$D_* = \left(\frac{\Delta g}{\nu^2}\right)^{1/3} D \quad \text{(Eq. 6)}$$

And:

$$\Delta = \frac{\rho_s - \rho}{\rho} \quad \text{(Eq. 7)}$$

θ_{cr} = Critical Shields parameter (-)
D_* = Dimensionless grain diameter (-)
ν = Kinematic viscosity (m^2/s)
ρ_s = Density of sediment (kg/m^3)
ρ = Density of water (kg/m^3)

Model output of the DFlow FM model provides both the flow velocity (u) and the Chézy roughness parameter (C). Substituting Equation 4 into Equation 3 and rewriting in terms of u and C gives:

$$\frac{u}{C} = \sqrt{\theta \Delta D} \qquad \text{(Eq. 8)}$$

For transport to occur, the Shields parameter needs to exceed the critical Shields parameter. From this it can be seen that the below given equation holds:

$$\frac{u}{C} > \sqrt{\theta_{cr} \Delta D} \quad \text{Transport}$$
$$\frac{u}{C} < \sqrt{\theta_{cr} \Delta D} \quad \text{No transport} \qquad \text{(Eq. 9)}$$

The assumptions made for the transport parameters in the Lunterse and Tungelroyse beek are presented in Table 18.

Table 18: Assumptions made with respect to the transport parameter values for the Lunterse and Tungelroyse beek

General	
ρ_s	2650 kg/m^3
ρ	1000 kg/m^3
ν	1.0*10^{-6} m^2/s
g	9.81 m/s^2
Lunterse beek	
D	258*10^{-6} m (Eekhout, 2014)
Tungelroyse beek	
D	141*10^{-6} m (Eekhout, 2014)

Using Equations 5, 6, 7 and 9 the following statements hold for the Lunterse beek and Tungelroyse beek respectively:

$$\frac{u}{C} > 4.236 * 10^{-3} \quad \text{Transport}$$
$$\frac{u}{C} < 4.236 * 10^{-3} \quad \text{No transport} \qquad \text{Lunterse beek}$$

$$\frac{u}{C} > 3.957 * 10^{-3} \quad \text{Transport}$$
$$\frac{u}{C} < 3.957 * 10^{-3} \quad \text{No transport} \qquad \text{Tungelroyse beek}$$

Maps will be created for 5 stationary discharge scenarios; T100, T10, T1, T0.05 and T0.005. The areas that will be analysed are shown in section 4.1.2 for the Lunterse beek and 4.1.3 for the Tungelroyse beek.

4.1.2 Lunterse beek

After looking into locations where transport is likely to occur, 2 methods will be used for the Lunterse beek to base morphological forecasts upon. For the first method, flow velocity and flow direction output of the Delft3D FM model will be used. Maps will be created showing flow velocity and flow direction for 5 stationary discharge scenarios; T100, T10, T1, T0.05 and T0.005. These maps will be created more specifically for the section highlighted in red in Figure 30, since bed level measurements were performed here.

The period that will be considered for developments in morphology is between 22-02-2012 and 20-04-2012. Bed levels were measured on both days and besides that, this period corresponds to the model period of 01-12-2011 till 15-02-2012 almost perfectly. Especially considering that the geometry of the bed is based upon measurements performed in February 2012 (Meet B.V., 2012).

Figure 30: Location where forecasted morphological developments will be compared to monitored developments for the Lunterse beek

For the validation, a qualitative comparison will be performed between the flow velocity and flow direction maps created for the different discharge scenarios and the monitored bed level developments.

The second method will be performed for the same section of the Lunterse beek, since validation data is available here. To start with, the discharge potential will be used to determine flow paths in the stream. These flow paths define the discharging direction of the water flow. After that, the flow velocity gradient on these flow paths will be determined and a map will be created based upon this output. Sedimentation is expected if the gradient is negative, while erosion is expected for a positive gradient (using a downwind scheme). The output of the second method will be validated with the monitored development between 22-02-2012 and 20-04-2012.

4.1.3 Tungelroyse beek

For the Tungelroyse beek only 1 method will be used to forecast morphological development, after looking into locations where transport might occur. The method will be the same as for the Lunterse beek, using flow velocity and flow direction output of the Delft3D FM model to make maps for a particular area of the stream. The same five stationary discharge scenarios will be used (T100, T10, T1, T0.05 and T0.005). The difference with the Lunterse beek is that no quantitative bed level measurements were performed after restoration, making that validation needs to be performed in a different way.

For the Tungelroyse beek, a section was found that is particularly interesting, since it is strongly winding but has proven to be very stable over time looking at its planform shape. This is shown in Figure 31 where both the 2012 situation and 2015 situation of this area are shown. Even though flow conditions are not necessarily the same for both photos, it becomes clear that no major changes have occurred in the meandering shape. This indicates that bank erosion is a process that likely did not occur in this section. Bed level development in the stream is therefore likely caused by bed erosion and sedimentation processes, but since no quantitative data is available this cannot be validated.

Figure 31: Section of the Tungelroyse beek in the 2012 and 2015 situation

The location of the section that is of interest for morphological developments is shown in Figure 32. The comparison between the flow velocity and flow direction maps with monitored developments will be performed qualitatively. More specifically, it will be analysed if flow velocities remain low. Also, flow direction patterns will be analysed to see if these are in agreement with the stability of the planform shape as seen in the aerial images.

Figure 32: Location where flow velocity maps with flow direction will be compared to monitored morphological change (background photo 2015)

4.2 Developments in vegetation

A literature study was performed to get more insight in the driving factors behind developments in vegetation. This literature study is summarized in Appendix K. The main conclusion of the literature study is that vegetation growth is dependent upon many factors, for example: light conditions, nutrient concentrations, substrate characteristics, trophic status, flood frequency and flow velocity. For this study, the forecasts in vegetation growth will be solely based upon depth averaged flow velocities though. The literature study showed that higher flow velocities in general lead to lower vegetation biomass and lower flow velocities to higher vegetation biomass. The 5 categories that will be used in the forecasts are shown in Table 19.

It has to be noted that only locations where water is present can be analysed in these forecasts, since the Delft3D FM model does not give output regarding groundwater levels. It is assumed that for locations where water is not present in the model, no vegetation will grow. It is known that in reality this might be different. Where possible, model locations without water depth are excluded in the analysis.

Table 19: Five different categories used in forecasting developments in vegetation

Category	Amount of vegetation	Depth averaged flow velocities (m/s)
1	Abundant vegetation	0 – 0.2
2	Quite a bit of vegetation	0.2 – 0.4
3	Vegetation	0.4 – 0.6
4	Small amounts of vegetation	0.6 – 1.0
5	No vegetation	> 1.0

The vegetation forecasts of both streams will be made for 5 discharge scenarios; T100, T10, T1, T0.05 and T0.005. Validation will be performed differently for both streams.

For the Lunterse beek validation will be performed by using an aerial image with a high resolution. This image was made on the 9th of September 2015 by Andrès Vargas Luna and has a resolution of 2.13 by 2.13 cm. Due to this high resolution, an estimation of vegetation biomass can be made based upon what is seen with the naked eye. Polygons will be drawn, differentiating between the classes as presented in Table 20. These categories agree with the categories as shown in Table 19. After that, the polygons will be compared to the forecasts to analyse for which area the forecasts agree with the monitored developments in vegetation.

Table 20: Description of vegetation classification for validation purposes

Category	Description	Estimation vegetation biomass (kg/m^2)
1	Dense and high vegetation	> 0.2
2	High vegetation with low density	0.15 – 0.2
3	Vegetation that is not low nor high	0.1 – 0.15
4	Low vegetation	0.01 – 0.1
5	No visible vegetation	< 0.01

For the Tungelroyse beek, validation will be performed using a map of the Normalized Difference Vegetation Index (NDVI). A NDVI map will be made for the 2013 situation using ArcMap software and the aerial image obtained from water board Peel and Maasvallei. This map gives an indication for the density of green on a patch of land, because the pigment in plant leaves strongly absorbs visible light for use in photosynthesis (Govaerts & Verhulst, 2010), while the cell structure of the leaves strongly reflects near-infrared light. The NDVI is calculated by the below given formula:

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \qquad \text{(Eq. 10)}$$

NIR = Near-infrared radiation
VIS = Visible red radiation

The result is a map with values ranging from -1 to +1. A higher density of green leaves results in a higher NDVI value. The NDVI map will be compared to the forecasts by dividing the NDVI values into 5 classes of vegetation amounts depending on the NDVI values. A disadvantage to using a NDVI map is that the in-stream development of vegetation cannot be assessed, since the water reflects the light differently.

5. Results Lunterse beek

The results for the Lunterse beek are presented in this chapter. First the simulated water levels are compared with monitored water levels in section 5.1. In section 5.2 the morphological forecasts are compared to monitored developments in morphology. Finally in section 5.3, a comparison is performed between forecasted and monitored developments in vegetation.

5.1 Water levels

Resulting water levels from the Delft3D FM model and the Sobek model are presented in Figure 33. Besides that the Q-h relationships based upon monitored water levels at the different locations are shown. An uncertainty of 10% in discharge measurements is included, since it was shown that uncertainty for discharges measured with an acoustic flow meter is often between 5 and 10% (Hartong & Termes, 2009). The fit characteristics for the Q-h relations are given in Appendix A and the fit characteristics for the relations fitted to the discharge measurements including 10% uncertainty are given in Appendix I.

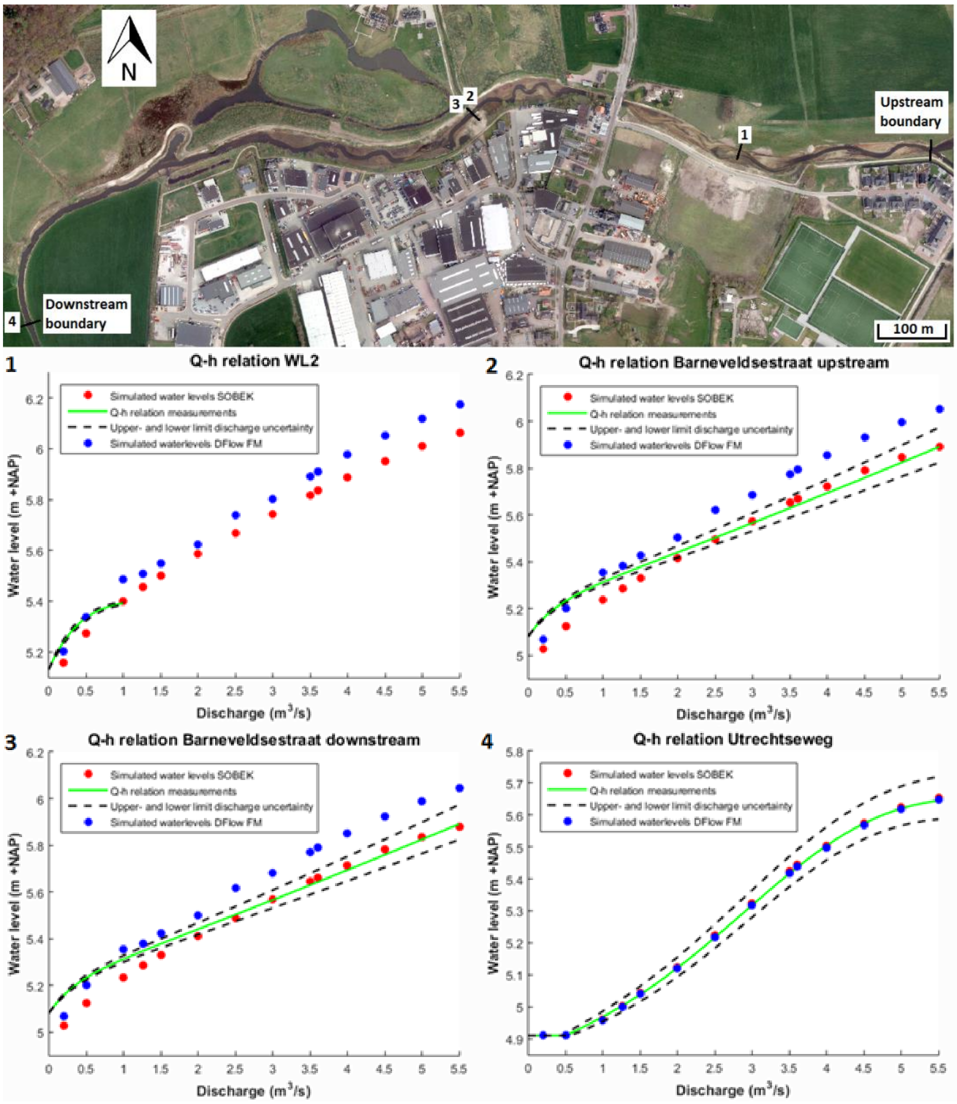

Figure 33: A comparison between modelled and monitored water levels for the Lunterse beek

As can be seen from the 4th graph in Figure 33, the simulated water levels from both the Sobek and the Delft3D FM model match with the monitored Q-h relation at the downstream boundary of the model. At this measurement station (Utrechtseweg) a water level boundary is imposed. Therefore this is not a measure of model performance, but it shows that model calculations at this location agree with the imposed boundary condition.

The 3rd graph in Figure 33 shows the water levels simulated at measurement location Barneveldsestraat downstream. The water levels predicted by the Sobek model agree quite well with the water levels described by the Q-h relation for discharges exceeding 2.5 m^3/s. For the lower discharges the Sobek model underestimates monitored water levels. In the 2nd graph of Figure 33 the same pattern is seen for the Sobek model at measurement location Barneveldsestraat upstream.

At measurement station WL2, the 1st graph in Figure 33, a Q-h relation is only fitted up to a discharge of 1 m^3/s because a limited amount of measurements is available for this location. Therefore it is difficult to evaluate the performance of the Sobek model for this location. Conclusions regarding performance of the Sobek model are therefore solely based upon the Barneveldsestraat measurement stations. It becomes clear that the model performs really well, especially taking into account that the model has not been calibrated.

For the Delft3D FM model graphs 2 and 3 in Figure 33 show that water levels exceed the fitted Q-h relations when discharge surpasses 1 m^3/s. The overestimation of water levels grows with increasing discharge, ending in an overestimation of around 16 cm for a 5.5 m^3/s discharge event. Based upon these measurement stations only, it can be stated that the Sobek model outperforms the Delft3D FM model when it comes to water level forecasts. It has to be noted though that both models have not been calibrated, which means that the performance of both models could likely improve. Therefore a sensitivity analysis was performed for both models to get more insight in how well the models can perform after calibration. Besides that, this sensitivity analysis might give additional understanding that can be used in the set-up of future models by adding experience and data related to working with the Delft3D FM and Sobek software in modelling stream restoration.

Sensitivity analysis

An initial sensitivity analysis was performed for the Delft3D FM model of the Lunterse beek, but in this model the floodplain bathymetry was not correct. The final model as used for water level calculations in this chapter has a different floodplain bathymetry. Still, the sensitivity analysis gave useful insight in the model parameters that had the most influence on simulated water levels in the Delft3D FM model. The three model parameters that turned out to be most important were: bed roughness, main channel bed level height and the bed level interpolation method. In Appendix I, the results of the initial sensitivity analysis are presented.

Using the initial sensitivity test as a guideline, the sensitivity of the final model was tested for two parameters using the 1, 3 and 5.5 m^3/s stationary discharge scenarios. Changes in roughness and the bed level interpolation method were investigated to assess how well the Delft3D FM model can perform after calibration. That the model is sensitive for changes in bed level of the main channel is clear from the initial sensitivity analysis. Besides that, the uncertainty introduced by the Surfis interpolation for the main channel height was investigated in Appendix F.

Just like in the initial sensitivity analysis, the uncertainty in water level and discharge measurements will be included. The uncertainty can be mainly expected in the discharge measurements, since for discharge measurements performed with an acoustic flow meter, uncertainty is often between 5 and 10 % (Hartong & Termes, 2009). Just like in the previous sensitivity analysis, this will be accounted for by assuming a 10% deviation in discharge measurements with equal water levels and fitting new Q-h relations to these newly created measurement series. The characteristics of these Q-h relations can be found in Appendix I.

Bed roughness

For the bed roughness, a plausible range of Manning roughness values was identified upfront for the Delft3D FM model as explained in section 3.5. The effect of selecting the lowest and highest bed roughness value for the entire Lunterse beek study area is shown in Figure 34, while the Manning bed roughness values that were used in this analysis are presented in Table 21.

Table 21: Lowest and highest Manning roughness values expected for the different area types in the Delft3D FM model

Type	n_{lower}	n_{upper}
Main channel	0.022	0.05
Floodplain close to main channel	0.022	0.05
Pasture	0.05	0.2
Large Woody Debris	0.075	0.125
Roads	0.029	0.067
Houses	1	1
Forest	0.1	0.5
Garden	0.05	0.2

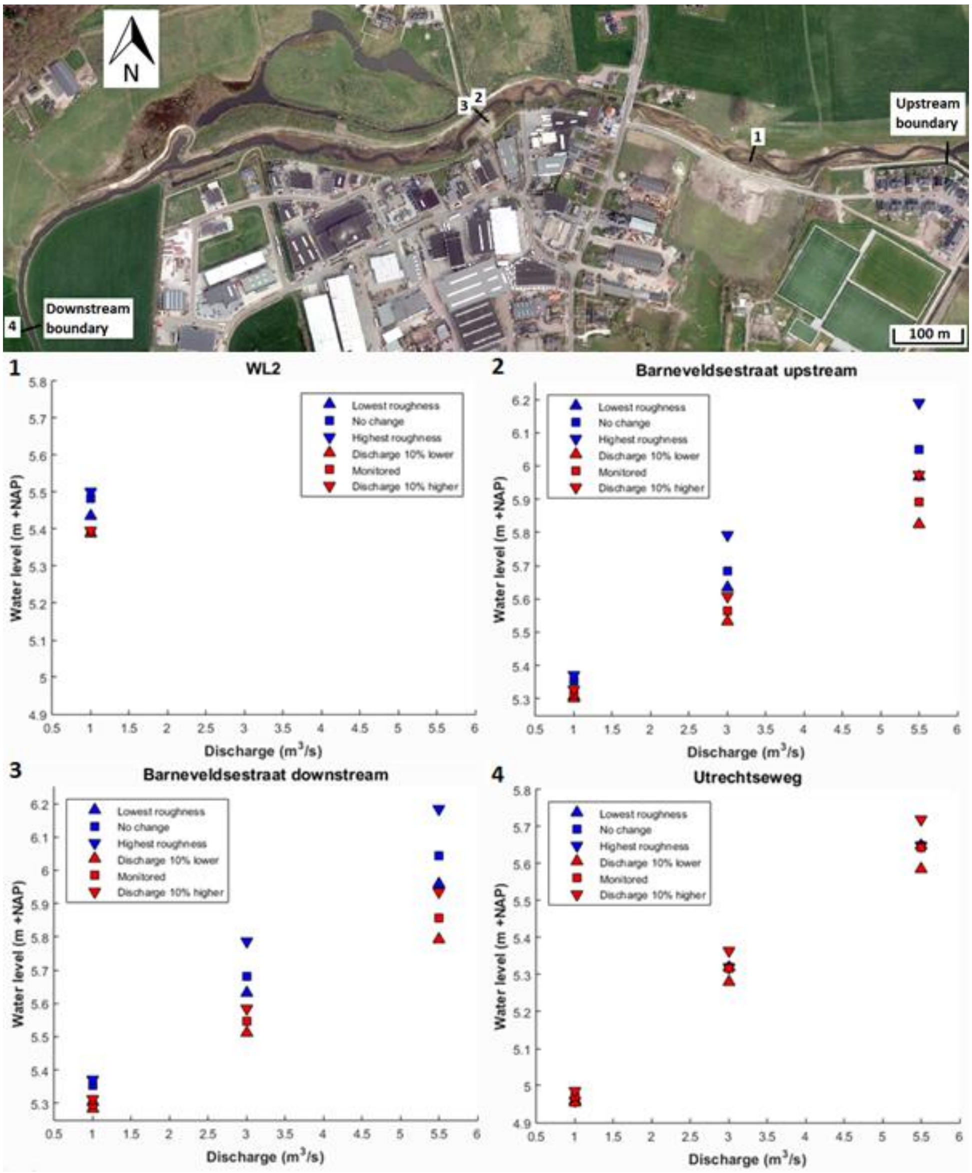

Figure 34: Sensitivity of the Delft3D FM model for changes in bed roughness

From Figure 34 it becomes clear that the bed roughness affects simulated water levels significantly. An overestimation of water levels remains present in the Delft3D FM model though, even if the lowest roughness is used for the entire study area. However, the modelled water levels approach the monitored water levels. Including the uncertainty in the discharge measurements, it can be seen that the simulated water levels fall within the range of uncertainty for both Barneveldsestraat validation locations if the discharge is 1 m^3/s and for the Barneveldsestraat upstream if the discharge is 5.5 m^3/s.

Interpolation method
To determine the bed level height in each cell, the default setting in Delft3D FM uses the average height of the neighbouring nodes for each cell. The effect of using the minimal and maximal values to determine the height in each cell is shown in Figure 35.

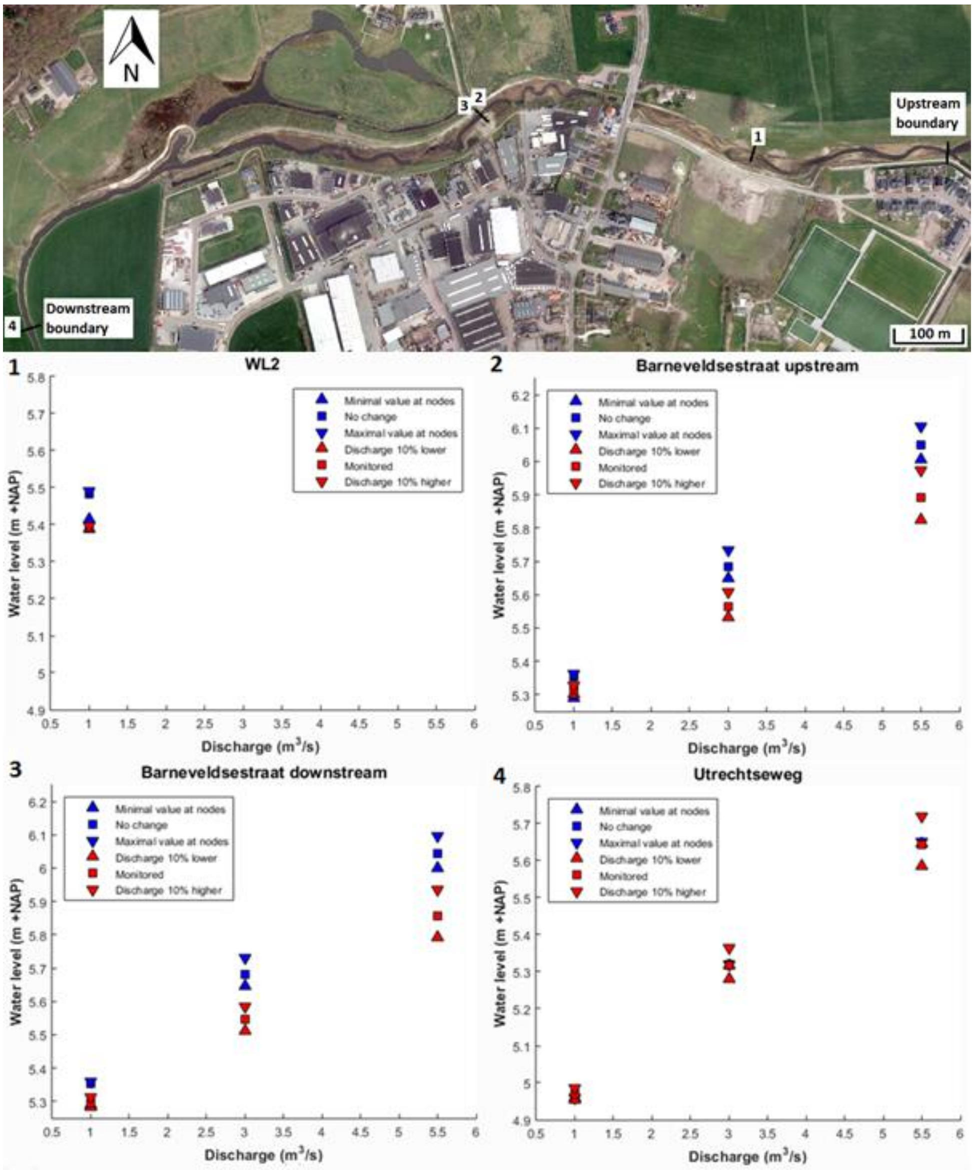

Figure 35: Sensitivity of the Delft3D FM model for changes in bed level interpolation method

Figure 35 shows that the effect of the bed level interpolation method on simulated water levels is considerable also, but slightly lower than for the bed roughness parameter. Using the minimal value at nodes to determine the height for each cell lists better results than the average and maximum node height. However, even if uncertainty is included for the measurements, the simulated water levels still overestimate monitored water levels.

Sensitivity analysis results

From this sensitivity analysis it has to be concluded that the uncalibrated Delft3D FM model can perform better with respect to water level forecasts if certain model parameter values are changed. However, since this investigation is targeted on stream restoration projects in their design phase, it has to be noted that calibration of the models is not possible. In this specific case, choosing the lowest roughness expected gives better results for simulated water levels. More research is needed to find out if this is also the case for other stream restoration studies. If this is the case, it becomes clear that roughness formulation for two-dimensional models in stream restoration projects should be more conservative compared to one-dimensional models.

A different conclusion from this sensitivity analysis is that changes in single model parameters are not able to describe fully why water levels simulated with the Delft3D FM model are consistently higher than those generated with the Sobek model and the monitored water levels. It might be that a combination of lower bed roughness and different bed level interpolation method results in water levels that fall within the monitored range though. Besides that, it was already explained that some uncertainties were introduced in the validation data since discharge measurements were shifted to obtain an upstream boundary condition. Also the hysteresis effect is neglected in the stationary discharge measurements, while this was included when the Q-h relations were fitted for validation purposes.

Still an additional test was performed with a straight channel in both the Sobek and Delft3D FM model. The purpose of this test was to analyse if the Delft3D FM and Sobek model simulate equal water levels if the model set-up between them is exactly identical. The results for these test are given in Appendix L. From the test with the straight channel it was concluded that the models indeed simulate identical water levels if the set-up between them is identical. Another important conclusion from this test is that the water level output is very sensitive for the amount of cells that are used in lateral direction in the Delft3D FM model. If cell resolution is not chosen high enough, the two-dimensional model is unable to represent the bathymetry as set-up in the one-dimensional Sobek model accurately. In this specific test, this led to a considerable overestimation of water levels due to a decrease in flow area.

Conclusion
From this study it can be concluded that water level forecasts made with the one-dimensional Sobek model show better agreement with monitored water levels after stream restoration than water level forecasts made with the two-dimensional Delft3D FM model for this case. Besides that, water levels simulated with the Sobek model agree with monitored developments really well as discharges exceed 2.5 m^3/s making it difficult to outperform the one-dimensional Sobek model with respect to forecasting water levels after stream restoration in its design phase.

However, additional analysis showed that the one-dimensional Sobek model and the two-dimensional Delft3D FM model provide equal results as long as the set-up is the same. Multiple explanations were found for the performance difference between the two-dimensional and one-dimensional model is this case study. Firstly, more data had to be used to set-up the bathymetry for the Delft3D FM model. This AHN2 data proved to be on average 0.27 m higher than the measurements used in the modelled period, making that water levels are overestimated if water flows in these areas. Secondly, it was found that water level forecasts of the Delft3D FM model would agree with monitored water levels better if either the lowest expected bed roughness was used or the bed level interpolation method was changed. More experience with the set-up of two-dimensional models in stream restoration projects might therefore improve performance also. Thirdly, it was found that other bathymetry differences between the one-dimensional model and the two-dimensional model might be present due to 2 reasons. The 1st reason is that an interpolation had to be performed of monitored bed level data for the main channel of the two-dimensional Delft3D FM model, which was done using the Surfis2D interpolation tool. An analysis showed that the bathymetry output of the Surfis2D tool depends highly on the amount of cross-sectional measurements used as input. The 2nd reason is that the bathymetry of the Lunterse beek in the Delft3D FM might have been affected by the amount of cells used in lateral direction for the calculation grid. In this study 18 cells were used to represent the main channel in lateral direction. It can be that this resolution is not high enough to accurately represent the bathymetry as present in the one-dimensional Sobek model.

5.2 Morphological developments

For the 5 discharge scenarios (T100, T10, T1, T0.05 and T0.005), maps were made of the locations where transport is expected. This was done using the method as explained in section 4.1.1. The flow velocity and Chézy roughness output of the Delft3D FM model were used determine the locations where the Shields parameter exceeds the critical Shields parameter. The result is shown in Figure 36, in which the original course of the main channel is shown by the black lines.

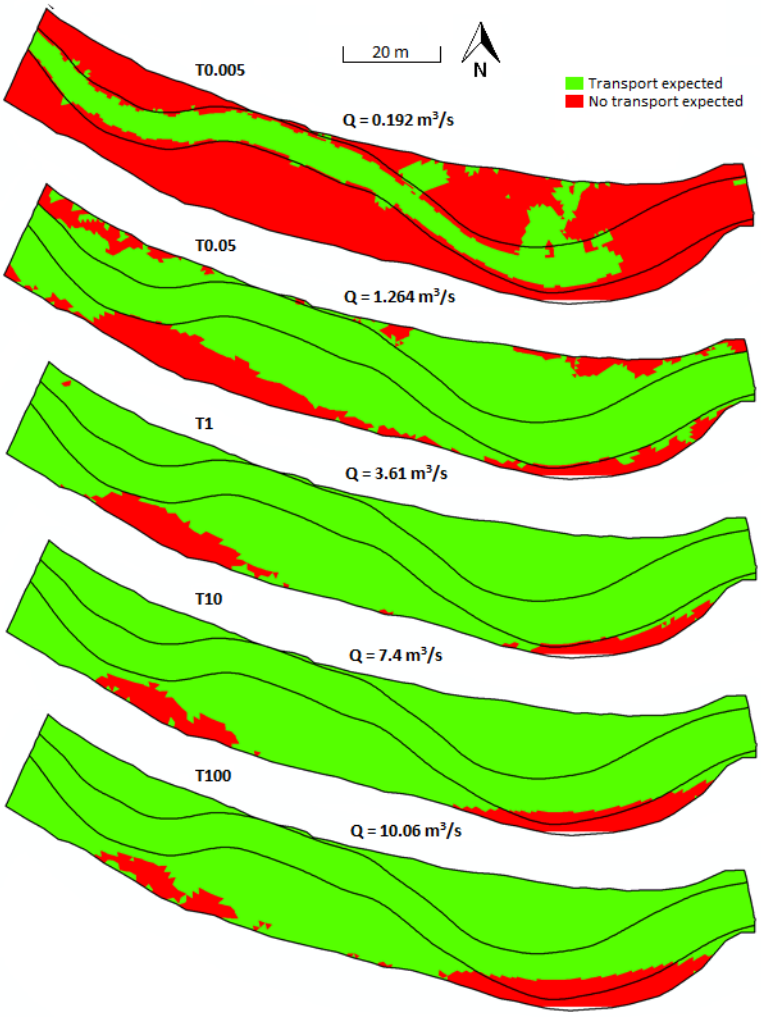

Figure 36: Locations where transport is expected in the Lunterse beek for 5 different discharge scenarios

Figure 36 shows that for the T0.005 discharge scenario, transport is primarily expected in the main channel. It becomes clear that there is a considerable area for which the critical Shields parameter is exceeded and where grains are likely picked up from the bed. This shows that an active bed can be expected in the main channel for a discharge with a recurrence time of 200 days per year, while the floodplains are expected to be stable for almost the entire area.

For the higher discharge scenarios Figure 36 shows that the area where the Shields parameter exceeds the critical Shields parameter increases. This shows that for these discharge scenarios it can be expected that large areas of the bed show morphological activity. Not only the main channel, but also the floodplains will likely show morphological changes over time.

As explained in Section 4.1.2, a comparison will also be made between monitored morphological developments of the Lunterse beek and flow velocity and direction output maps of the Delft3D FM model. Figure 37 shows this comparison. The upper image indicates the monitored development of the stream between the 22nd of February 2012 and the 20th of April 2012. The other figures show the flow velocity and direction for the different stationary discharge scenarios. The arrows indicate the flow direction, the black line in the middle of those figures is the original course of the main channel.

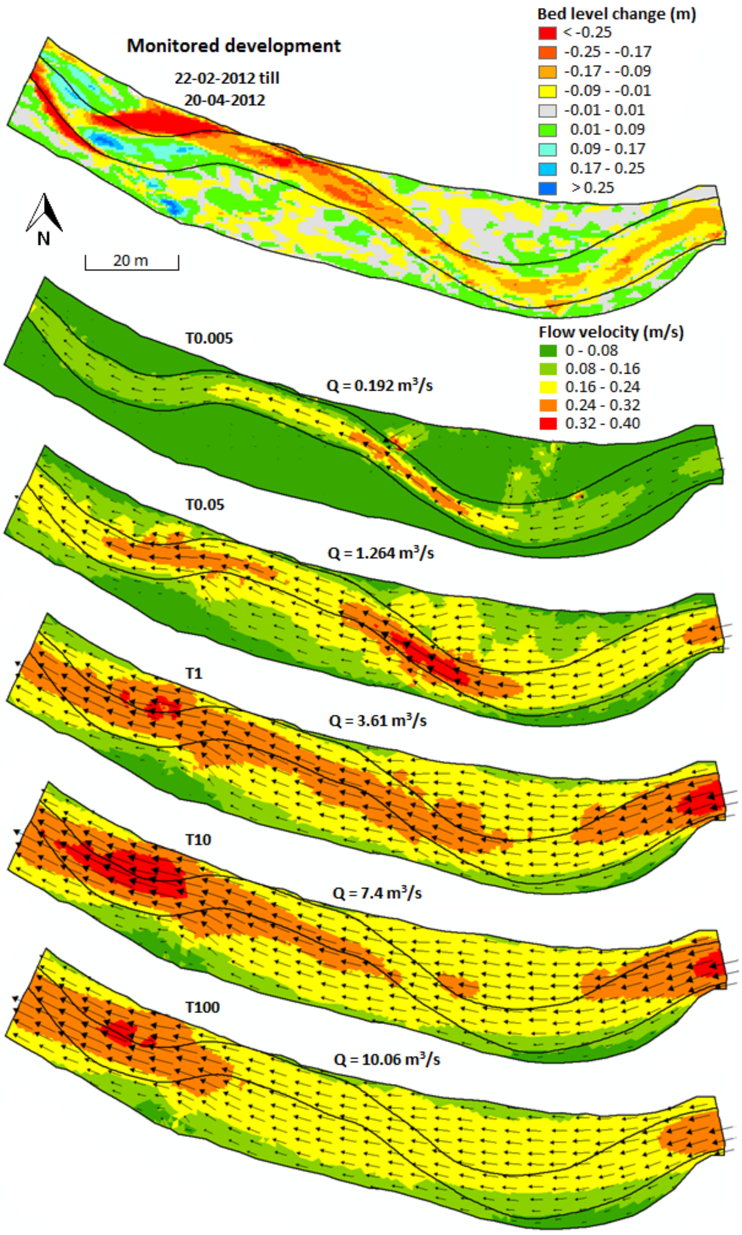

Figure 37: Comparison between monitored morphological development and flow velocities plus direction for 5 discharge scenarios

It can be seen from Figure 37 that the monitored developments are considerable. Erosion exceeds 25 cm in some locations. Remarkable is that in the upstream section erosion is mostly seen in the main channel, while in the floodplains changes are mostly minor with either small amounts of sedimentation or erosion. However, in the downstream section this is not the case. It can also be seen that over the course of 2 months, the main channel shifted somewhat, which is likely a result of bank erosion.

During a discharge event occurring 200 days per year (T0.005), stream velocities are relatively low and flow is mostly present in the main channel. Besides that, the flow direction follows the main channel shape really well. It was already shown in Figure 36 that the main channel bed can be expected morphologically active for almost the entire study area. This shows that even though flow velocities are low, morphological changes can be expected in the main channel. These will mainly be vertical processes, since flow direction does not give an indication for bank erosion. This means that the scenario shows some agreement with monitored developments, but cannot explain the considerable shift in main channel shape.

For a discharge event with a recurrence time of 20 days per year (T0.05), flow velocities increase. Flow is present outside the main channel also, but still the direction of flow follows the main channel quite well. Erosion and sedimentation can be expected during this discharge as also shown in Figure 36. Still the changes will probably be mainly due to vertical erosion processes, thus bed erosion and sedimentation. It is not likely that the shift in main channel shape is caused by this discharge scenario.

For the discharge scenarios with a recurrence time of 1, 0.1 and 0.01 days per year (T1, T10 and T100) respectively, flow velocities increase even further. In all scenarios the flow area covers nearly the entire section and flow direction hardly follows the main channel anymore. It already became clear from Figure 36 that the bed is likely active for nearly the entire study area during these scenarios. However, it is also obvious that bank erosion might become important for these scenarios since flow direction does not follow the main channel. Since all scenarios show increasing velocities near the bank where the main channel shifted, it can be stated that the patterns seen for these discharge scenarios match with monitored developments nicely.

To verify that the Delft3D FM software is helpful in forecasting morphological developments, the discharge that occurred in the period between 22-02-2012 and 20-04-2012 is shown in Figure 38.

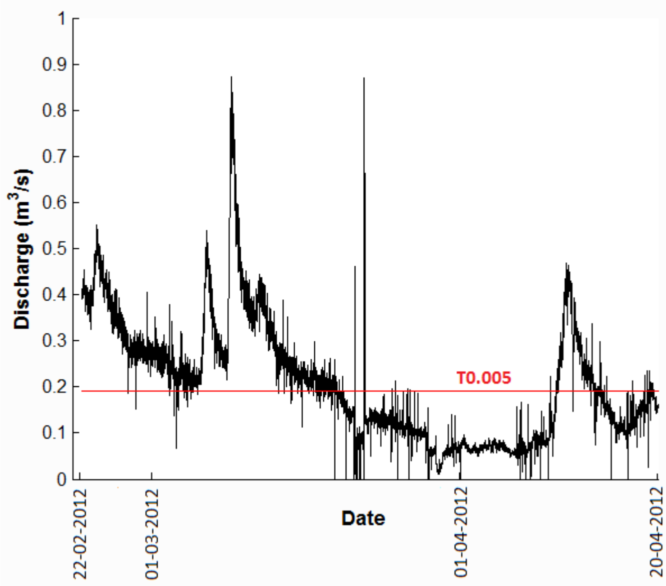

Figure 38: Discharge Lunterse beek between 22-02-2012 and 20-04-2012

It becomes clear from Figure 38 that the maximum discharge that occurred in the given period was relatievely low, around 0.9 m^3/s. This means the maximum discharge sits inbetween the discharges used to force the T0.005 (0.192 m^3/s) and T0.05 (1.264 m^3/s) scenarios. Based on the comparison between the flow velocity and direction maps and monitored morphological developments, a higher discharge was expected since especially the high discharge scenarios correspond well to monitored developments. The vertical processes can also be explained partly by the T0.005 and T0.05 scenarios but the bank erosion cannot. This shows that the flow velocity and flow direction output of the Delft3D FM model does not necesarilly provide usefull information about plausible morphological developments.

It has to be noted here, that in this study water levels are overestimated for the Delft3D FM model of the Lunterse beek. This also means that for equal discharge, flow velocities are underestimated. This can explain why the T0.05 scenario does not show patterns corresponding to monitored morphological developments. Accuracy of the morphological forecasts are therefore likely to improve if the water levels are forecased more accurately.

Besides the comparison with flow velocity and flow direction maps a comparison with flow velocity gradients was performed. The results of this comparison are shown in Figure 39. The upper image shows the monitored development between 22-02-2012 and 20-04-2012. The lower images show the forecasts based upon the flow velocity gradients for the stationary discharge scenarios with a recurrence time of 20 days and 1 day per year (T0.05 and T1).

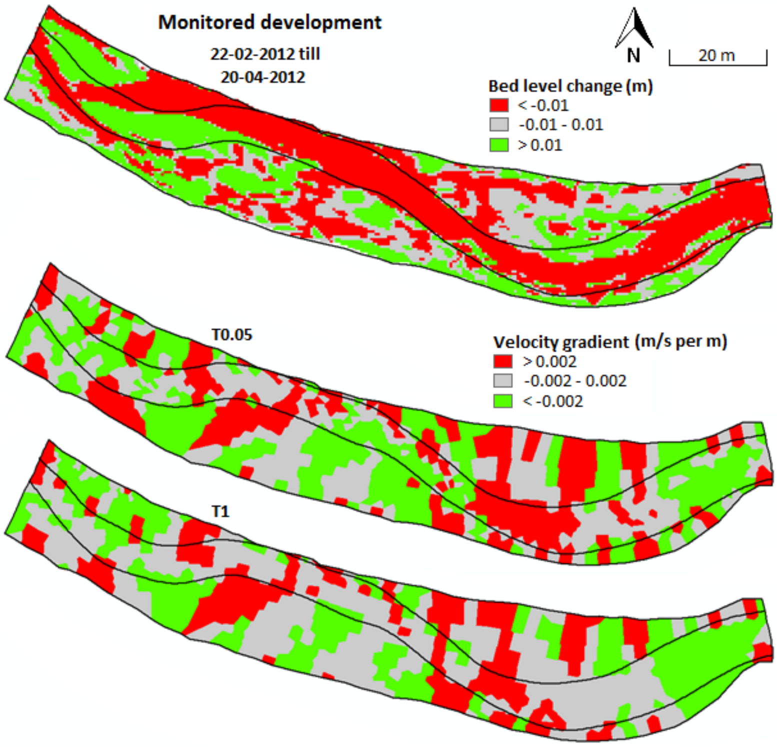

Figure 39: Comparison monitored morphological developments with flow velocity gradients

From Figure 39 it can be seen that the forecasts do not correspond to monitored bed level developments really well looking at the colour patterns. In the forecasts, rectangular patterns are visible which is likely caused by the 2.5 m interval used when determining the gradients. A much smoother pattern is visible in the monitored bed level developments. Choosing a larger interval to base the gradients upon results in even less correspondence, due to lower gradients in flow velocity. It turns out to be difficult to replicate the morphological processes that appear in the direction of the flow using this method, making that flow velocity gradients are not necessarily a good indicator in forecasting morphological developments. There are certainly sections that agree with monitored developments for the T0.05 and T1 stationary discharge scenarios. However, results obtained with the method looking at the Shields and critical Shields parameter and the method using flow velocity and flow direction maps are better.

Conclusion
From this analysis it was learned that using flow velocity, flow direction and Chézy roughness output of a two-dimensional Delft3D FM model does not necessarily, but can, provide good information about plausible morphological developments for a stream after restoration. It was found that flow velocity and flow direction maps in combination with maps of locations where transport is expected, can be useful in forecasting locations for which bank erosion and sedimentation can be expected. Maps of flow velocity and direction for the higher discharge scenarios (T100, T10 and T1) also showed the location where bank erosion could be expected. However, the discharge that was monitored for the given period proved to be much lower than in these scenarios. The disagreement might be explained by the overestimation of water levels in the Delft3D FM model, which under equal discharge causes an underestimation of flow velocities.

5.3 Developments in vegetation

The method explained in section 4.2 was used to forecast amounts of vegetation that will grow in certain locations. Based upon flow velocity output of the Delft3D FM model, 5 classes of vegetation were distinguished. These forecasts were compared to monitored developments. For the monitored developments, polygons were drawn distinguishing 5 vegetation classes based upon a high resolution aerial image. Based upon what was seen with the naked eye, it was determined how much vegetation was present for the study area. The matching descriptions for the 5 classes between forecasts and monitored developments are shown in Table 22, with the forecasts in yellow and the validation in green.

Table 22: Matching classes in vegetation between forecasts (yellow) and monitored developments (green)

Category	Amount of vegetation	Depth averaged flow velocities (m/s)	Description for validation based upon aerial photo	Estimation vegetation biomass (kg/m²)
1	Abundant vegetation	0 – 0.2	Dense and high vegetation	> 0.2
2	Quite a bit of vegetation	0.2 – 0.4	High vegetation with low density	0.15 – 0.2
3	Vegetation	0.4 – 0.6	Vegetation that is not low nor high	0.1 – 0.15
4	Small amounts of vegetation	0.7 – 1.0	Low vegetation	0.01 – 0.1
5	No vegetation	> 1.0	No visible vegetation	< 0.01

A comparison was performed to see how often the forecasts agreed with the monitored developments. This was done looking at the area that was forecasted correctly. The results of the comparison for the different discharge scenarios are shown in Table 23.

Table 23: Results forecasts for developments in vegetation for the different discharge scenarios

Model description	Area compared (m²)	Area forecasted correctly (m²)	Percentage area correct (%)
T0.005	9792	2865	29.3
T0.05	9792	6554	66.9
T1	9792	4778	48.8
T10	9792	3975	40.6
T100	9792	4687	47.9

It becomes clear from Table 23 that especially the T0.05 discharge scenario (high spring discharge) does a really good job in forecasting the developments in vegetation for the stream. A success rate of almost 67% is established, where a completely random forecast would likely have a success rate of 20% (based upon 5 possible classes). A spatial overview of the forecasted developments in vegetation for the T0.05 discharge scenario and the aerial image used to quantify the monitored developments are shown in Figure 40 and Figure 41.

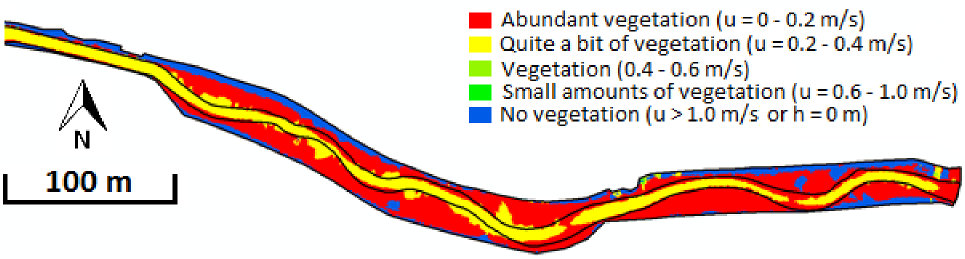

Figure 40: Forecasted developments in vegetation using a T0.05 discharge scenario for the Lunterse beek

Figure 41: Aerial image of the Lunterse beek in September 2015

It becomes clear from Figure 40 and Figure 41 that the forecast corresponds with monitored developments especially in the floodplains close to the main channel. In these locations, abundant vegetation is forecasted and this is also seen on the aerial image, since dense and high vegetation is identified. This shows that making vegetation forecasts with the Delft3D FM software might be useful, especially taking into account that there are a lot of other factors besides flow velocity that influence vegetation biomass. It has to be noted though that this method might not list equal results in other streams. More research is needed to confirm that the method used in this study can be useful in forecasting locations where vegetation might develop after stream restoration.

6. Results Tungelroyse beek

In this chapter the results for the case study of the Tungelroyse beek are presented. A comparison of monitored with modelled water levels is performed in section 6.1. In section 6.2 the morphological forecasts are compared to monitored developments in morphology. Finally, a comparison between monitored developments in vegetation and forecasted developments in vegetation is performed in section 6.3.

6.1 Water levels

Simulated water levels for the uniform discharge scenarios were compared to measured water levels for the Delft3D FM model. Results at the downstream boundary for both models agreed with the Q-h relation as expected. The results for the Castertbrug validation location are shown in Figure 42.

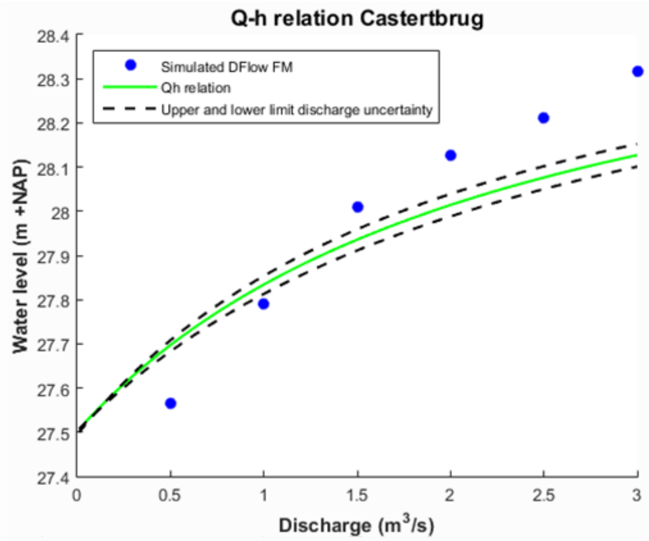

Figure 42: Modelled water levels compared to measured water levels for different discharges at the Castertbrug

As becomes clear from Figure 42, the water levels forecasted by the Delft3D FM model are lower than the water levels in the Q-h relation up to a discharge of 1 m^3/s. For a discharge of 1.5 m^3/s and higher, water levels in the Delft3D FM model overestimate the water levels of the Q-h relation. The steepness of the simulated Q-h relation is obviously much higher than the steepness of the established Q-h relation.

This result shows much similarity with the Delft3D FM model output for the Lunterse beek, for which also an underestimation of water levels was found for low discharges and an overestimation for high discharges. Still, for the Tungelroyse beek, no Sobek model was set-up and therefore a comparison with one-dimensional model results is not possible. Since an extensive sensitivity analysis was already performed for the Lunterse beek, this will not be done again for the model of the Tungelroyse beek.

For the model of the Tungelroyse beek, a lot of uncertainty was introduced in the model since the discharge for the upstream boundary was established based upon a measurement station located 7.5 km downstream. This will likely affect the results presented in this section. Other factors that affect the model performance are fairly similar to the factors mentioned for the Lunterse beek. AHN2 data had to be used to complete the model bathymetry. On average the bottom was 11 cm higher in the AHN2 data than in the measurements performed by Menten & Strigencz (2012). Besides that, the Surfis2D interpolation software was used again to interpolate the main channel cross-sectional bed level measurements to a spatially covering bathymetry. It was shown that bathymetry output of the Surfis2D software is sensitive for the amount of cross-sectional bed level measurements used as input. Finally, for the main channel of the Tungelroyse beek only 8 cells were used in lateral direction. It was shown in Appendix L for a straight channel that enough cells are needed in lateral direction to represent the bathymetry of the one-dimensional Sobek model accurately. Otherwise differences in bathymetry between the models will lead to differences in simulated water levels also.

Even though the factors mentioned above might have influenced simulated water levels with the Delft3D FM model, it is unlikely that this causes the different steepness in Q-h relation that is observed. This difference might be caused by the roughness formulation used in this study, that does not account for roughness changes due to changing water depths. Especially if water depths are low, which is the case for the Tungelroyse beek, changes in water depth also affect roughness considerably. More research is needed into this subject, but using a roughness formulation that is dependent upon water depth is expected to list more accurate results for the entire range of discharge scenarios compared to the roughness formulation used in this study.

6.2 Morphological developments

Using the method explained in section 4.1.1, the locations where the Shields parameter exceeds the critical Shields parameter were determined for 5 different stationary discharge scenarios. In these locations morphological changes are expected, since grains are likely picked up from the bed. The results for the T0.005 and T0.05 discharge scenarios are shown in Figure 43. For the T1, T10 and T100 discharge scenarios the results are shown in Figure 44.

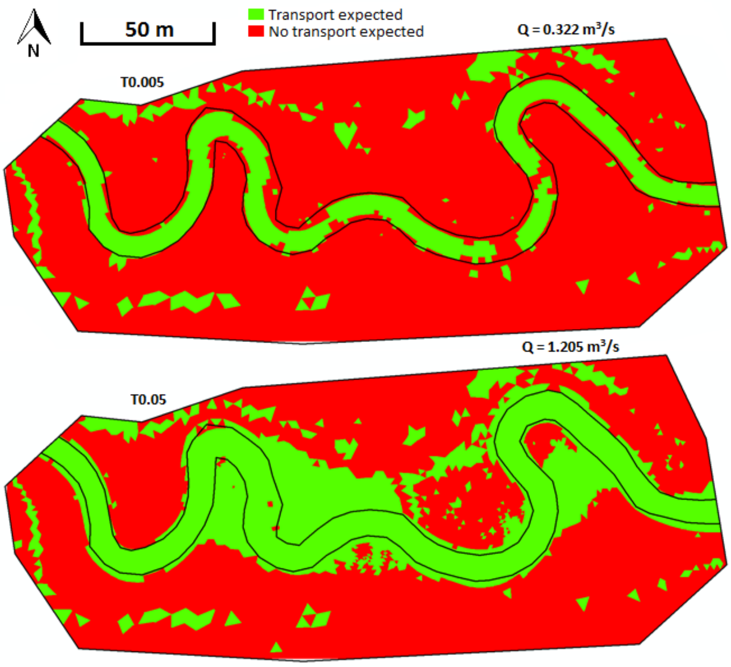

Figure 43: Locations where transport is expected in the Tungelroyse beek during stationary discharge events with a recurrence time of 200 and 20 days per year

It can be seen from Figure 43 that for a discharge scenario with a recurrence time of 200 days per year (T0.005), large parts of the main channel bed are expected to be active. In the floodplains only few locations are seen where transport is expected to occur.

For the discharge with a recurrence time of 20 days per year (T0.05), the Shields parameter exceeds the critical Shields parameter in more locations. Vertical processes are likely going on in almost the entire main channel. Besides that, transport is also expected in the floodplains, especially in the inner corners of the meanders.

In Figure 44 it can be seen that for a T1 discharge event there are locations in the main channel where the bed is not expected to be active anymore. This must be caused by decreasing flow velocities in these locations compared to the T0.005 and T0.05 scenarios, which in its turn can only be explained by increasing flow through the floodplains. It also becomes clear that the floodplains become more active compared to the lower discharge scenarios, wherefore transport in the floodplains is expected to increase.

For the scenarios with a recurrence times of 0.1 (T10) and 0.01 (T100) days per year respectively, the Shields parameter is lower than the critical Shields parameter for almost the entire main channel. Therefore morphological activity is hardly expected in the main channel anymore, only at the upstream section (flow is directed from West to East). Besides that, the area in the floodplains where bed activity is expected decreases as well compared to the T1 discharge scenario. This is remarkable and can only be explained by further increases in flow area for the floodplains.

In the T10 and T100 discharge scenarios it is also seen that the bed will likely become active in some areas that are located further from the main channel. Still for the higher discharge scenarios, low morphological activity is expected with respect to vertical processes.

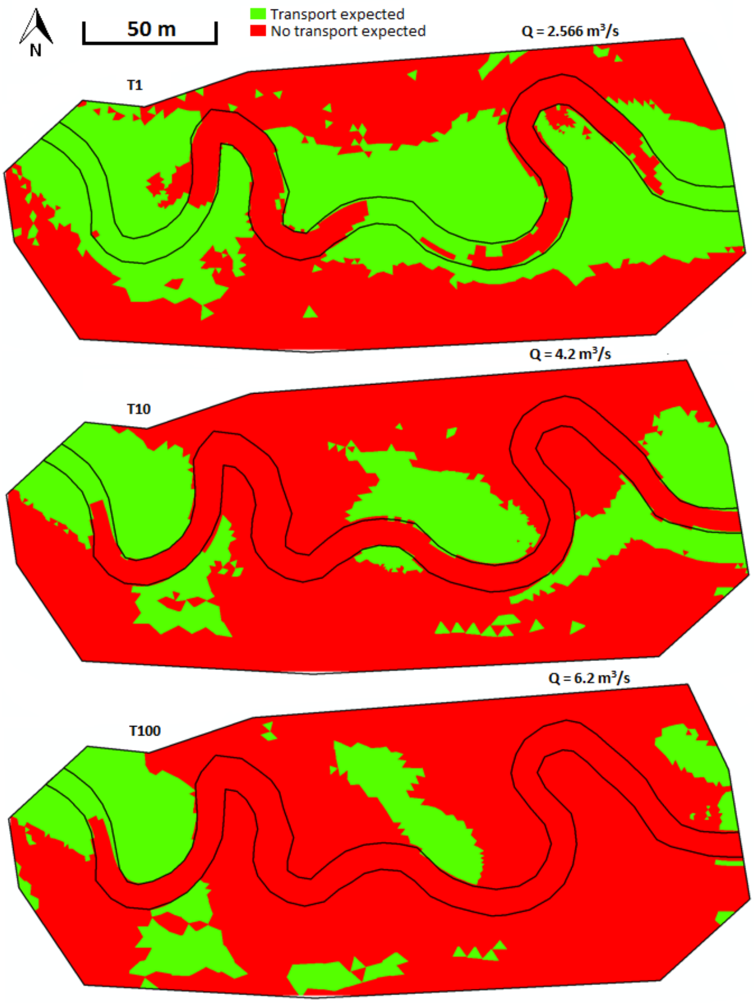

Figure 44: Locations where transport is expected in the Tungelroyse beek during stationary discharge events with a recurrence time of 1, 0.1 and 0.01 days per year

Besides looking at locations where the Shields parameter exceeds the critical Shields parameter, maps were made to show the flow velocity and flow direction during 5 discharge scenarios. As explained in section 4.1.3. no quantitative data is available for validation of the forecasted developments in morphology. Therefore the flow velocity and flow direction maps will be compared for a specific section to analyse if the maps give a good indication for the stable planform shape over a 3 year period.

The flow velocity and flow direction maps during stationary discharge events with a recurrence time of 200 and 20 days per year (T0.005 and T0.05) are presented in Figure 45.

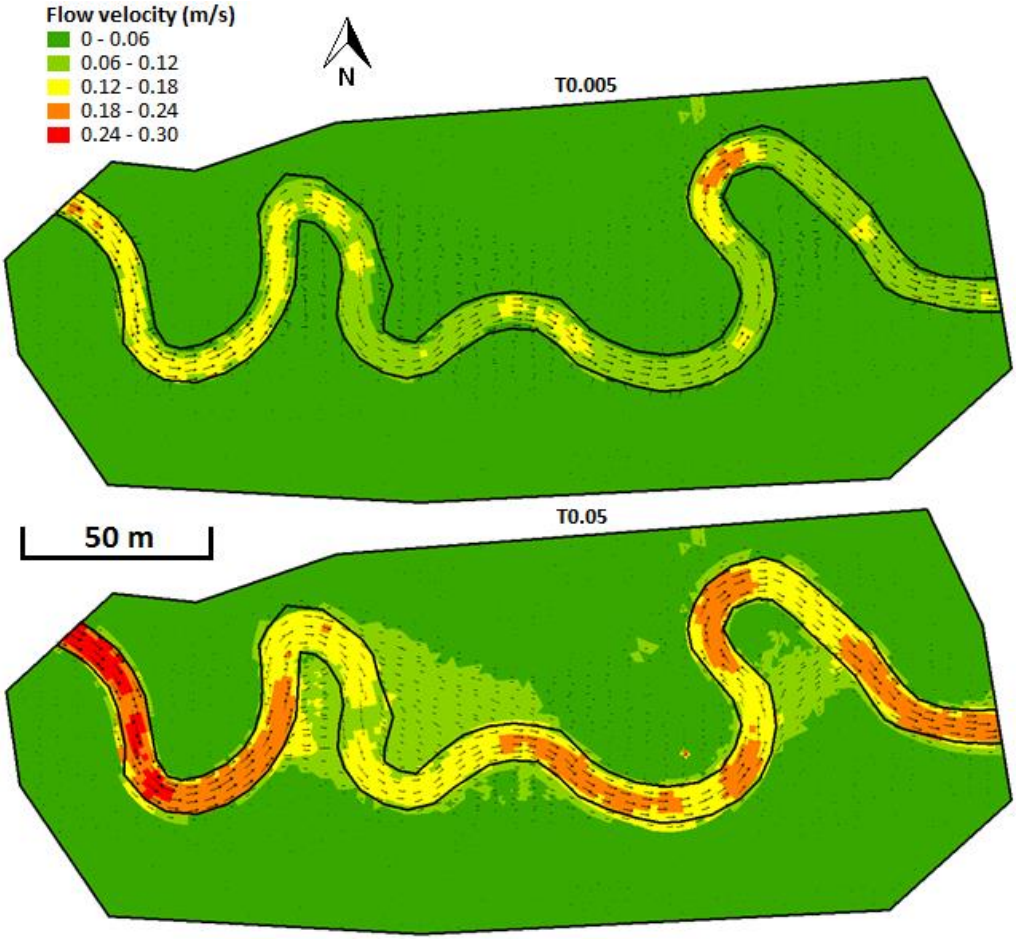

Figure 45: Flow velocity and flow direction maps for a section of the Tungelroyse beek during stationary discharge events with a recurrence time of 200 and 20 days per year

It can be seen from Figure 45 that flow velocities are quite low for both discharge events, remaining under 0.3 m/s. For the event with a recurrence time of 200 days per year (T0.005) flow is almost entirely restricted to the main channel, while flow direction follows the main channel shape. It was already shown in Figure 43 that transport can be expected in the main channel. There is no reason to assume that bank erosion might occur though, since flow velocities are low and follow the main channel shape.

For a discharge event with a recurrence time of 20 days per year (T0.05) flow velocities increase slightly compared to the T0.005 discharge event. Flow starts to occur outside of the main channel also and as shown in Figure 43 some transport is expected here, despite the low flow velocities. Still, the direction of flow in the main channel follows the main channel shape really well. Therefore during this discharge no bank erosion is expected.

For the higher discharge scenarios (T100, T10 and T1), the flow velocity and flow direction maps are presented in Figure 46.

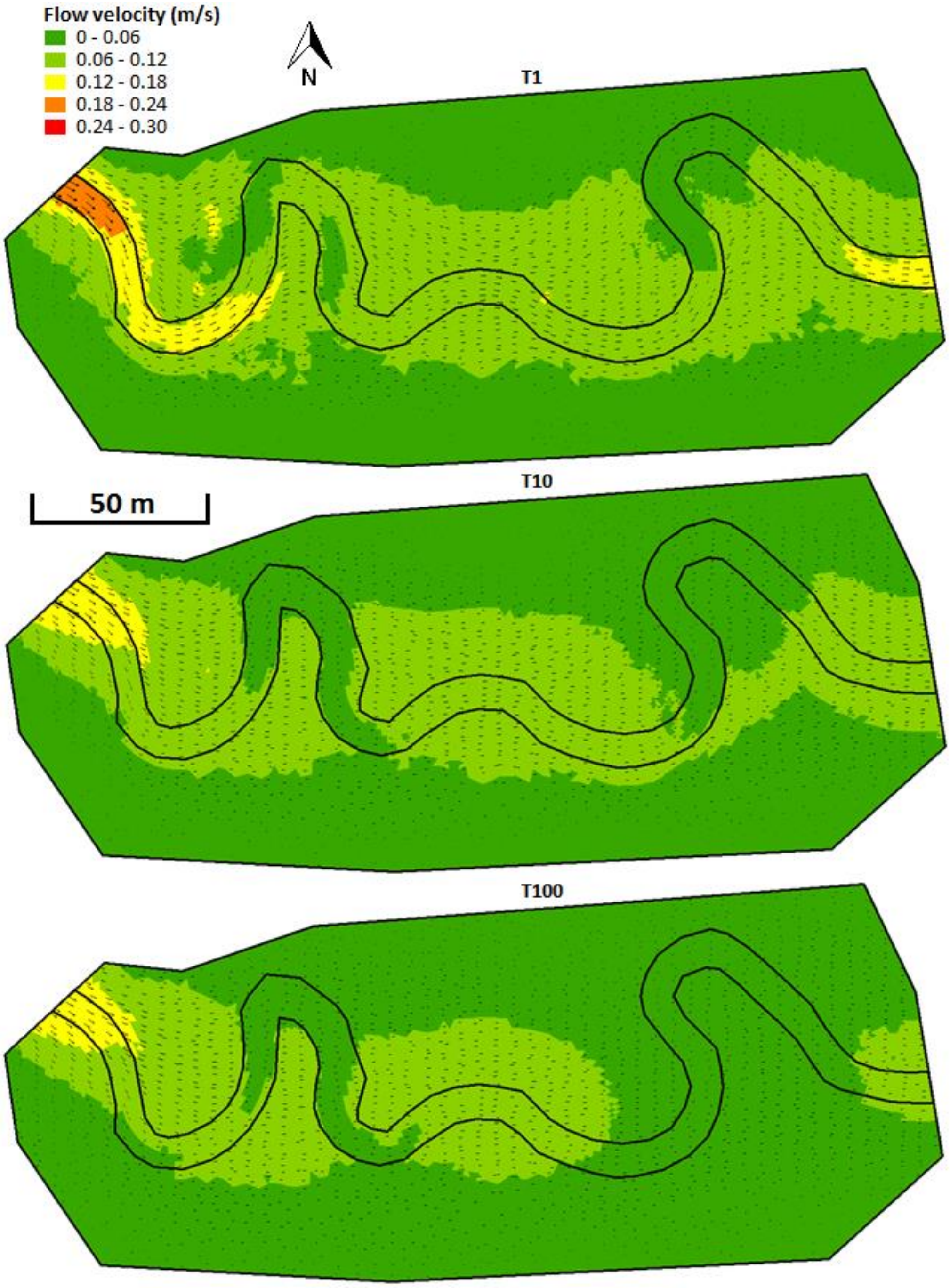

Figure 46: Flow velocity and flow direction maps for a section of the Tungelroyse beek during stationary discharge events with a recurrence time of 1, 0.1 and 0.01 days per year

Figure 46 shows that the flow velocities decrease for the higher discharge scenarios while flow area increases further. This was also expected from Figure 44, since morphological activity is decreasing for the higher discharge scenarios. For the discharge scenario with a recurrence time of 1 day per year (T1) the highest flow velocities never exceed 0.24 m/s, while for the discharge scenarios with a recurrence times of 0.1 and 0.01 days per year (T10 and T100), these are even lower with a maximum of 0.18 m/s.

It was already shown in Figure 44 that activity in the main channel likely decreases as discharges become higher. Looking at the flow direction it shows that the flow does not follow the main channel shape anymore for all discharge scenarios. Still, because flow velocities are so low only few locations will show morphological activity and bank erosion is not likely to occur.

Conclusion

From this analysis it can be concluded that the flow velocity and flow direction patterns for the 5 stationary discharge scenarios do not give an indication for bank erosion to be expected in this section of the Tungelroyse beek. This corresponds to the planform stability of the main channel observed over the 3 year period in the aerial photo.

However, since no quantitative measurements of bed level developments were performed, it cannot be determined how well the flow velocity and direction maps match with morphological developments in the field. This comparison gives a reason to assume that flow velocity and flow direction output of a two-dimensional Delft3D FM model might contribute to forecasting morphological developments of a stream after restoration. However, more research is needed to confirm this.

6.3 Developments in vegetation

For the comparison between forecasted developments in vegetation and monitored developments in vegetation a NDVI map of the 2013 situation was created. As explained in section 4.2, the numbers in the NDVI map range from -1 to 1 depending on the reflection of incoming radiation. This gives a measure for the amount of vegetation that is present. The forecasts are based upon flow velocities, as explained in section 4.2.

In the NDVI map water reflection leads to negative numbers. Therefore, in-stream developments of vegetation cannot be assessed. To exclude this area from the assessment, a clip was made of the study area as shown in Figure 47. The red line shows the study area, while the black lines show the clipped area.

Figure 47: Clip made to validate forecasts in vegetation development for the Tungelroyse beek, with in red the study area and in black the clipped area (background photo 2014)

To compare the forecasts with the NDVI values, 5 classes were made based upon the NDVI values. These classes are presented in Table 24.

Table 24: Vegetation classes based upon NDVI values

Category	Description	NDVI lower limit	NDVI higher limit
Class 1	Abundant vegetation	0.25	1.00
Class 2	Quite a bit of vegetation	0.20	0.25
Class 3	Vegetation	0.15	0.20
Class 4	Small amounts of vegetation	0.10	0.15
Class 5	No vegetation	-1.00	0.10

After defining the different classes for the NDVI map, the forecasts were compared to this map. The area for which the forecasts agreed with the NDVI classes was determined. The results for the 5 discharge scenarios are shown in Table 25.

Table 25: Results of a comparison between forecasted amounts of vegetation and monitored vegetation based on a NDVI map made of the 2013 situation for the Tungelroyse beek

Model description	Area compared (m^2)	Forecasted correctly (m^2)	Percentage correct (%)
T0.005	75256	13656	18.1
T0.05	75256	21035	28.0
T1	75256	40852	54.3
T10	75256	42515	56.5
T100	75256	41468	55.1

As becomes clear from Table 25, the forecasts for the higher discharge scenarios perform the best. The expected developments for the low discharge scenarios are not very good. The discharge with a recurrence period of 200 days per year (T0.005) is only correct for 18.1% of the area observed, while a random forecast is expected to be correct for 20%, considering there are 5 categories. This can most likely be explained by the assumption that was made with respect to locations where no water is present. It is assumed that no vegetation will develop in those locations, while this is often not the case. Especially if discharge is low, flow will be limited mostly to the main channel making that forecasts are often incorrect for the floodplains.

The discharge with a recurrence time of 20 days per year (T0.05), correctly forecasts the amount of vegetation for 28 % of the area analysed. This is better than a random forecasts, but still not very good. This can again be explained by many locations in the floodplains where water is absent, making that forecasts expect no vegetation while in the field vegetation develops in those areas.

The discharge scenarios with a recurrence time of 1, 0.1 and 0.01 days per year (T1, T10 and T100) forecast the amount of vegetation expected upfront correctly for 54.3, 56.5 and 55.1% of the area respectively. This result is good, considering that a random forecast is expected to forecast 20% of the area correctly.

Conclusion
It was found that using the flow velocity to forecast developments in vegetation lists good results for the higher discharge scenarios (T100, T10 and T1). However, the NDVI validation does not allow for in-stream vegetation analysis while this is often very important. It is therefore stated that two-dimensional Delft3D FM software might contribute in forecasting developments in vegetation after stream restoration, but more research is needed to confirm that this is also the case for in-stream vegetation developments.

7. Discussion

The research objective for this study was: *to determine if modelling stream restoration projects, in their design phase, with a two-dimensional (Delft3D FM) model has advantages over a one-dimensional (Sobek) model regarding water level forecasts and the possibility to forecast developments in morphology and vegetation.* It was found that a two-dimensional model might have some advantages with respect to forecasting developments in morphology and vegetation. However, more research is needed to confirm that this is indeed true. In this chapter the methods that are used in this research as well as uncertainties encountered in the study are discussed.

Data

The data used for the set-up and validation of the model results is important for this study. For both the models of the Lunterse beek and the Tungelroyse beek, no discharge measurements were performed at the upstream boundary of the studied area. Therefore, discharge had to be determined in a different way. For the Lunterse beek discharge measurements performed around 740 m further downstream were used instead, assuming no change in discharge between the upstream boundary and the discharge measurement location. For the Tungelroyse beek, discharge measurements performed almost 7.5 km further downstream were used. Since these measurements were affected by inflow from another stream and a considerable amount of inflow through run-off and groundwater flow, the discharge was multiplied with 8/15. Since these measurements were used for model set-up and validation, uncertainty was introduced in the models but also in the validation data. It has to be noted though, that the one-dimensional and two-dimensional model for the Lunterse beek at least were set-up and validated using the same data, justifying the comparison between them.

For validation of the simulated water levels, 3 locations were present for the Lunterse beek. One of the locations was hardly usable for validation of simulated water levels because of limited data. Therefore validation was performed mainly using 2 locations that were relatively close to each other. For the Tungelroyse beek, 1 validation location was present. It is difficult to base model results upon only a few validation locations, especially considering that the study area of the Lunterse and Tungelroyse beek are around 1.6 and 3.8 km in length respectively. Therefore it might be helpful to have more validation data for future studies. In the end though, the quality of the data is even more important.

Water level forecasts

Stationary discharge events were used as model input for a two-dimensional Delft3D FM and a one-dimensional Sobek model of the Lunterse beek. The water levels simulated with the models were compared to each other and to monitored water levels and it was found that the one-dimensional model performs better than the two-dimensional model for this particular situation. Due to uncertainties though, it cannot be concluded that the one-dimensional model will always outperform the two-dimensional model. The most important aspects affecting the outcome are discussed below.

Since this study resembles the design phase of a stream restoration project, models cannot be calibrated. Bed roughness values often show a plausible range though, while only one value can be selected for both models. A sensitivity analysis proved that the simulated water levels were indeed sensitive for modelling choices made with respect to bed roughness. It became clear that the two-dimensional Delft3D FM model would have performed better if lower roughness values were selected, while the roughness values selected for the one-dimensional Sobek model were close to optimal. It is likely that this can partly be explained by the fact that much more experience is present with respect to setting up one-dimensional (Sobek) models. It is therefore better known which roughness values need to be selected. For the two-dimensional model, more experience is needed with respect to the roughness values that should be used, also because two-dimensional effects should be excluded from the roughness values selected while for the one-dimensional models these need to be included.

The methods used to create the bathymetry for both models of the Lunterse beek were considerably different in this study. For both models the cross-section measurements performed by Meet B.V. (2012) were used, however for the one-dimensional Sobek model this was the only input, while for the two-dimensional Delft3D FM model this was not. For the main channel bathymetry of the Delft3D FM model an interpolation of the cross-section measurements (Meet B.V., 2012) was performed using Surfis2D (RIZA Rijkswaterstaat, 2004). The output of the Surfis2D interpolation was then used as input for the Delft3D FM model. Also, since the extent of the study area was larger for the Delft3D FM model, additional AHN2 data (Publieke Dienstverlening Op de Kaart, 2015) was used to define the bed level height for locations outside the measured area. It was shown that the bathymetry created with the Surfis2D software strongly depends upon the amount of cross-sectional bed level measurements used as input. Besides that it was shown that the AHN2 data is on average 27 cm higher than the measurements performed by Meet B.V. (2012). This showed that two-dimensional models need different input data with respect to bed level data than one-dimensional models. In the design phase of stream restoration this data might be difficult to obtain, since the height of the surrounding area might also be changed through the restoration process.

In the sensitivity analysis, it was found that the simulated water levels are sensitive for changes in bathymetry. Therefore a comparison was made between the bathymetry of both models. It was found that the bathymetry of the one-dimensional and two-dimensional were nearly identical at the locations where bed level measurements were performed. However, it could not be checked if this was also the case for sections in-between measurement locations, since the Sobek model does not allow for this. It is expected that differences in simulated water levels are partly caused by differences in bathymetry between the models. It is possible that using different interpolation methods to create the bathymetry for the two-dimensional Delft3D FM method provides a bathymetry that is more comparable to the one-dimensional Sobek model. In the design phase of restoration projects is might even be possible to provide a two-dimensional bathymetry already, which eliminates the uncertainty caused by the interpolation performed with the Surfis2D software in this study.

Finally, an additional test was performed with a straight channel in both the one-dimensional Sobek and two-dimensional Delft3D FM model. The test proved that if the model set-up between the models is exactly the same, the simulated water levels are also identical. However, if the cell resolution in lateral direction for the Delft3D FM model is not chosen large enough the bathymetry of the one-dimensional Sobek model cannot be accurately represented. This also shows that if the bathymetry of the stream after restoration differs considerably from the bathymetry as specified in the design phase, water level forecasts made with the Delft3D FM model might become inaccurate. More research is needed to analyse if this is also the case for the Sobek software.

Morphology forecasts

To identify if the Delft3D FM model is capable of forecasting morphological developments of a stream after restoration in the design phase, an analysis was performed to identify the locations where the Shields parameter exceeded the critical Shields parameter. This analysis showed the locations where bed erosion could be expected. Besides this flow velocity and flow direction output of 5 discharge scenarios were used to create maps. A qualitative comparison with monitored development in the Lunterse beek showed good correspondence for the higher discharge scenarios (T100, T10 and T1). However, the monitored discharge showed that only low discharges occurred (lower than T0.05) in the period that was analysed. It was noted though that simulated water levels with the Delft3D FM model are overestimated, which will lead to underestimation of flow velocities if discharge remains the same. This likely affects the results obtained with the flow velocity and flow direction maps.

Additional comparison for the Lunterse beek using flow velocity gradients showed little correspondence to monitored morphological developments. For the Tungelroyse beek, the flow velocity and flow direction maps showed patterns that agreed well with stream developments observed. However, no quantitative measurements were performed of the bed level developments for the Tungelroyse beek, making validation impossible.

The method used in this study only takes into account flow velocity, flow direction and Chézy roughness values to analyse whether the two-dimensional Delft3D FM model is able to forecast developments in morphology. Therefore an important aspect that is neglected is the effect that developments in vegetation can largely affect morphological developments and the other way around. It is very clear that developments in vegetation and morphology interact with and affect each other. Roots of vegetation can greatly decrease sediment mobility and plants might trap sediment, affecting monitored developments in morphology. This also works the other way around. If in a certain section of a stream the bed is eroded a lot, it is unlikely that vegetation can develop in this location. Including this effect in future studies might be useful. However, it will also increase complexity of the models.

Finally, developments in morphology are affected by the hydraulic situation of a stream, but this is also a feedback system. If morphology changes so does the hydraulic situation which in its turn affects morphology again. This means that morphological developments are often highly dynamic, indicating that stationary discharge scenarios therefore might not give the best indication for bed level development.

Forecasts vegetation development

Flow velocity output of the two-dimensional Delft3D FM model was used to forecast developments in vegetation. For the Lunterse beek a qualitative comparison was performed using high resolution aerial images while for the Tungelroyse beek the comparison was made using NDVI maps of the study area. Though developments in vegetation depend upon many more factors than flow velocity, good results were achieved with this method for both streams. This showed that a two-dimensional model might be helpful in making forecasts for developments in vegetation after stream restoration in its design phase.

An advantage of the method used in this research to forecast developments in vegetation is that the method is relatively simple and does not require a lot of resources except for a two-dimensional model with flow velocity output. However, it is uncertain how well the method applies to other streams, since it does not take into account all aspects that are important for developments in vegetation. Aspects like light conditions, groundwater levels and nutrient concentrations are neglected in this study but might improve upon results. It has to be noted though that including those aspects will also increase complexity and require more resources than only a two-dimensional model.

An important aspect that needs to be discussed is that validation of in-stream vegetation developments was hardly possible in this study. Often, only little information is available with respect to in-stream vegetation developments. Besides that, using NDVI for validation purposes does not allow for quantifying vegetation developments under the water surface due to disturbed reflection patterns. This while in-stream vegetation developments are often very important for water boards. Therefore it cannot be stated that this method also provides good results if only in-stream vegetation developments are forecasted.

Practical applicability

It is important to point out that other factors than model performance also determine the practical applicability of two-dimensional models in stream restoration projects in their design phase by water boards. Two-dimensional models need different input data compared to one-dimensional models and are overall more resource intensive. Besides that, calculation times of a two-dimensional model differ significantly from those of a one-dimensional model. For this study, the simulations with the one-dimensional model were often completed within one minute for the stationary discharge calculations, while the two-dimensional model performed the same calculations in the order of days. Those aspects are not necessarily an issue, but are important to take into account.

8. Conclusions

The main research question for this study was formulated as: *Are there advantages in using a two-dimensional (Delft3D FM) model compared to a one-dimensional (Sobek) model in the design phase of stream restoration projects to forecast water levels after stream restoration and is there an added benefit of the two-dimensional (Delft3D FM) model with respect to forecasting developments in vegetation and morphology based on hydraulic model output if the model forecasts are compared to monitored developments in vegetation and morphology?* First an answer is provided to the sub-questions and after that to the main research question.

1. *What are the differences in water level between the output of the one-dimensional Sobek model and the monitored data and between the two-dimensional Delft3D FM model and monitored data for the Lunterse beek and the Tungelroyse beek after stream restoration and how do the model results compare to each other?*

The water levels simulated with the one-dimensional Sobek model for the Lunterse beek correspond quite well with monitored water levels, while water levels simulated with the two-dimensional Delft3D FM model for the Lunterse beek overestimate monitored water levels a bit for the higher discharges. This showed that a two-dimensional model does not necessarily outperform a one-dimensional model in making water level forecasts. In fact, the one-dimensional model performed better for this particular situation.

It was found that performance of the Delft3D FM model could increase if different roughness values were selected or if the bed level interpolation method was changed, while the set-up of the Sobek model was nearly optimal already. It is likely that increasing experience with the set-up of two-dimensional models for streams will therefore increase the performance.

For the Tungelroyse beek, the simulated water levels of the Delft3D FM model showed an overestimation of monitored water levels for the higher discharge scenarios too. However, no Sobek model was set-up for the Tungelroyse beek making a comparison between the two-dimensional and one-dimensional impossible.

In the end it is concluded that it is unlikely that a two-dimensional model will improve upon water level forecasts for a stream after restoration in its design phase, since the water level forecasts made with a one-dimensional model agree with monitored water levels accurately for higher discharge scenarios. It is expected that increasing experience with the set-up of two-dimensional models will increase performance though, which should lead to accurate forecasts of water levels for the two-dimensional model too.

2. *What are expected morphological developments for both streams based on the hydraulic model output of the Delft3D FM model and how do these expected developments correspond to monitored developments?*

A qualitative comparison between flow velocity and flow direction maps created from the output of the Delft3D FM model for the Lunterse beek showed good correspondence between higher discharge scenarios (T100, T10 and T1) and the monitored morphological developments. For bed erosion and sedimentation the low discharge scenarios (T0.05 and T0.005) also showed some agreement with monitored developments. It was found that only low discharges occurred (lower than T0.05) in the period that was analysed and the maps created for these scenarios did not agree with the shift in main channel observed in the field. However, since water levels are overestimated in this study, it can be understood that for equal discharges the flow velocities are underestimated. Therefore, flow velocity and direction output of the Delft3D FM model can still be useful. A different method, using flow velocity gradients to forecast morphological developments showed little correspondence to monitored developments in morphology.

The flow velocity and flow direction maps made for the Tungelroyse beek showed patterns that agreed with the stability of the main channel in planform shape over a three year period. However, there were no quantitative bed level measurements to prove that these forecasts agreed with morphological development.

It can be concluded that there might be benefits of using a two-dimensional model with respect to forecasting morphological developments after stream restoration in its design phase. However, in this study that could not be confirmed.

3. *What are expected developments in vegetation for both streams based on the hydraulic model output of the Delft3D FM model and how do these expected developments correspond to monitored developments?*

Flow velocity output of the Delft3D FM model was used to make forecasts of developments in vegetation for both streams. It was found that the forecasts corresponded quite well with monitored developments in vegetation for both streams for a few scenarios. Though validation could not be performed for in-stream vegetation development, this clearly shows that two-dimensional modelling might be helpful in forecasting developments in vegetation after stream restoration during the design phase of stream restoration projects.

Conclusion

In this research it was found that using a two-dimensional Delft3D FM model in the design phase of stream restoration projects to make forecasts in vegetation development might be beneficial. Using flow velocity output of the two-dimensional model to base these forecasts upon gave good results for a few discharge scenarios for both streams. There might also be a benefit in two-dimensional modelling with respect to making forecasts in morphological developments, however this is only partly supported by this research. Finally, it became clear that advantages of a two-dimensional model compared to one-dimensional model are likely not present in water level forecasts since the one-dimensional model already performs very well. It is expected though, that the water level forecasts made with the two-dimensional model can be improved by gathering more experience. This should eventually lead to water level forecasts that are just as accurate for the two-dimensional model as for the one-dimensional model.

9. Recommendations

The most important recommendation is that *more case studies should be performed* to analyse the advantages of a two-dimensional model compared to a one-dimensional model in modelling stream restoration projects in their design phase. This study pointed out that two-dimensional models might be helpful in forecasting developments in morphology and vegetation after stream restoration. However, more studies are needed to improve upon methods applied in this research and to increase understanding about when and how two-dimensional models should be used. Also an increase in experience with respect to using two-dimensional models in stream restoration can improve upon results obtained with the model. Besides that, those studies can provide different insights with respect to advantages of two-dimensional modelling in stream restoration projects.

General

The most difficult aspect with respect to modelling stream restoration projects in its design phase is that models cannot be calibrated, since the future situation of the stream is still unknown. This has consequences for multiple aspects of the modelling challenge.

Future boundary conditions and bed roughness values will change compared to the situation before stream restoration. It was shown in this research that simulated water levels were sensitive for changes in bed roughness, while research of Warmink et al. (2013) proved that boundary conditions are a main source of uncertainty in hydraulic river models. It would be useful to understand how this uncertainty can best be dealt with. An interesting research to dealing with uncertainty in hydraulic river modelling is momentarily being performed by Koen Berends. This study, that is part of the RiverCare research programme, is looking into the possibility and validity of using models that are calibrated for an old situation to represent a new situation by adjusting the model. The research focuses on making a qualification scheme for model use that can be linked to model validity (Berends et al., 2016). Such a scheme can be useful in stream restoration projects also. *It is recommended to look into the possibility to applicate this method in stream restoration projects*. A method that can also be investigated with respect to uncertainty is to look at stochastic modelling to derive probability distributions that might be beneficial in determining a best estimate for the future situation.

Another difficulty lies in the bed levels of the stream. It was shown for the Delft3D FM model that the amount of bed level measurements strongly affects the created bathymetry and that the water level output was sensitive for the model bathymetry. It is therefore interesting for future research *to investigate how the stream bathymetry after restoration corresponds to the stream bathymetry assumed in the design phase*.

Finally, it is recommended for future studies to increase the amount of validation data for the models and to make sure the data is of good quality. It is not suggested that this is useful for future studies, since in the design phase this data is not available. However, it does help to objectify the comparison between the one-dimensional and two-dimensional model with respect to validation of the results. This might increase the understanding about advantages of the models compared to each other.

Research methods

Looking more specifically at the methods used in this research, it was found that the grid used in the Delft3D FM model is probably important for the simulated water levels. *Especially the amount of cells in lateral direction needs more attention in future studies*. A suggestion is to do this by creating multiple grids, with different cell sizes in the lateral direction to assess the effect on simulated water levels. Subsequently a comparison with monitored water levels can give more insight in the best approach, which might eventually lead to practical guidelines on the lateral resolution needed for future studies using the Delft3D FM model.

This study showed that flow velocity and flow direction maps do not necessarily give a good indication for morphological developments but can be helpful. *It is interesting to investigate which results are obtained when a morphological model is coupled with the Delft3D FM model*. It is recommended to investigate this method further once Deltares finishes the validation of this coupled model, which will likely be in the near future. This method also allows to account for interaction between morphology and hydraulics so that changes of bed level and hydraulics can be investigated over time.

Another suggestion is to investigate the practical applicability of a model that couples developments in vegetation and morphology. These models already exist but might be too complex for the purpose of this study. It is obvious that the interaction between morphology and vegetation is important for both morphological developments and developments in vegetation though. It is not clear if this can be accurately modelled for stream restoration projects in their design phase though, since many uncertainties are still present.

Finally, regarding developments in vegetation it is strongly recommended to do more research with respect to in-stream vegetation development. Vegetation forecasts, based upon flow velocity output, gave good results for the near stream vegetation development. However, for this research it could not be validated how successful the method was with respect to forecasting in-stream vegetation developments. It is suggested to apply the same method as used in this research, since the method is simple, does not need a lot of resources and achieved good results in this research.

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Appendix A: Fitted Q-h relations Lunterse beek

This appendix explains how Q-h relationships were fitted for the different validation locations and the downstream boundary of the Lunterse beek model. Data collected between 01-12-2011 and 15-02-2012 was used only, since the modelled geometry is representative. The locations are presented again in Figure 48, with their characteristics in Table 26.

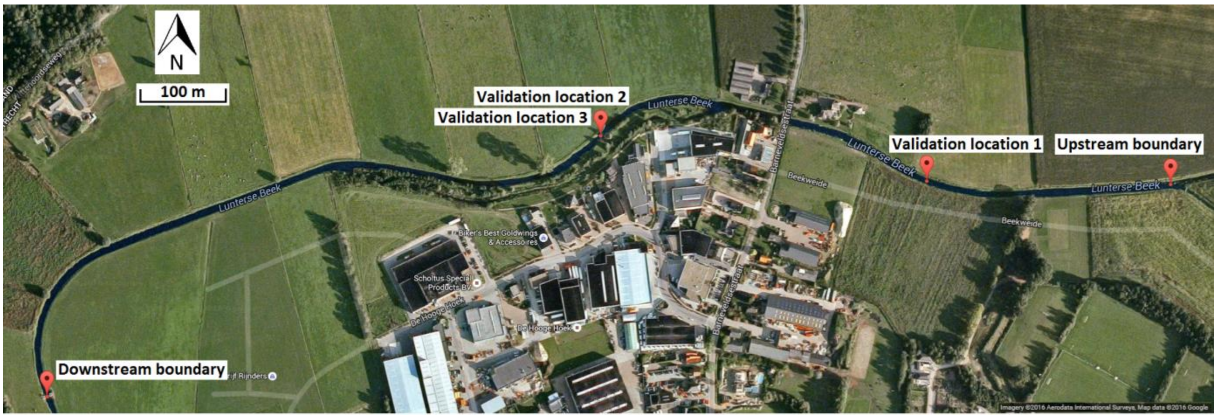

Figure 48: Locations for model validation of the Lunterse beek (Google Maps)

Table 26: Different validation locations with their names

Location	Type of measurement	Name
Upstream boundary	Nothing	Groot Abbelaar downstream
Validation point 1	Water levels	WL2
Validation point 2	Water levels and discharge	Barneveldsestraat upstream
Validation point 3	Water levels and discharge	Barneveldsestraat downstream
Downstream boundary	Water levels	Utrechtseweg

The MatLab curve fitting tool was used to make the Q-h relationships. For the Utrechtseweg a linear model was used. The relation is presented in Figure 49 while the fit characteristics are shown in Table 27.

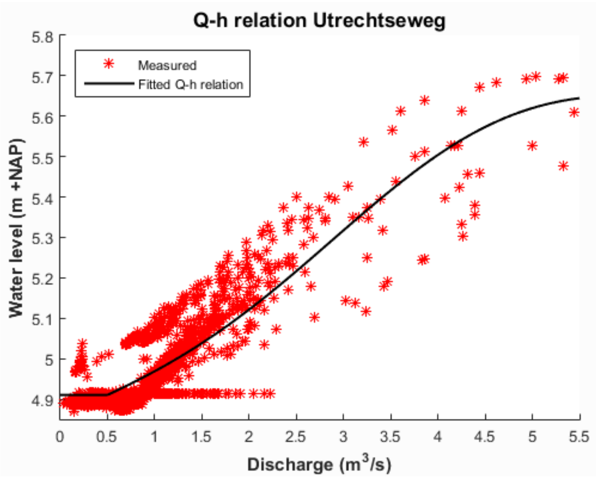

Figure 49: Fitted linear model for the Q-h relation at the Utrechtseweg with the measurements

Table 27: Characteristics of the linear model fitted for the Utrechtseweg

Type curve	Linear model
Fitted relation	$f(x) = a * \sin(x - \pi) + b * (x - 10)^2 + c$
Parameter values	a = 0.07452 b = -0.009241 c = 5.778
Fit characteristics	SSE: 6.312 R-square: 0.7946 Adjusted R-square: 0.7944 RMSE: 0.05295

It becomes clear from Figure 49 that the curve is levelling off towards the higher discharges. This is something that might be expected, and was also the underlying reason for selecting the linear model. Since at certain discharges water will overtop the floodplains of the stream, water levels will increase slower than at lower discharges. However, it is not expected that the curve will level off as much in reality as the curve fitted to the measurements here. Eventually this linear fit will even show decreasing water levels at higher discharges which is impossible. Therefore this curve is only used to determine boundary conditions for the validation scenarios that range up to a discharge of 5,5 m^3/s. For the higher discharge events, an exponential model was fitted using the MatLab curve fitting tool. This fit is shown in Figure 50 and its characteristics are given in Table 28.

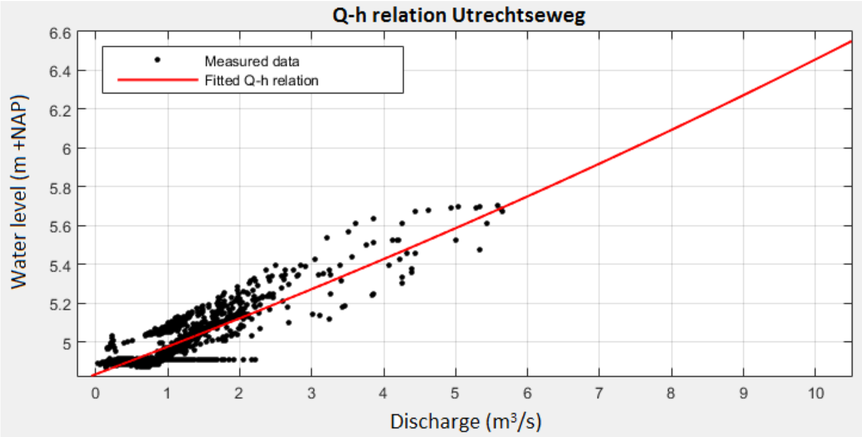

Figure 50: Fitted exponential model for the Q-h relation at the Utrechtseweg with the measurements

Table 28: Characteristics of the exponential model fitted for the Utrechtseweg

Type curve	Exponential model
Fitted relation	$f(x) = a * e^{bx} + \mathrm{c} * e^{dx}$
Parameter values	a = 0.1655 b = -5.082 c = 4.803 d = 0.03274
Fit characteristics	SSE: 5.766 R-square: 0.8124 Adjusted R-square: 0.8121 RMSE: 0.05062

Figure 50 clearly shows a curve that is not smoothing out and keeps increasing. Even though this is a pattern that is unlikely to be expected, this curve gives a better indication of water levels that might be expected during extreme discharge scenarios than the linear fit. The fit is therefore used to determine the downstream boundaries for the T100 and T10 discharge events.

For the Barneveldsestraat upstream, an exponential model was fitted to the measurements. The resulting curve is given in Figure 51 and the fit characteristics are presented in Table 29.

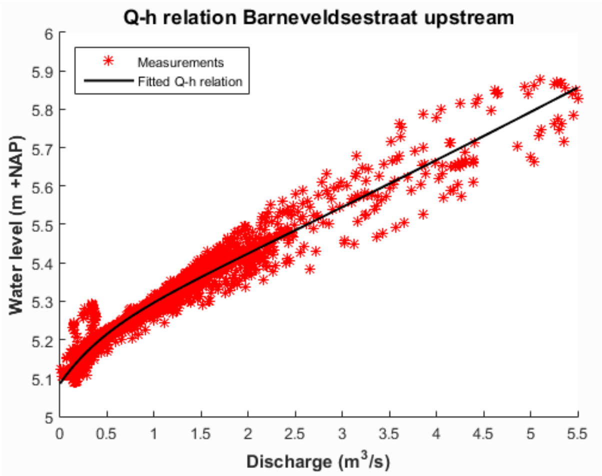

Figure 51: Fitted exponential model at the Barneveldsestraat upstream with the measurements

Table 29: Characteristics of the exponential model fitted for the Barneveldsestraat upstream

Type curve	Exponential model
Fitted relation	$f(x) = a * e^{bx} + c * e^{dx}$
Parameter values	a = 5.193 b = 0.02182 c = -0.1109 d = -2.193
Fit characteristics	SSE: 2.295 R-square: 0.9659 Adjusted R-square: 0.9659 RMSE: 0.01902

The reason for choosing the exponential model for the Barneveldsestraat upstream location are the fit characteristics. It can be seen from Table 29 that these are really good and also from Figure 51 that the Q-h relation follows the pattern of the measurements really well.

For the Barneveldsestraat downstream, measured water levels were very similar to water levels measured at the Barneveldsestraat upstream measurement location. Therefore an exponential model was fitted to the measurements also, as can be seen in Figure 52. The fit characteristics are presented in Table 30.

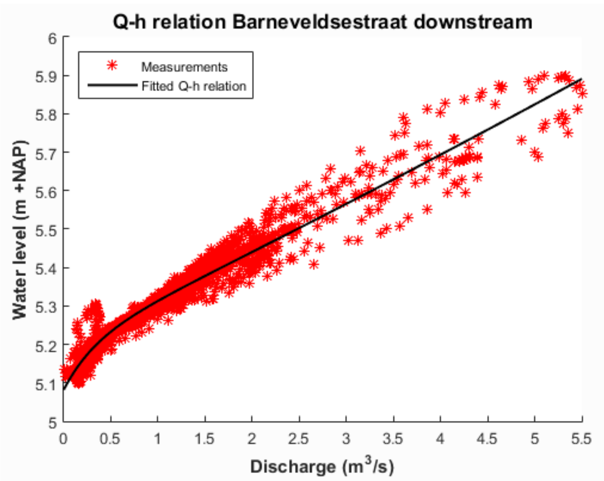

Figure 52: Fitted exponential model at the Barneveldsestraat downstream with the measurements

Table 30: Characteristics of the exponential model fitted for the Barneveldsestraat downstream

Type curve	Exponential model
Fitted relation	$f(x) = a * e^{bx} + c * e^{dx}$
Parameter values	a = 5.198

	b = 0.02271 c = -0.1207 d = -3.042
Fit characteristics	SSE: 2.322 R-square: 0.9669 Adjusted R-square: 0.9669 RMSE: 0.01913

It can be seen from Figure 52 that the exponential model describes the measured water levels really well. This is also confirmed by the fit characteristics, that are comparable to the fit characteristics for the Barneveldsestraat upstream measurement location.

Finally, an exponential model was fitted to the measurements at location WL2. This Q-h relation was only used for validation up to a range of 1 m^3/s though, since very few measurements are available for this location. The fitted Q-h relation is shown in Figure 53 and the fit characteristics are presented in Table 31.

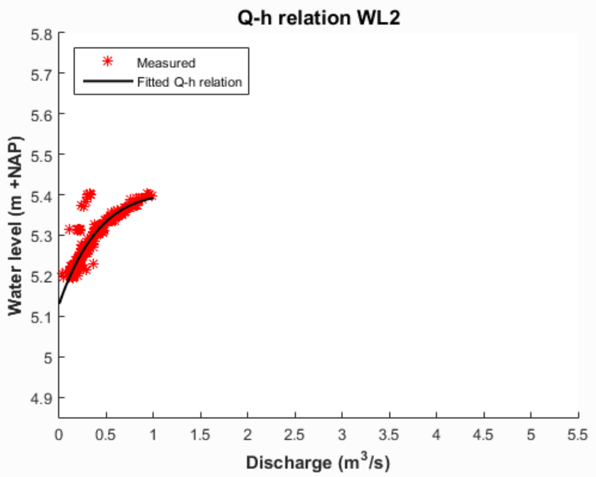

Figure 53: Fitted exponential model at measurement location WL2 with the measurements

Table 31: Characteristics of the exponential model fitted for WL2

Type curve	Exponential model
Fitted relation	$f(x) = a * e^{bx} + c * e^{dx}$
Parameter values	a = 5.501 b = -0.0105 c = -0.3771 d = -1.981
Fit characteristics	SSE: 2.141 R-square: 0.8893 Adjusted R-square: 0.8886 RMSE: 0.02031

The exponential model was chosen for measurement location WL2, since it was best able to describe the measured water levels up to a discharge of 1 m^3/s.

Appendix B: Schematisation Tungelroyse beek with available data

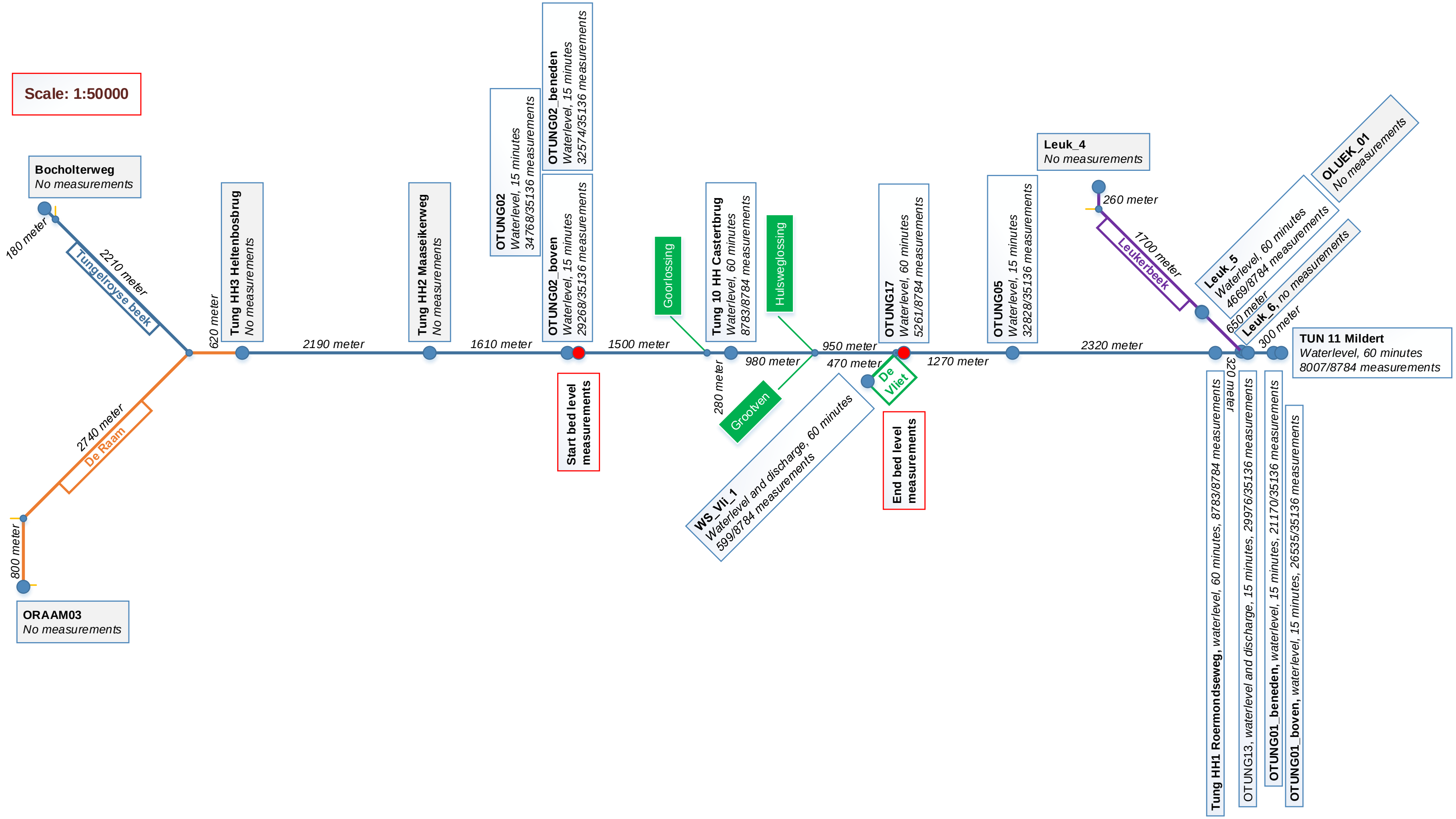

Figure 54: Overview of available data for the Tungelroyse beek

Appendix C: Fitted Q-h relations Tungelroyse beek

This appendix shows the fitted Q-h relations for the Tungelroyse beek. Only data collected in December 2011 was used. The locations of importance, with their characteristics are shown in Figure 55 and Table 32 respectively.

Figure 55: Model boundaries and validation location for the Tungelroyse beek (Google Maps)

Table 32: Boundaries and validation location for the Tungelroyse beek

Location	Type of measurement	Name
Upstream boundary	Nothing	Wisbroek
Validation point	Water level	Castertbrug
Downstream boundary	Water level	OTUNG17

The MatLab curve fitting tool was used to fit the Q-h relationships through the measurements. A rational model was fitted to the measurements performed at the Castertbrug. The Q-h relation is presented in Figure 56 and the fit characteristics are shown in Table 33.

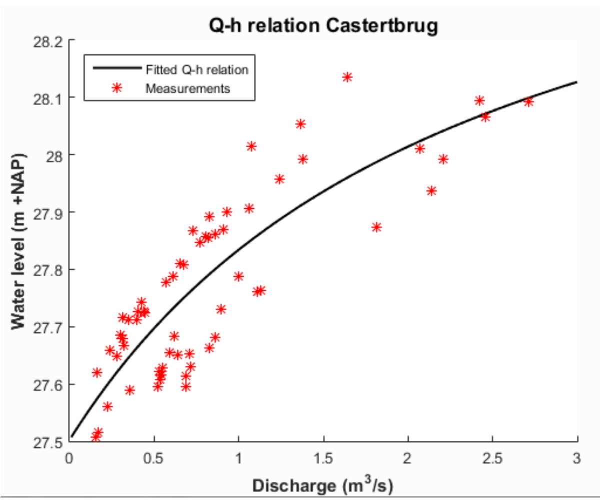

Figure 56: Fitted rational model for the Q-h relation at the Castertbrug along with the measurements

Table 33: Characteristics of the rational model fitted for the Castertbrug

Type curve	Rational model
Fitted relation	$f(x) = \frac{(p_1 * x + p_2)}{(x + q_1)}$
Parameter values	p_1 = 28.62 p_2 = 65.07 q_1 = 2.366
Fit characteristics	SSE: 0.4262 R-square: 0.7108 Adjusted R-square: 0.7007 RMSE: 0.08647

The rational model was selected because it had good fit characteristics. On top of that, the curve shows a decreasing steepness with increasing discharge which is something that can be expected once overtopping of the main channel starts to occur.

For the downstream boundary a linear model was fitted to the measurements. This is shown in Figure 57. The fit characteristics are presented in Table 34.

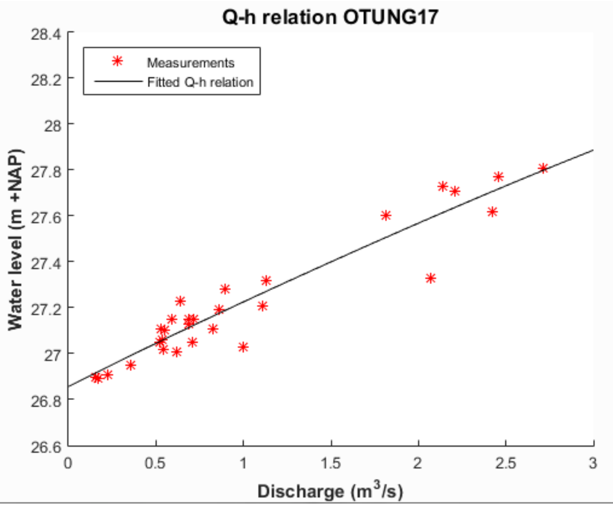

Figure 57: Fitted linear model for the Q-h relation at the downstream boundary with the measurements

Table 34: Characteristics of the linear model fitted for OTUNG17

Type curve	Linear model
Fitted relation	$f(x) = a * \sin(x - \pi) + b * (x - 10)^2 + c$
Parameter values	a = 0.0189 b = -0.02027 c = 28.88
Fit characteristics	SSE: 0.2077 R-square: 0.9023 Adjusted R-square: 0.8948 RMSE: 0.08937

As can be seen from Figure 57 and Table 34, the linear model describes the measurements quite accurately. The reason for selecting the linear model was that it had the best fit characteristics.

Appendix D: Sensitivity analysis Sobek Lunterse beek

This appendix describes the results of the sensitivity analysis that was performed for the Sobek model of the Lunterse beek. The analysis was performed to identify the effect of certain modelling choices. The effect of selecting different roughness values is presented in Figure 58.

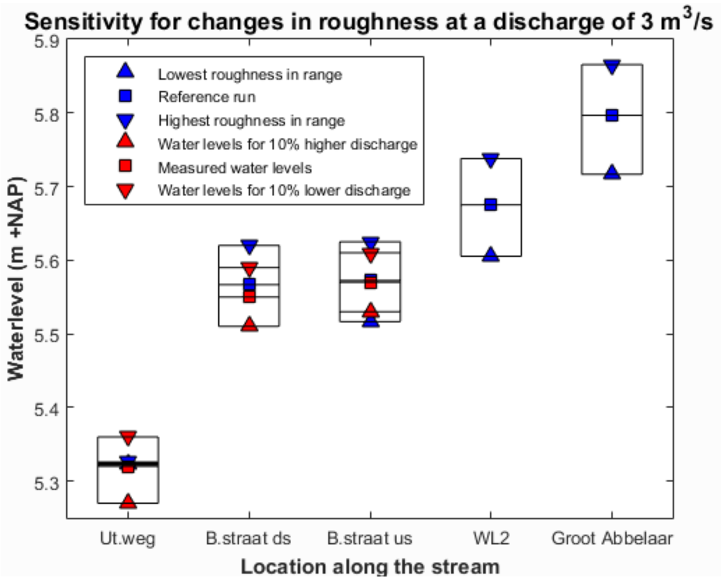

Figure 58: Effect of changes in roughness on simulated water levels in the Sobek model for a discharge of 3 m^3/s

As can be seen from Figure 58, the simulated water levels are sensitive to changes in bed roughness. It becomes clear once more that the simulated water levels correspond really well with the monitored water levels.

Besides roughness, sensitivity was tested for using a Chézy roughness description instead of a Manning roughness description for the main channel of section 2. Since LWD is present in this section, a Chézy roughness formulation might be more appropriate for this section specifically. The result of the analysis is shown in Figure 59.

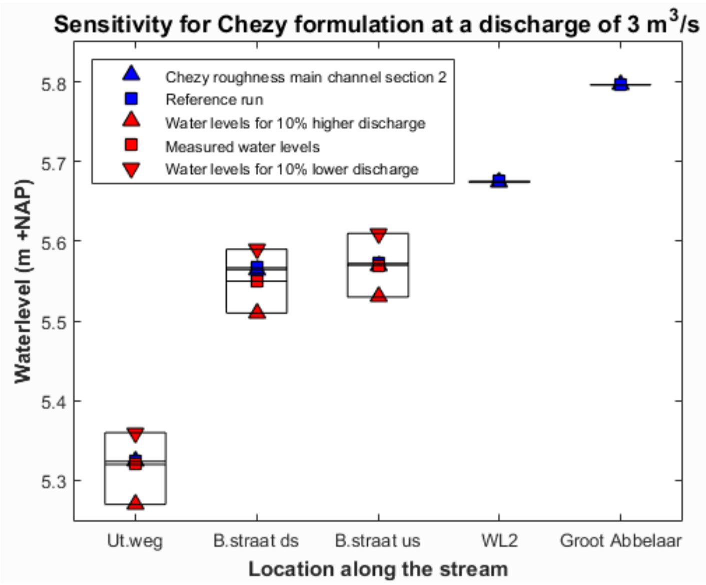

Figure 59: Effect of different roughness formulation on simulated water levels in the Sobek model for a discharge of 3 m^3/s

Figure 59 shows that the effect of using a different roughness formulation for a small part of the stream has almost no effect on simulated water levels.

Appendix E: Bed roughness Sobek

The reasons for selecting the Manning roughness values for the Sobek model as presented in Tables 8 and 9 are described in this Appendix. The arguments are given per parameter.

Parameter n_b

The channel material determines the roughness values for parameter n_b. The selected roughness values for this parameter are summed up in Table 35.

Table 35: Values for Manning parameter n_b

Section	Part	Condition	Uniform discharge		
			$n_{b;low}$	$n_{b;high}$	$n_{b;avg}$
1	Main channel	Sand-fine gravel	0.024	0.024	0.024
1	Close floodplain	Sand-fine gravel	0.024	0.024	0.024
1	Distant floodplain	Sand-fine gravel	0.024	0.024	0.024
2	Main channel	Sand-fine gravel	0.024	0.024	0.024
2	Close floodplain	Sand-fine gravel	0.024	0.024	0.024
2	Distant floodplain	Sand-fine gravel	0.024	0.024	0.024
3	Main channel	Sand-fine gravel	0.024	0.024	0.024
3	Close floodplain	Sand-fine gravel	0.024	0.024	0.024
3	Distant floodplain	Sand-fine gravel	0.024	0.024	0.024

As becomes clear from Table 35, for all sections and both periods the sand-fine gravel is selected as channel and floodplain material. For the restored sections, sand was used to create the meander bends. On top of that, the top layer for the whole area consists of sandy soil as can be seen in Figure 60 and Figure 61 (TNO, 2016). Strictly speaking the top layer is described as the “Formatie van Boxtel”, which is a sandy soil type (Schokker et al., 2005).

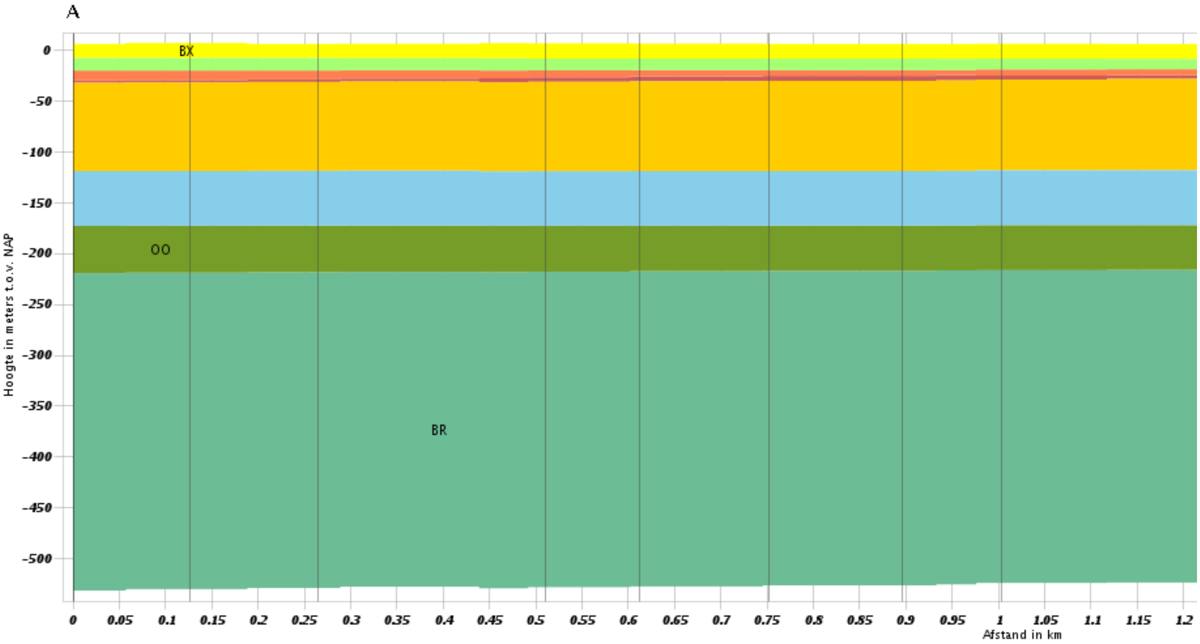

Figure 60: Ground layers in the upstream part of the study area (TNO, 2016)

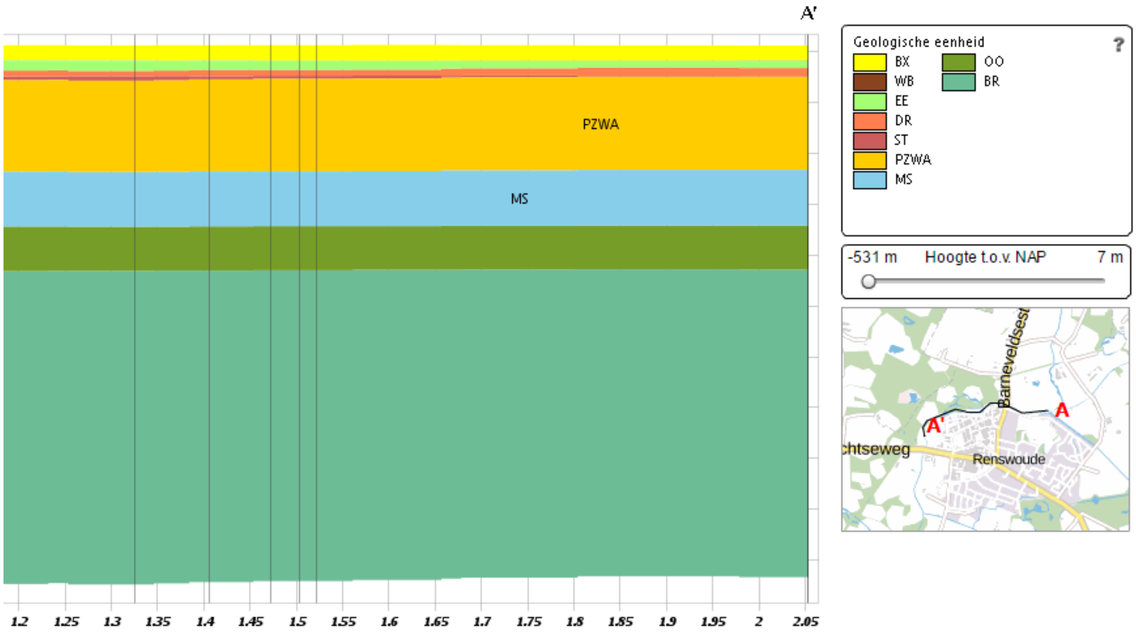

Figure 61: Ground layers in the downstream part of the study area (TNO, 2016)

Parameter n_1
For parameter n_1, that describes the degree of irregularity in the channel/floodplains, the selected roughness values are presented in Table 36.

Table 36: Values for Manning parameter n_1

Section	Part	Condition	Uniform discharge		
			$n_{1;low}$	$n_{1;high}$	$n_{1;avg}$
1	Main channel	Minor	0.001	0.005	0.003
1	Close floodplain	Moderate	0.006	0.010	0.008
1	Distant floodplain	Moderate	0.006	0.010	0.008
2	Main channel	Minor	0.001	0.005	0.003
2	Close floodplain	Moderate	0.006	0.010	0.008
2	Distant floodplain	Minor	0.001	0.005	0.003
3	Main channel	Moderate	0.006	0.010	0.008
3	Close floodplain	Minor	0.001	0.005	0.003
3	Distant floodplain	Minor	0.001	0.005	0.003

As can be seen from Table 36, minor irregularity was selected for the main channel in sections 1 and 2.. This was done, because minor irregularity can be applied for excavated channels in good condition. In the modelled period, excavation took place recently due to stream restoration, making this the appropriate category for sections one and two. For section three, no restoration, and therefore also no excavations, took place. Therefore moderate irregularity was selected here, also since some height variation was present in this section. Therefore regular rises and dips is a description that fits best.

For the floodplains in section one, moderate irregularity was selected for both the close and distant floodplains. This was done since height shows quite some variation along the channel. The description of regular rises and dips therefore shows good agreement.

In section two, moderate irregularity was selected for the close floodplains while minor irregularity was selected for the distant floodplains. Again this was based upon the height. The close floodplains show variation on regular basis, while the distant floodplains show only little variation in height. Thus regular rises and dips fits the close floodplains best while the distant floodplains are explained best by slightly irregular shape, a few rises and dips.

For section three, the floodplains are characterized by minor irregularity. Besides the fact that no active restoration took place in this part, the height is relatively constant along the stream. Therefore this fits best in the category slightly irregular shape, a few rises and dips.

Parameter n_2
For parameter n_2, that describes the variations in cross-sectional area, the selected roughness values are presented in Table 37.

Table 37: Values for Manning parameter n_2

Section	Part	Condition	Uniform discharge		
			$n_{2;low}$	$n_{2;high}$	$n_{2;avg}$
1	Main channel	Gradual	0.001	0.005	0.003
1	Close floodplain	(-)	0	0	0
1	Distant floodplain	(-)	0	0	0
2	Main channel	Gradual	0.001	0.005	0.003
2	Close floodplain	(-)	0	0	0
2	Distant floodplain	(-)	0	0	0
3	Main channel	Uniform	0	0	0
3	Close floodplain	(-)	0	0	0
3	Distant floodplain	(-)	0	0	0

For the main channel in sections one and two, gradual variation in cross-sectional area was selected. This was based upon changes in cross-sectional area present in these sections. The profiles change slightly along the stream. In section one this is mainly due to the meanders, while in section two this is caused by LWD in the channel. The description of large and small cross-sections that alternate occasionally is thus selected.

In section three, uniform cross-sectional area was chosen for the main channel. The description for this category states it should be selected for near-uniform channel cross-section. This is correct for section three, where main channel area is nearly uniform in alongshore direction.

For the floodplains the parameter n_2 is not applicable in the Cowan method, therefore zero is selected for all floodplains.

Parameter n_3

For parameter n_3, that describes the effect of obstructions (excluding vegetation), the selected roughness values are presented in Table 38.

Table 38: Values for Manning parameter n_3

Section	Part	Condition	Uniform discharge		
			$n_{3;low}$	$n_{3;high}$	$n_{3;avg}$
1	Main channel	Negligible	0	0.004	0.002
1	Close floodplain	Negligible	0	0.004	0.002
1	Distant floodplain	Appreciable	0.02	0.03	0.025
2	Main channel	Appreciable	0.02	0.03	0.025
2	Close floodplain	Negligible	0	0.004	0.002
2	Distant floodplain	Minor	0.005	0.015	0.010
3	Main channel	Negligible	0	0.004	0.002
3	Close floodplain	Negligible	0	0.004	0.002
3	Distant floodplain	Minor	0.005	0.015	0.010

For the main channel in sections one and three, negligible effect of obstructions was selected. This was done since no real obstructions are present in these sections. The description given lists: a few scattered obstructions that occupy less than 5% of the channel. It therefore does not match perfectly, but this is the option with the smallest n_3 values that is listed. Besides that, obstructions in a river are of quite different scale than obstructions in a stream (a tree in a river might be comparable to a small tree branch in a stream for example).

For the main channel in section two, appreciable effect of obstructions was selected. This was done because four packages of LWD are present in this section. In total these account for a blocked distance of 71 m alongshore on a section with a length of 446 m over the full length of the main channel. This comes down to 15,9%, which fits best in the appreciable category where obstructions occupy 15-50% of the channel.

For the close floodplains in all sections, negligible effect of obstructions was selected. In this section no real obstructions are present, therefore with the same reasoning as for the main channel in section one and three negligible effect fits best.

For the distant floodplain in section one, appreciable effect of obstructions was selected. This selection was based mainly upon trees in this area, but also a bridge obstructing the flow as well as a house with a yard in the floodplains. Since the trees are spread along the channel also, it is difficult to quantify how much of the section is obstructed. It is chosen to go for 15 till 50% of the floodplain flow area.

For the distant floodplain in sections two and three, minor effect of obstructions was selected. For both sections this was done because some trees are present spread along the channel. Without quantifying, it was estimated that these trees obstruct 5 till 15% of the floodplain flow area.

Parameter n_4
For parameter n_4, that describes the amount of vegetation, the selected roughness values are presented in Table 39.

Table 39: Values for Manning parameter n_4

Section	Part	Condition	Uniform discharge		
			$n_{4;low}$	$n_{4;high}$	$n_{4;avg}$
1	Main channel	Small	0.002	0.01	0.006
1	Close floodplain	Small	0.002	0.01	0.006
1	Distant floodplain	Large	0.025	0.05	0.0375
2	Main channel	Small	0.002	0.01	0.006
2	Close floodplain	Small	0.002	0.01	0.006
2	Distant floodplain	Large	0.025	0.05	0.0375
3	Main channel	Small	0.002	0.01	0.006
3	Close floodplain	Small	0.002	0.01	0.006
3	Distant floodplain	Large	0.025	0.05	0.0375

For the main channel and the close floodplains in all sections, small amount of vegetation was selected. Since the stream was still clean shortly after restoration, this is not completely correct. However, this category lists the lowest selectable Manning roughness values for the parameter n_4 in the Cowan method.

For the distant floodplains, large effect of vegetation was selected amongst all sections. This was based upon grasses and weeds growing in this area. Besides that, if these sections are flooding, water levels will be low. This matches well with the description: grasses/weeds with flow depth equal to vegetation height.

Parameter m
For parameter m, that describes the degree of channel meandering, the selected roughness values are presented in Table 40.

Table 40: Values for Manning parameter m

Section	Part	Condition	Uniform discharge		
			m_{low}	m_{high}	m_{avg}
1	Main channel	Minor	1	1	1
1	Close floodplain	(-)	1	1	1
1	Distant floodplain	(-)	1	1	1
2	Main channel	Appreciable	1.15	1.15	1.15
2	Close floodplain	(-)	1	1	1
2	Distant floodplain	(-)	1	1	1
3	Main channel	Minor	1	1	1
3	Close floodplain	(-)	1	1	1
3	Distant floodplain	(-)	1	1	1

For all floodplains the meander parameter is not applicable, therefore a value of one was selected. For the main channel, the sinuosity was calculated. The distance along the stream was determined and divided by the straight line distance for every section. The results are listed below.

$$Sinuosity\ period\ one, main\ channel\ section\ 1 = \frac{745}{661} = 1.13$$

$$Sinuosity\ period\ one, main\ channel\ section\ 2 = \frac{446}{371} = 1.20$$

$$Sinuosity\ period\ one, main\ channel\ section\ 3 = \frac{415}{356} = 1.17$$

This means that channel sinuosity is minor for sections one and three, while it is appreciable for section two in both periods. The minor category is selected when channel sinuosity is lower than 1.2. The appreciable category holds for a sinuosity between 1.2 and 1.5.

Summation
Using the parameter values described above, a range for the roughness values was given for all three sections in the stream. The values are presented in Table 41.

Table 41: Summary of the range of roughness values for all sections of the Lunterse beek in different periods

		Uniform discharge		
Section	**Part**	n_{low}	n_{high}	n_{avg}
1	Main channel	$2.80*10^{-2}$	$4.80*10^{-2}$	$3.80*10^{-2}$
1	Close floodplain	$3.20*10^{-2}$	$4.80*10^{-2}$	$4.00*10^{-2}$
1	Distant floodplain	$7.50*10^{-2}$	$1.14*10^{-1}$	$9.45*10^{-2}$
2	Main channel	$5.52*10^{-2}$	$8.51*10^{-2}$	$7.02*10^{-2}$
2	Close floodplain	$3.20*10^{-2}$	$4.80*10^{-2}$	$4.00*10^{-2}$
2	Distant floodplain	$5.50*10^{-2}$	$9.40*10^{-2}$	$7.45*10^{-2}$
3	Main channel	$3.20*10^{-2}$	$4.80*10^{-2}$	$4.00*10^{-2}$
3	Close floodplain	$2.70*10^{-2}$	$4.30*10^{-2}$	$3.50*10^{-2}$
3	Distant floodplain	$5.50*10^{-2}$	$9.40*10^{-2}$	$7.45*10^{-2}$

Appendix F: Test Surfis interpolations

In this Appendix the results of some tests with the Surfis interpolation software are discussed. In the model of the Lunterse beek, 22 cross-sections were used to generate the main channel bathymetry for the Delft3D FM model. The study area had a distance of close to 1600 m. This means on average 13.8 cross-sections per km were used to generate the bathymetry of the main channel.

For the Tungelroyse beek, more measurements were available. The length of the study area is 3800 m for this stream. In total 517 cross-sections measurements are available in this stream. To test what the effect is of the density of cross-section measurements on the bathymetry that is generated with Surfis, multiple interpolations were performed with different cross-section density. The effect of using 50, 20, 10 and 5% of the measurements respectively is analysed compared to using all measurements. The amount of cross-sections used for the interpolations and the average density are presented in Table 42.

Table 42: Data used for the different Surfis interpolations

Amount of measurements	**100%**	**50%**	**20%**	**10%**	**5%**
Cross-sections	577	290	115	59	30
Density (cross-sections/kilometre)	151.8	76.3	30.3	15.5	7.9

As becomes clear from Table 42, the amount of cross-sections are not exactly the percentages as listed. This is due to the fact that the first and last cross-sections were used in all the interpolations. Otherwise, the Surfis interpolation tool cannot establish a bathymetry at the edges. For all the different interpolations, the difference with respect to using all measurements was calculated. The average difference, the standard deviation and the highest over- and underestimation in the bathymetry are presented in Table 43.

Table 43: Results of the different interpolations compared to using all measurements

Percentage of measurements used	**50%**	**20%**	**10%**	**5%**
Maximal underestimation (m)	2.07	2.10	2.08	1.62
Maximal overestimation (m)	0.73	0.97	0.93	0.94
Average difference (m)	0.06	0.10	0.14	0.16
Standard deviation (m)	0.12	0.19	0.26	0.30

As becomes clear from Table 43, the average difference between the interpolations grows if less cross-section measurements are used. The same goes for the standard deviation. The difference between the interpolations can become large also, as the bed level can become 2.10 m lower and 0.97 m higher at some locations when 20% of the measurements are used.

To give some more insight in the differences for the different interpolations, Figure 62 till Figure 65 give three-dimensional images of the same location, showing the differences in interpolated height compared to the interpolation where all measurements were used.

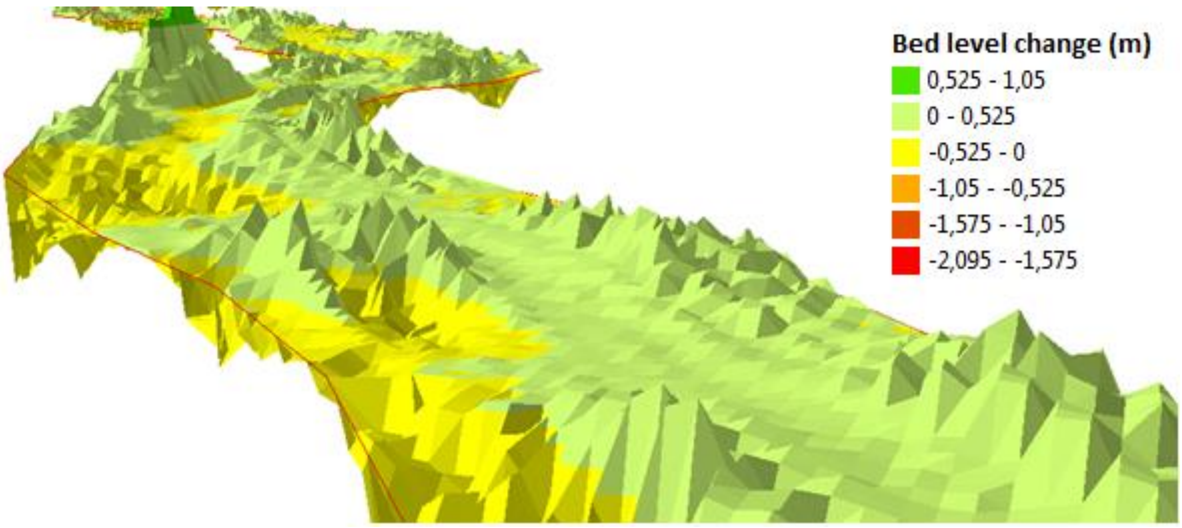

Figure 62: Difference in interpolated bed level height when 50% instead of 100% of the cross-section measurements are used in Surfis

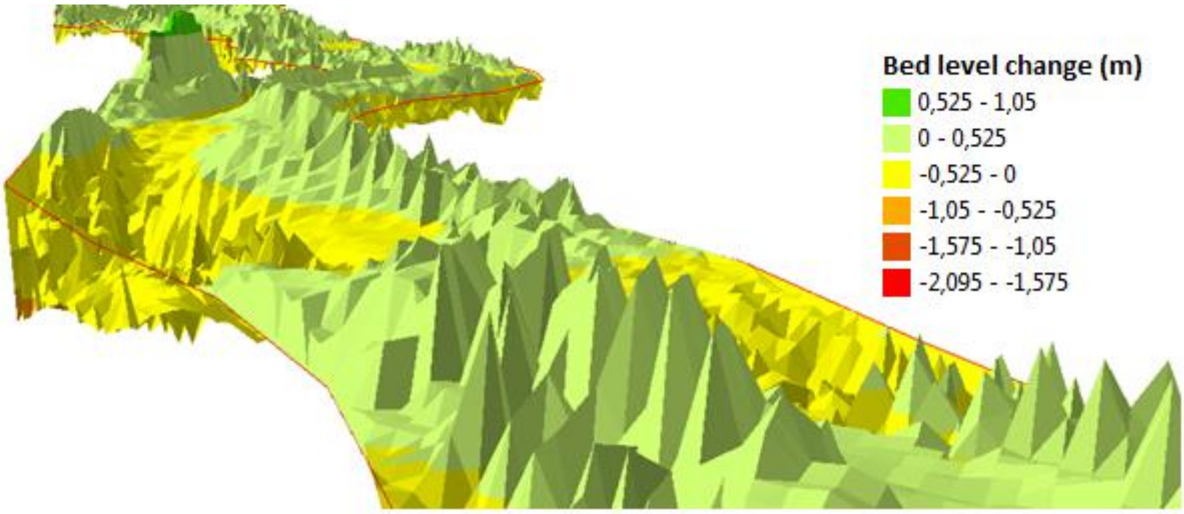

Figure 63: Difference in interpolated bed level height when 20% instead of 100% of the cross-section measurements are used in Surfis

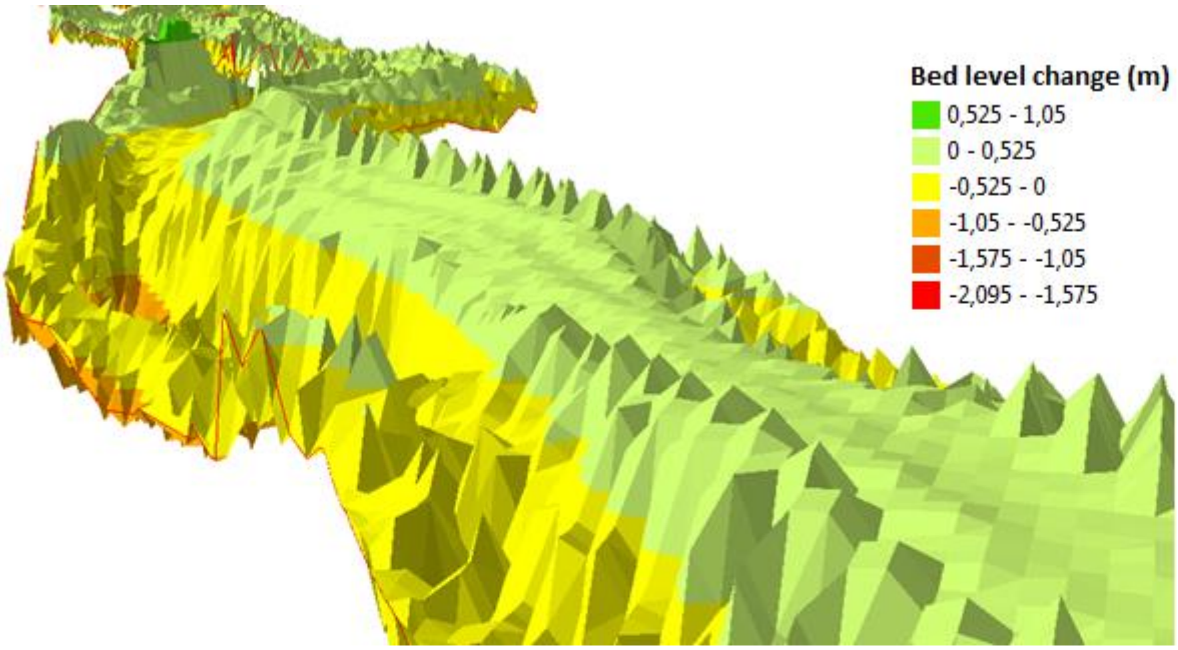

Figure 64: Difference in interpolated bed level height when 10% instead of 100% of the cross-section measurements are used in Surfis

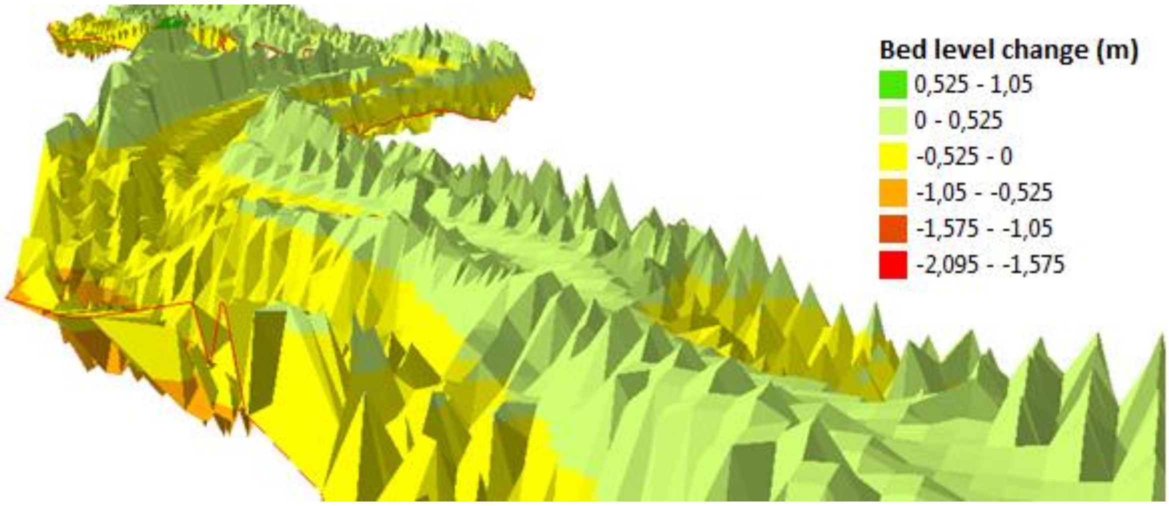

Figure 65: Difference in interpolated bed level height when 5% instead of 100% of the cross-section measurements are used in Surfis

As becomes clear from Figure 62 till Figure 65, the amount of measurements used for the interpolation affects the created bathymetry considerably. Especially the scour holes and ridges can influence simulated hydraulics with the models. Besides that a sensitivity analysis already showed that simulated water levels are sensitive for changes in model bathymetry. This research showed that the bathymetry differs, depending on how many input measurements are used for the Surfis interpolation. It can be concluded that the created bathymetry is influenced by the amount of cross-section measurements performed, which in turn influences simulated water levels.

Appendix G: Difference AHN2 and measurements

This Appendix describes differences found in AHN2 data and measurements of bed level. These differences might occur due to uncertainties in the measurement equipment. More importantly though, differences are caused since heights are determined in different periods.

Difference AHN2 data and measured data Lunterse beek

Since AHN2 data was collected in 2010 (Zon, 2013), while the model for the Lunterse beek was made for the 2012 situation, a check is performed for differences between the two sources. This was done using all cross-sectional measurements performed in February 2012. To start with, the AHN2 height was subtracted from the measurement height for all locations. After that, the locations where AHN2 data was absent were removed, as were the locations that were present in the main channel. This was done since no AHN2 data was used for the bed level interpolations here, only the measurements in the Surfis software. The final results of this analysis are presented in Table 44.

Table 44: Statistics of comparison between AHN2 (2010) data and bed level measurements (2012)

Amount of locations	Maximal underestimation (m)	Minimal underestimation (m)	Average difference (m)
189	0.91	-2.03	-0.27

From Table 44, it becomes clear that there is a significant difference between the measured data in 2012 and the AHN2 data in 2010. A total of 189 locations were compared to each other. The maximum positive difference between the measurements and the AHN2 data is 0,91 m (at this location the measurement showed a higher bed level than the AHN2 measurement). The maximum negative difference was 2,03 m though, with AHN2 bed levels higher than the measurements. On average the bottom level was 0,27 meter higher in the AHN2 measurements.

To get an understanding for what this means for model output, a new interpolation was performed with Surfis. This time all measurement data from Meet B.V. (2012) was used for this interpolation. A new geometry was made based upon outcome of this interpolation and this geometry was compared to the geometry used in the Lunterse beek model. The resulting difference is presented in Table 45.

Table 45: Statistics of a comparison between a geometry created using all bed level measurements vs. a geometry created using only cross-sectional bed level measurements

Maximal underestimation (m)	Minimal underestimation (m)	Average difference (m)
2.38	-1.61	-0.13

As becomes clear from Table 45, the average difference is smaller than between the measured data and the AHN2 data. Still, the geometry would become on average 13 cm lower if the model was set-up differently.

Difference AHN2 data and measured data Tungelroyse beek

For the Tungelroyse beek AHN2 data was collected in 2012 (Zon, 2013). The model for the Tungelroyse beek was set-up for the December 2011 situation though. For this model all measurements were used in the Surfis interpolation, which differs from the Lunterse beek model. To still get an indication for what this might mean for the flood plains, the overlapping data between the Surfis interpolation and AHN2 data was subtracted from each other. The results are shown in Table 46.

Table 46: Statistics of comparison between AHN2 (2012) data and bed level measurements (2010/2011.)

Amount of locations	Maximal underestimation (m)	Minimal underestimation (m)	Average difference (m)
27955	0.32	-0.62	-0.11

This means that on average the bottom level was 0.11 meter higher in the AHN2 measurements.

Appendix H: Bed roughness Delft3D FM Lunterse beek

The reasons for selecting the Manning roughness values for the Delft3D FM model as presented in Table 11 are described in this Appendix. The arguments are given per area type.

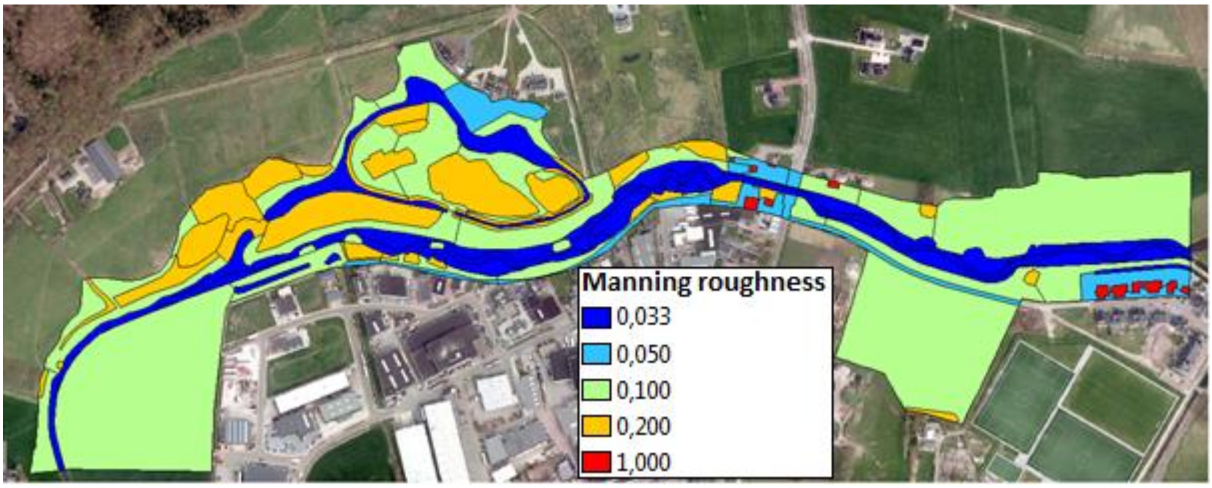

Figure 66: Manning roughness used for the Delft3D FM model of the Lunterse beek

Main channel

Shortly after stream restoration, no vegetation was present in the stream. Therefore the main channel was classified as “clean to very clean”. Following the Cultuurtechnisch Vademecum on this, the k_m roughness will be inbetween 20-35 $m^{1/3}/s$ for a clean waterway and inbetween 30 and 45 $m^{1/3}/s$ for a very clean waterway (Dreven, et al., 2000). With the formula (Ribberink & Hulscher, 2012):

$$C = R^{1/6} * k_m = \frac{R^{1/6}}{n}$$

It can be seen that: $n = \frac{1}{k_m}$

In the end a k_m roughness value of 30 $m^{1/3}/s$ was selected. The value represents a clean till very clean stream and the Manning value thus is 0.033 $s/m^{1/3}$.

Floodplain close to main channel

With floodplain close to main channel, the section of the stream that was also actively restored is designated. This section also had no vegetation shortly after restoration. Since the bottom is also sandy like the main channel, the same k_m roughness value of 30 $m^{1/3}/s$ was selected. Using the same formulas, this lists a Manning value of 0.033 $s/m^{1/3}$ also.

Pasture

Pasture grounds were characterized as having a moderate to quite strong vegetation cover. Moderate vegetation cover has k_m values between 20 and 10 $m^{1/3}/s$, while quite strong vegetation cover has k_m values between 16 and 5 $m^{1/3}/s$. A k_m roughness value of 10 $m^{1/3}/s$ was eventually selected, since this value belongs to both categories. This makes a Manning roughness of 0.1 $s/m^{1/3}$.

Large Woody Debris

Quantifying the roughness of the Large Woody Debris was quite difficult. An article of Dudley et al. (1998) was eventually used as guidance. In this article, Dudley et al. (1998) assess roughness values in a stream prior to and following removal of woody debris. They used the flow parameter VR (m^2/s) as a guidance. This flow parameter is calculated by multiplying the flow velocity (u) with the hydraulic radius (R).

To estimate the flow parameter, the hydraulic radius was assumed equal to one. This was done because during a T1 discharge scenario the water depth at the Barneveldsestraat measurements locations is around 1.4 m. The width of the main channel is around 7.5 m at this location. So assuming a rectangular stream shape, hydraulic radius can be calculated by:

$$R = \frac{A}{O} = \frac{7.5 * 1.4}{7.5 + 2 * 1.4} = 1.02$$

The average flow velocity during a T1 discharge event for the five measurement locations (Groot Abbelaar, WL2, Barneveldsestraat upstream and downstream and Utrechtseweg) equals 0.28 m/s. For a flow parameter of around

0.28, the Manning roughness value found lies between 0.075 and 0.125 s/m$^{1/3}$. Therefore 0.1 s/m$^{1/3}$ was selected as Manning roughness for the LWD packages.

Roads
Roads were classified as clean to slightly rough. Roughness value k_m are in-between 20-35 m$^{1/3}$/s, while slightly rough terrain shows k_m values between 25 and 15 m$^{1/3}$/s. Eventually a k_m roughness value of 20 m$^{1/3}$/s was selected since this applies to both categories. This means the Manning roughness value equals 0.05 s/m$^{1/3}$.

Houses
No real category could be applied for the roughness of houses. In normal conditions, water will never reach houses in the Lunterse beek floodplain. Still, if water reaches the houses, these will completely obstruct the flow. Therefore a Manning roughness of 1 s/m$^{1/3}$ was applied here.

Forest
Forest was categorized as having a pretty strong to very strong vegetation cover. k_m roughness values in the pretty strong vegetation cover category range from 16 to 5 m$^{1/3}$/s. For very strong vegetation cover k_m values are lower than 10 m$^{1/3}$/s. Eventually a k_m value of 5 m$^{1/3}$/s was selected, since this fits in both categories. This means a Manning roughness value of 0.2 s/m$^{1/3}$ will be applied here.

Appendix I: Sensitivity analysis Delft3D FM Lunterse beek

This appendix shows the results obtained during the initial sensitivity analysis performed for the Delft3D FM model of the Lunterse beek. As mentioned in section 5.1, this model differed from the final Delft3D FM model for the Lunterse beek, since the bed level height of the floodplains was not yet correctly modelled.

Besides sensitivity for model parameters, uncertainty in water level and discharge measurements will be included in this analysis. The uncertainty can be mainly expected in the discharge measurements, since for discharge measurements performed with an acoustic flow meter, uncertainty is often between 5 and 10 % (Hartong & Termes, 2009). To include the effect of this uncertainty in this sensitivity analysis, a 10 % uncertainty in discharge measurements was assumed. New measurement series were created by multiplying measured discharges with 0.9 and 1.1 to account for this uncertainty, keeping water levels the same. Finally, Q-h relations were fitted to the new measurement series. The characteristics of the newly fitted Q-h relations are presented in Table 47 (figures are omitted).

Table 47: Characteristics of the Q-h relations assuming a deviation of 10% in discharge measurements

Location	Change in discharge	Type curve	Fitted relation	Parameter values	Fit characteristics
WL2	-10 %	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.501 b = -0.1167 c = 0.3771 d = -2.201	*SSE*: 2.141 *R-square*: 0.8893 *Adjusted R-square*: 0.8886 *RMSE*: 0.02031
WL2	10 %	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.501 b = -0.00955 c = 0.3771 d = -1.801	*SSE*: 2.141 *R-square*: 0.8893 *Adjusted R-square*: 0.8886 *RMSE*: 0.02031
B.straat upstream	-10 %	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.193 b = 0.01983 c = -0.1109 d = -1.994	*SSE*: 2.295 *R-square*: 0.9659 *Adjusted R-square*: 0.9659 *RMSE*: 0.01902
B.straat upstream	10 %	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.193 b = 0.02424 c = -0.1109 d = -2.437	*SSE*: 2.295 *R-square*: 0.9659 *Adjusted R-square*: 0.9659 *RMSE*: 0.01902
B.straat down-stream	-10%	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.198 b = 0.02064 c = -0.1207 d = -2.765	*SSE*: 2.322 *R-square*: 0.9669 *Adjusted R-square*: 0.9669 *RMSE*: 0.01913
B.straat down-stream	10 %	Exponential model	$f(x) = a * e^{bx} + c * e^{dx}$	a = 5.198 b = 0.02523 c = -0.1207 d = -3.38	*SSE*: 2.322 *R-square*: 0.9669 *Adjusted R-square*: 0.9669 *RMSE*: 0.01913
Utrechtse-weg	-10 %	Linear model	$f(x) = a * \sin(x - \pi) + b * (x - 10)^2 + c$	a = 0.07244 b = -0.01024 c = 5.875	*SSE*: 6.413 *R-square*: 0.7913 *Adjusted R-square*: 0.7911 *RMSE*: 0.05339
Utrechtse-weg	10 %	Linear model	$f(x) = a * \sin(x - \pi) + b * (x - 10)^2 + c$	a = 0.07739 b = -0.00845 c = 5.703	*SSE*: 6.216 *R-square*: 0.7977 *Adjusted R-square*: 0.7975 *RMSE*: 0.05256

Multiple parameters will be changed in this sensitivity analysis. This will be done for the uniform discharge scenario of 3 m^3/s. Only if the model turns out to be sensitive for a certain parameter, model runs with a discharge of 1 and 5.5 m^3/s will also be performed. That way, the initial effect of changing certain parameters becomes clear for the 3 m^3/s discharge scenario and additional effects for high and low discharge scenarios.

An overview of the parameters that will be changed is given below:

- Roughness
- Horizontal Eddy viscosity
- Bed level type interpolation method
- Bed level
- Hydraulic radius calculation method

An overview of the locations in the Lunterse beek study area that are of importance for validation is shown in Figure 67. The names of these locations are presented in Table 48.

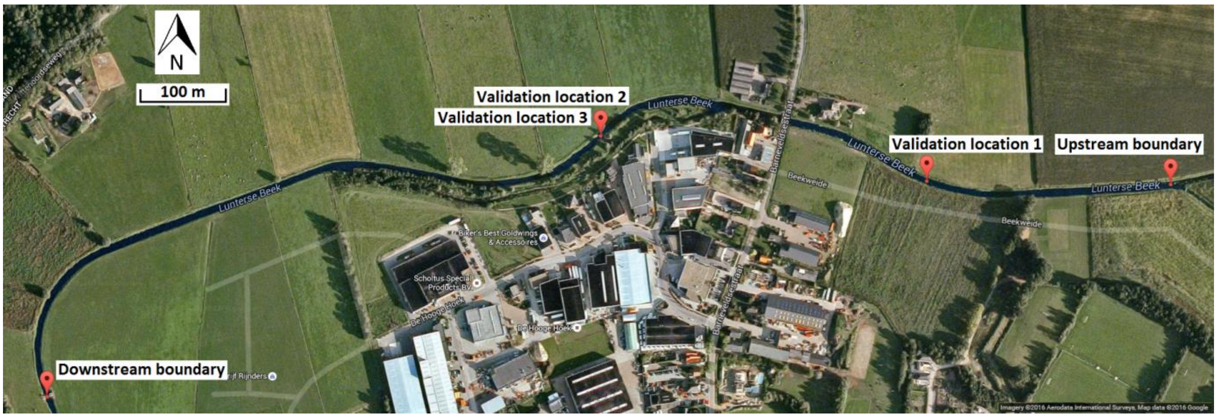

Figure 67: Locations in the Lunterse beek study area that are important for validation

Table 48: Names of validation locations Lunterse beek

Location	**Name**
Upstream boundary	Groot Abbelaar
Validation location 1	WL2
Validation location 2	Barneveldsestraat upstream
Validation location 3	Barneveldsestraat downstream
Downstream Boundary	Utrechtseweg

Roughness
The roughness will be changed since upfront a range of plausible values was identified for the bed level roughness in the stream and the floodplains. The minimal values in this range will be used once, just like the maximal values in the range. This means simulations are performed only using the most extreme roughness configurations expected upfront. The roughness values that will be used in the simulations are presented in Table 21.

Table 49: Lowest and highest Manning roughness values expected upfront

Type	n_{lower}	n_{upper}
Main channel	0.022	0.05
Floodplain close to main channel	0.022	0.05
Pasture	0.05	0.2
Large Woody Debris	0.075	0.125
Roads	0.029	0.067
Houses	1	1
Forest	0.1	0.5
Garden	0.05	0.2

The effects of changes in bed roughness on simulated water levels is shown in Figure 68. As becomes clear from Figure 68, effects are considerable. The effects on simulated water levels are larger for the higher discharge scenarios. Take note that changes in roughness cannot account for the overestimation of water levels in the Delft3D FM model with a wrong floodplain bathymetry. Most important is that changes in bed roughness might considerably improve model performance with respect to simulated water levels.

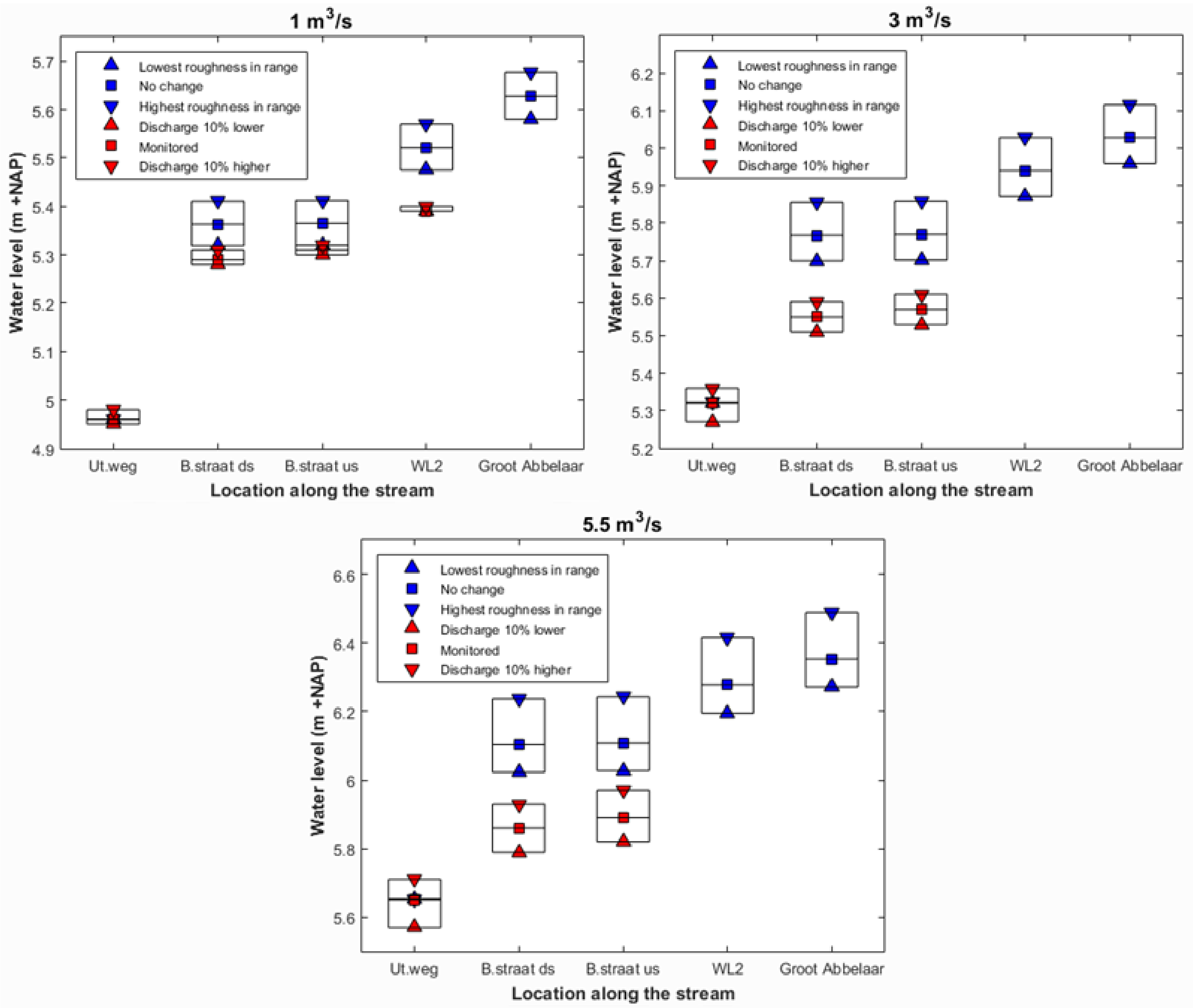

Figure 68: Sensitivity of the Delft3D FM model for changes in roughness

Horizontal Eddy viscosity
The horizontal Eddy viscosity is a parameter that determines how viscous the water behaves during the simulations. The default horizontal Eddy viscosity in the Delft3D FM model is 1 m^2/s. To see how important this parameter is for the simulated water levels in Delft3D FM, the parameter is altered to values of 0.5 and 1.308 m^2/s respectively. The value of 0.5 was selected since it is a value that is often used in hydrodynamic simulations. The value of 1.308 was based upon a multiplication of the kinematic viscosity in water (with a temperature of 10 degrees Celsius) with a factor hundred thousand. The effect on simulated water levels can be seen in Figure 69.

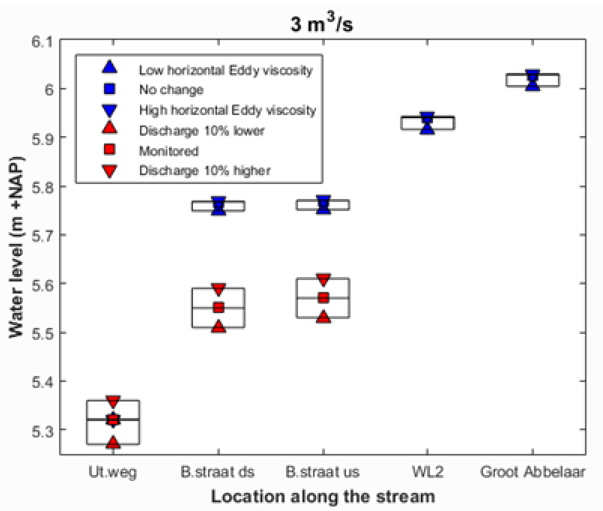

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Figure 69: Sensitivity of the Delft3D FM model for changes in horizontal Eddy viscosity

As can be seen in Figure 69, the effect of different horizontal Eddy viscosity values on simulated water levels is not significant for the 3 m^3/s discharge scenario. This means there is no reason to assume that the default horizontal Eddy viscosity cannot sufficiently describe the flow for the Lunterse beek.

Bed level interpolation
In the Delft3D FM model, all grid cells have a uniform bed level height. In the default settings, this height is determined based upon the average height of all neighbouring nodes. To assess the effect of this method, sensitivity is assessed using the minimal and maximal heights of neighbouring nodes. The effect is shown in Figure 70.

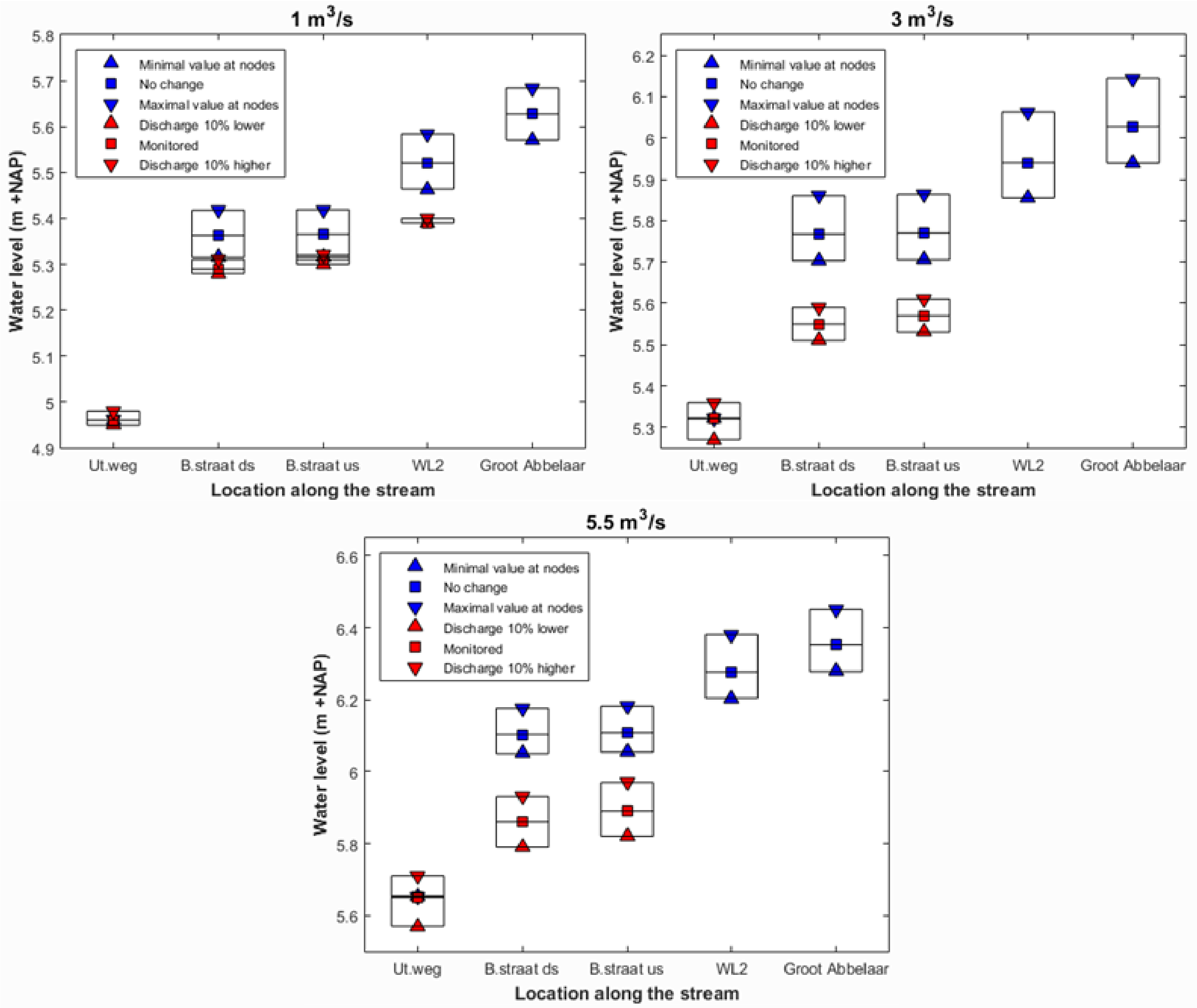

Figure 70: Sensitivity of the Delft3D FM model for changing bed level interpolation methods

As can be seen from Figure 70, the model sensitivity for this interpolation method with respect to simulated water levels is considerable. The effect is largest for the discharge of 3 m^3/s. This shows that bed level interpolation method can increase model performance with respect to simulated water levels.

Bed level
An uncertain aspect in the model setup was determining the bathymetry of the Lunterse beek. The bathymetry for the main channel was based upon 391 bed level measurements distributed over 22 cross-sections along the almost 1600 m long stream. To investigate the sensitivity of the model for changes in the bed level height of the main channel, the bed was once lowered with 10 cm and once heightened with 10 cm. The effect is presented in Figure 71.

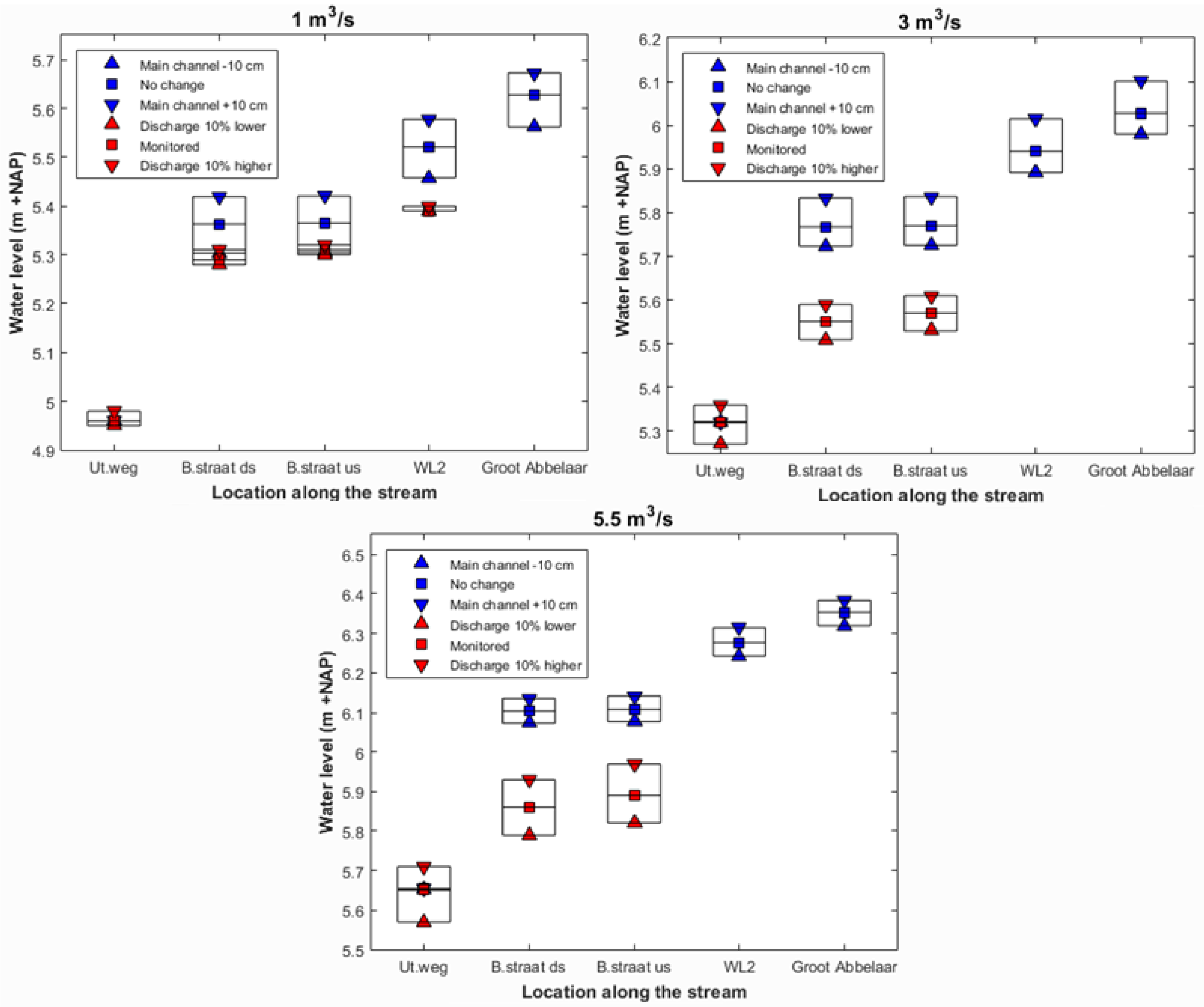

Figure 71: Sensitivity of the Delft3D FM model for main channel bed level height

As can be seen from Figure 71, the effect of changes in the main channels bed level height are considerable. This was also expected, since bed level height directly determines water level considering constant water depth. Still, effects differ among discharge scenarios since water also flows outside the main channel. Therefore effect is largest for a discharge of 1 m^3/s and lowest for a discharge of 5.5 m^3/s. This proves that bed level height of the main channel is important for simulated water levels.

Hydraulic radius

In the Delft3D FM models default settings, the hydraulic radius is determined by using the water depth in the flow velocity points. Strictly speaking, this approximates the hydraulic radius by assuming that it is equal to the water depth. Especially for wide and narrow channels this approximation is not correct. Therefore, the sensitivity for a different hydraulic radius formulation was investigated. The effect of selecting $R = A/P$ is shown in Figure 72.

Figure 72 shows that a different calculation method of the hydraulic radius gives a small decrease in simulated water levels along the stream. However, because decrease in water levels is this small the default calculation method for hydraulic radius is not changed.

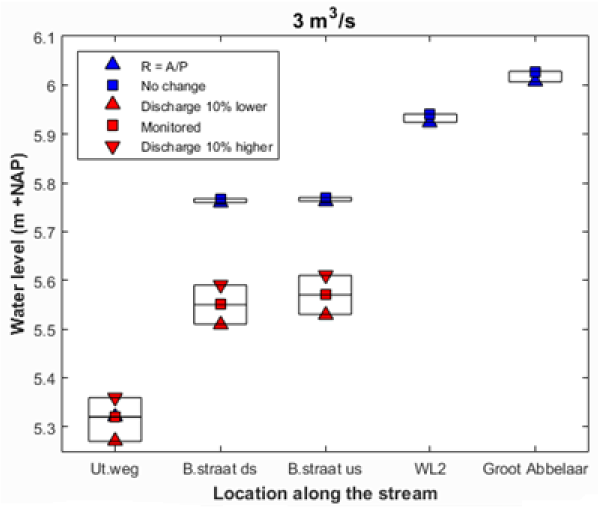

Figure 72: Sensitivity of the Delft3D FM model for a different calculation method of the hydraulic radius

Roughness LWD
To assess the effect of the LWD on simulated water levels, a model run was performed with a roughness equal to the main channel for the 4 packages of LWD. In this simulation, it is assumed that no LWD is present in the stream. The results of this simulation are shown in Figure 73

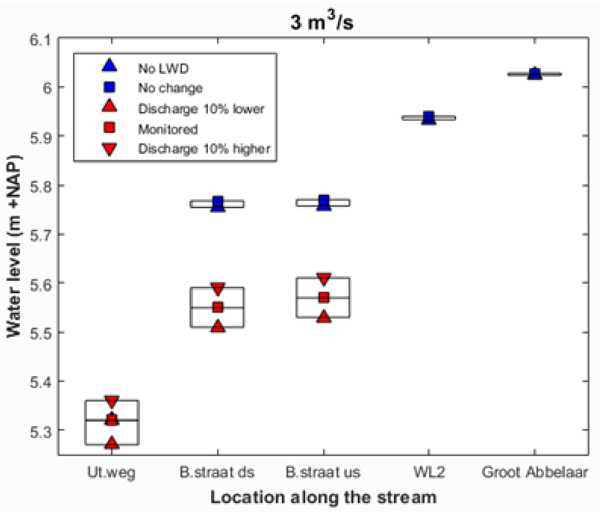

Figure 73: Sensitivity of the Delft3D FM model for the 4 packages of LWD

Figure 73 shows that the LWD barely affects simulated water levels. Besides that it becomes clear that the effects are largest at the measurement locations close to the LWD compared to the more upstream measurement locations. It thus becomes clear that the LWD roughness does not considerably affect simulated water levels with the Delft3D FM model.

Other
Besides the sensitivity tests explained above, some other more extreme scenarios were investigated. These were mainly performed to assess what was needed to simulate water levels correctly with the Delft3D FM model, mostly by combining the parameter changes described above. However, since it was later found that the model bathymetry was not correct, the relevance of these sensitivity tests is gone. Therefore those tests are not shown.

Appendix J: Bed roughness Delft3D FM Tungelroyse beek

In this appendix the motivation is given for selecting the Manning roughness values for the Delft3D FM model of the Tungelroyse beek. The arguments are given per area type.

Roads

Since asphalt roads are present in the study area, roughness was classified as clean to slightly rough. With k_m roughness values for clean vegetation cover between 20-35 $m^{1/3}/s$ and slightly rough vegetation cover between 15-25 $m^{1/3}/s$ the range was defined as 15-35 $m^{1/3}/s$. A value of 20 $m^{1/3}/s$ was selected, meaning Manning roughness values are 0.05 $s/m^{1/3}$ for the selected and 0.029 and 0.067 $s/m^{1/3}$ for the minimum and maximum roughness respectively.

Water

December is a winter month in which vegetation is only sparsely present. Therefore the main channel was classified as clean to slightly rough. The same classification was made for ponds, ditches and De Vliet (another stream), since it might be expected that vegetation shows is fairly similar in those places. This also means that the range in k_m roughness is between 15-35 $m^{1/3}/sn$. The selected value was 25 $m^{1/3}/s$, which is right in the middle of the range. The Manning coefficients are thus 0.04 $s/m^{1/3}$ for the selected and 0.029 and 0.067 $s/m^{1/3}$ for the minimum and maximum roughness respectively.

Floodplains close to main channel

In the floodplains different sections were distinguished. More sandy sections with some leftover vegetation and sections with denser leftover vegetation. In winter, the leftover vegetation still has some roughness but nothing comparable to the summer situation. For the sandy sections clean to slightly rough vegetation cover was selected, while for the brushy parts slightly to moderately rough was selected. The range for the sandy section is therefore 15-35 $m^{1/3}/s$ and for the brushy parts 10-25 $m^{1/3}/s$. Eventually 20 $m^{1/3}/s$ and 15 $m^{1/3}/s$ were selected, meaning Manning is 0.05 and 0.067 $s/m^{1/3}$ respectively. The ranges are thus 0.029-0.067 $s/m^{1/3}$ and 0.04-0.1 $s/m^{1/3}$ for the sandy and brushy floodplains.

Nature

Two sections of nature are present in the area. Both are typically covered with moorland. Even in winter, the cover gives a certain roughness. Therefore a moderate to quite strong vegetation cover was selected with k_m roughness values between 5-20 $m^{1/3}/s$. A value of 10 $m^{1/3}/s$ was eventually selected so Manning roughness was 0.1 $s/m^{1/3}$ with a minimum expected value of 0.05 $s/m^{1/3}$ and a maximum of 0.2 $s/m^{1/3}$.

Agriculture

Most of the area was characterized as land used for agriculture. Typical crops like maize, onions, peas and salsify have growing seasons outside the winter though, making that these areas will be relatively smooth in December. The only exception to this are asparagus lands, where the typical land shape has higher roughness in winter also. Therefore most agriculture lands were characterized as smooth to slightly rough, while asparagus lands were defined as moderate to quite rough. This makes that Manning roughness ranges are 0.029-0.067 $s/m^{1/3}$ and 0.05-0.2 $s/m^{1/3}$ for agriculture and asparagus agriculture.

Houses

There was one house located in the study area. A Manning roughness of 1 $s/m^{1/3}$ was used since it totally blocks the flow. In a normal situation, water will never reach the house though.

Pasture

The pasture lands have a grass cover that is defined as moderate to quite rough. The situation is comparable to the pasture grounds in the Lunterse beek model since a winter period is investigated for the Tungelroyse beek as well. This makes that a Manning roughness of 0.1 $s/m^{1/3}$ is selected.

Forest

Forest was categorized as having a pretty strong to very strong vegetation cover, like in the Lunterse beek model. Therefore a Manning roughness value of 0.2 $s/m^{1/3}$ will be used.

Appendix K: Summary literature study vegetation

This appendix gives a short summary of the information found doing a literature study with respect to vegetation development in streams.

In general vegetation in streams can be divided into multiple categories, depending on which criteria are used for this. Deviation can be based upon the type of plants. For example, Gecheva et al. (2013) did this for aquatic macrophytes that were represented in seven plant divisions: Cyanobacteria, Chlorophyta, Rhodophyta, Xantophyta, Bryophyta, Pteridophyta and Spermatophyta. Biggs (1996) also used this method but divided water plants into three main categories, namely periphyton, bryophytes and macrophytes.

Another method is to deviate based upon vegetation characteristics like Mesters (1995) did in his research. He distinguished five categories: emergent, floating-leaved, submerged, emergent/floating-leaved and floating-leaved/submerged. This deviation method was also used by Clarke (2002) who characterized three categories of macrophytes. Firstly, species with finely divided leaves, trailing stems and dense stands. Secondly, broad-leaved species with open to dense stands depending on species and finally ribbon-leaved species with open stands. The deviation method also depends upon the objectives of the research and environment that is studied.

The Lunterse and Tungelroyse beek can be characterized as lowland streams, typically streams with lower slopes, flow velocities and finer substrate types at the stream bottom. Clarke (2002) stated that vegetation may be abundant in lowland streams and that it also may reach high volumes of biomass during the growing season. One would expect macrophytes to occur commonly in lowland streams (Suren & Riis, 2010). However, bryophytes are a macrophytes type that would not be expected, since these plants are associated with hard and immobile substrates like rocks as well as a variable flow regime (Gecheva et al., 2013; Suren & Riis, 2010). It was also found that vascular plants are inversely correlated to bryophytes, with bryophytes often occurring in conditions of higher altitude and vascular plants in lowland rivers (Gecheva et al., 2013). Therefore vascular macrophyte types could be expected to occur in the Lunterse and Tungelroyse beek also.

Which types of macrophytes occur in streams depends on many factors and variables. Factors that are commonly believed to affect macrophyte cover are (Baattrup-Pedersen et al., 2003; Chambers et al.,1991; Gecheva et al., 2013; Grinberga, 2011; Mesters, 1995; Riis et al., 2008; Riis & Biggs, 2003; Suren & Riis, 2010; Tabacchi et al., 2000; Vesipa et al., 2016; www.hawaii.edu, sd):

- Light conditions
- Nutrient concentrations
- Trophic status
- Substrate characteristics
- Stream flow velocity
- Flood frequency

There are also other factors mentioned that affect macrophyte occurrence in streams. These are for example water level fluctuation, pH, flood intensity, water depth, cutting regime, invertebrate species and fish species. However, these are not as abundantly mentioned as the other factors.

The way in which these factors influence macrophyte cover are complex. Riis et al. (2008) state that one would expect a higher plant cover in streams where low flow events are common and extended as species richness is most strongly related to flow magnitude. This was also concluded by Riis & Biggs (2003) when their research showed increasing vegetation abundance at velocities between 0 till 0.3 m/s and decreases after flow velocities exceeded 0.4 m/s. They even concluded that interflood vegetation abundance shows a negative quadratic relationship with mean water velocity in the vegetation-free hydrological space. However, the investigation of Chambers et al. (1991) contradicts this and states that biomass always decreases with increasing flow velocity between 0.01 and 1 m/s. Grinberga (2011) then again draw a different conclusion, stating that macrophyte composition was species poor and had sparse cover in streams with sandy substrate and flow velocities above 0.2 m/s. Based on these studies, more vegetation is assumed to be present in the Lunterse and Tungelroyse beek for lower flow velocities.

The study of Grinberga (2011) in Latvian streams also showed mutually different typical macrophyte communities depending on flow velocity and substrate type. For fast flowing streams (>0.2 m/s) on sandy substrate *Sparganium emersum* was often found (94%) followed by *Elodea Canadensis* (41%) and *Alisma plantago-aquatica* (41%). In slow flowing streams (<0.1 m/s) with sandy substrate *Phalaris arundinacea* (78%) is most often found, followed by *Spanganium erectum s1* (72%) and *Nuphar lutea* (67%). Besides this, Grinberga (2011) also found that in general macrophytes species are small in deeper sites of slow streams and more abundant in shallower sites of slow streams.

The investigation by Riis & Biggs (2003) looked specifically at four types of vegetation and also showed that flow velocity and substrata type are important for type of vegetation cover. They also found water depth to be of importance. Based on these three flow characteristics they determined the most optimal circumstances for the four most common macrophytes found in New Zealand streams. The findings are presented in Table 50.

Table 50: Four macrophyte types with preferences for settlement

Macrophyte name	**Optimal water velocity (m/s)**	**Minimum required water depth (m)**	**Substrate preference**
Elodea Canadensis	0.1-0.4	0.9	Sand and small gravel
Myriophyllum triphyllum	0.1-0.4	0.5	Sand
Potamogeton cheesemanii	0.1-0.4	0.7	Small gravel
Ranunculus trichophyllus	0.4-0.6	0.3	No preference

A different research of Suren & Riis (2010) showed that *Ranunculus* plants are often found in lowland streams, while Baattrup-Pedersen et al. (2003) showed for Danish streams that cutting regime was very important for macrophyte species found. In highly disturbed streams *E. canandensis, R. peltatum* and *Callitriche spp*. could be found as well as some tall reed plants. Less disturbed streams showed other species like *B. erecta, G. fluitans, M. palustris* and *M. aquatic*a.

A symposium held in Arnhem, The Netherlands has brought to mind that in the upper courses of natural streams more riparian vegetation is present, causing mostly *Ranunculus fluitans* and *Potamogeton densus* to occur in those areas. In the more downstream parts, characterized by slowly flowing and stagnant waters mostly occurring were *Nuphar lutea, Sagittaria sagittifolia, Potamogeton natans, Sparganium emersum, Potamogeton alpinus, Ranunculus aquatilus, Elodea Canadensis, E. nuttalli* and *Callitriche spp*. The investigation of Gecheva et al. (2013) in Bulgarian streams also confirmed that decreasing shading gradient shows an increase in vascular plants. It was already shown by Biggs (1996) though, that vascular macrophytes need high hydraulic stability and stable beds due to much slower rates of colonization and growth.

This leads to some more evidence that it is hard to base vegetation types only on hydraulic characteristics. A research of Mesters (1995) showed that eutrophication increases the presence of *C. platycarpa* and *P. trichoides*, while it decreases *Ranunculus peltatus spp.* and *heterophyllus*. Also in the same research it was found that increased nutrient loads increase the presence of *Callitriche platycarpa, C. obtusangula, Glyceria fluitans* and even of species that normally do not occur in streams like *Elodea nuttallii* and *Potamogeton trichoides*. Finally some species needed clear water to survive: *Elodea Canadensis, Myriophyllum alterniflorum, Ranunculus aquatilis, R. peltatus* and *R. fluitans*.

Finally, a research of Baattrup-Pedersen et al. (2003) showed that European lowland streams have experienced a decline in macrophyte species diversity due to both eutrophication and pollution. Another interesting finding in this research was that there is a significant linear relationship between species richness in riparian vegetation and vegetation in the stream.

From the literature study it can be concluded that it is impossible to objectively and exactly determine upfront which types of vegetation will grow at certain locations is streams, just because there are so many factors affecting vegetation growth. However, for this research a vegetation map will be constructed based upon hydraulic model output since it was found that flow velocity might be a good indicator for the vegetation biomass that can be expected.

Appendix L: Straight channel tests

Since simulated water levels in the Sobek and Delft3D FM software differ considerably, a test case was set-up with equal model parameters to investigate the possibility for the software packages to list equal model results. For this test case a straight channel was modelled in both the Sobek and Delft3D FM software with the dimensions as found in the most downstream section of the Lunterse beek model:

- Length channel: 322.21 meter
- Width channel: 20.185 meter
- Lowest point upstream boundary: 4.51 meter
- Lowest point downstream boundary: 4.21 meter
- Manning roughness: 0.033 s/m$^{1/3}$
- Discharge upstream boundary: 3 m^3/s
- Water level downstream boundary: 5.32 meter

The channel cross-section is uniform throughout the channel with dimensions as shown in Figure 74.

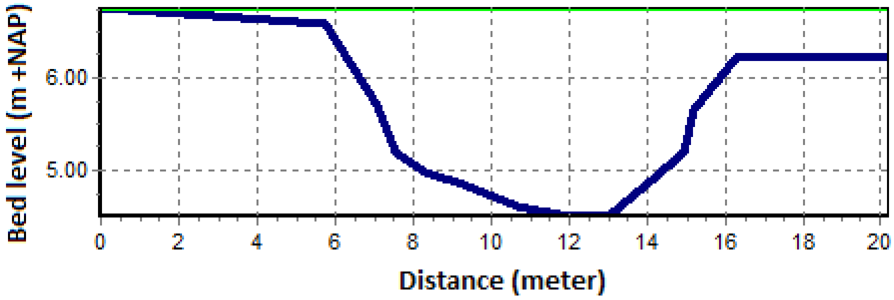

Figure 74: Dimensions cross-section straight channel test case

For the calculation grid in the Sobek model different spacing was used between the calculation points. This means two different Sobek models were used in this research. The information is given in Table 51.

Table 51: Description of the Sobek model grid used for the straight channel test case

Model name	Distance between calculation points (m)
Sobek model 1	10
Sobek model 2	3.221

For the Delft3D FM model two different grids were used. Therefore also two Delft3D FM models were set-up as can be seen from Table 52.

Table 52: Description of the Delft3D FM model grid used for the straight channel test case

Model name	Amount of cells perpendicular to flow direction	Amount of cells in flow direction
Delft3D FM model 1	20	100
Delft3D FM model 2	80	100

The results for the different models are shown in Figure 75.

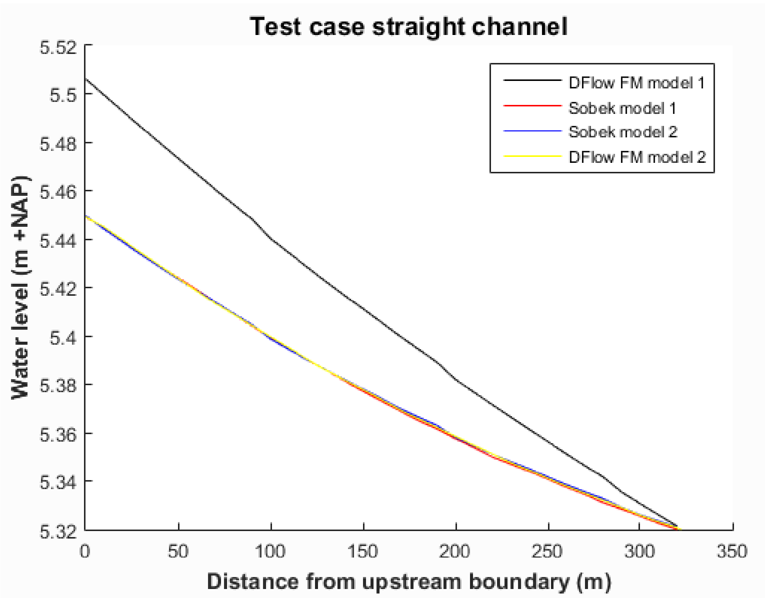

Figure 75: Results for the straight channel test case

As becomes clear from Figure 75, the model results from the two Sobek models and Delft3D FM model 2 are very similar. The deviation in water levels is a few millimetres at most. Remarkable to see is that Delft3D FM model 1 results in a considerably higher water level than the other models. The reason for this is the cell resolution in the lateral direction. The bed level height can only be specified at the four corners of each cell. This means that the cross-section is specified at 21 location in the y-direction for Delft3D FM model 1. For Delft3D FM model 2 the cross-section is specified at 81 locations since cell resolution is higher. Figure 76 shows a plot of the cross-sections of all four models.

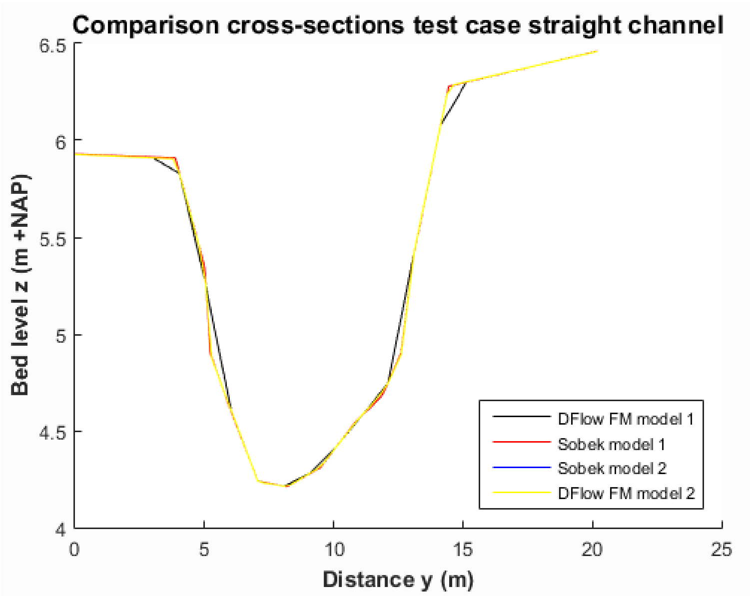

Figure 76: Cross-sections in the different models for the straight channel test case

It can be seen from Figure 76 that the bathymetry in the first Delft3D FM model indeed differs from the other three models. Since the cross-sectional area is smaller in Delft3D FM model 1, higher water levels are simulated.

From this small investigation it becomes clear that the bathymetry of a 2D model needs different data than the bathymetry in a 1D model. For the Sobek model, measuring bed level heights at locations where slope changes are present provides enough information to set-up a model. Sobek will interpolate linearly between these locations. For the Delft3D FM model on the other hand this is only sufficient if the grid cell resolution is chosen high enough. It has to be realised though that in the design phase of stream restoration, bed level measurements of the stream after restoration are not available.