UNIVERSITEIT TWENTE.

MEASURES RELATED TO THE FIXED LAYER AT NIJMEGEN

An approach with 1D modelling

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SUMMARY

The Waal river experiences erosion of roughly 2 cm per year. Over the years this has caused the fixed layer at Nijmegen, which was construction was finished in 1988, to become an obstacle for shipping during periods of low water. Five variants have been modeled in the 1D model of the Riverlab:

- Filling the erosion pit
- Lowering the fixed layer
- Filling the erosion pit and lengthening the fixed layer
- Filling the erosion pit and lengthening & lowering the fixed layer
- Increase the bed level of the Upper-Waal towards the situation of 2012

These five variants have been modeled and results to morphology and hydrology over a simulation period of 100 year have been analyzed. These results are summarized in the table below. Issues with the model, as well as the model not being validated, harm the reliability of the results.

Variant	Results to bed level	Results to water levels
1) Filling the erosion pit downstream of the fixed layer	Erosion pit forms again	Reduction of water depth at fixed layer of 0-10 cm
2) Lowering of the fixed layer	Erosion occurs upstream of the fixed layer and sedimentation occurs downstream of the fixed layer	Increase of the water depth at the fixed layer with ca. 30 cm. However, at Erlecom a reduction of 10 cm can be observed.
3) Filling the erosion pit + lengthening the fixed layer	A new erosion pit forms downstream of the lengthened fixed layer, but forms much slower than the 'old' erosion pit.	The water depth at the fixed layer remains similar.
4) Filling the erosion pit + lengthening the fixed layer + lowering the fixed layer	A new erosion pit forms downstream of the lengthened fixed layer, but forms much slower than the 'old' erosion pit.	Increase of the water depth at the fixed layer with ca. 30 cm. However, at Erlecom a reduction of 5-10 cm can be observed.
5) Increasing the bed level of the Upper-Waal	Increases the bed level downstream the fixed layer over 100 years	Increase of water depth at the fixed layer with ca. 2 cm. Downstream of the fixed layer

1 INTRODUCTION

Rivers in the Netherlands usually have a clear navigation channel and clear floodplains. However, due to erosion and sedimentation river profiles change over time. River erosion is currently one of the biggest challenges in the Dutch river systems that Rijkswaterstaat is dealing with. To gain knowledge on this issue and other river related issues, a national research program on lowland rivers was initiated in 2017, this program is called Rivers2Morrow. This program is part of the larger National Knowledge and Innovation program (NKWK). In the Rivers2Morrow program extensive modelling is used to accurately predict changes to the river system on the long term and test new research. A platform was setup where 3D, 2D and 1D models could be shared and developed, this platform is called the Numerical River Laboratory. Mainly the 1D model of the Numerical River laboratory is still in development (Spruyt et al., 2019).

A specific problem regarding river bed erosion can be found near the city of Nijmegen, where a fixed layer has been constructed in the bend of the river Waal, see Figure 1. This has been done between 1986 and 1988. At the time, sediment deposition at the inside of the bend formed a problem as it limited space for navigation. Therefore, a fixed layer was constructed in the outer bend, preventing sediment transport from happening in the outer bend. This aimed to increase erosion of the inner bend and hence increasing the navigational width in the bend. The fixed layer turned out to work well (van Reen, 2002).

FIGURE 1 - MAP OF THE WAAL RIVER NEAR NIJMEGEN WITH A GRAPHICAL REPRESENTATION OF THE LOCATION OF THE FIXED LAYER IN RED (MAP FROM CHART ROOM, 2019)

However, the Waal river has experienced degradations of 2-3 cm per year, while the fixed layer does not erode (Blom, 2016). Consequently, the fixed layer starts to stick out of the river bed. At low water levels, the fixed layer now starts causing issues for shipping, caused by insufficient navigable depth. This is a problem, as the Act of Mannheim requires the navigable depth of the Waal river to be at least 2.80 meter. Moreover, an erosion pit has formed downstream of the fixed layer. This could lead to instability of the fixed layer and possibly also for the river banks.

To avoid the mentioned issues becoming bigger in the future, research should be done on possible solutions for this problem. These solutions can be tested in the 1D model of the Numerical River Laboratory. The solutions should be tested on possible changes to the morphology, water levels and discharge partitioning at the bifurcation point in Pannerden. This research should answer the following question:

(1) What are the effects on morphology, water levels and the discharge partitioning of possible measures which mitigate the problems the shipping industry experiences at the fixed layer near Nijmegen. (2) How can these be modelled with the 1D model of the Numerical River Laboratory?

The purpose of the research is to gain knowledge on the fixed layer and possible measures. Also the model of the Numerical River Laboratory will be tested.

2 BACKGROUND INFORMATION

This chapter described the background information, which is useful to have prior to reading the report. The history of origin of the fixed layer is described in this section, as well as the different research questions and sub-questions which will be answered in this report.

2.1 History of origin of the fixed layer

The fixed layer was constructed between 1985 and 1988 in the bend of the river Waal between Nijmegen and Lent. This was done because sedimentation at the inside of the bend caused the navigational width to be insufficient at multiple locations in the bend. The fixed layer was constructed with a top layer and a filter layer, the filter layer making sure the top layer would stay in place. The filter layer was constructed with fine sediment of 10-60 mm, 800 kg/m³ and was constructed by three equal layers of 0.15 m. The top layer was constructed with rocks of 10-80 kg, 1100 kg/m³ and was constructed by two layers of 0.375 m. The fixed layer was constructed with a slope of 1:100 with the river bed (Franssen, 1995). The location and elevation of the fixed layer as constructed can be seen in Figure 2. Currently the fixed layer sticks out approximately 0.70 m above the river bed (Boersema et al., 2019).

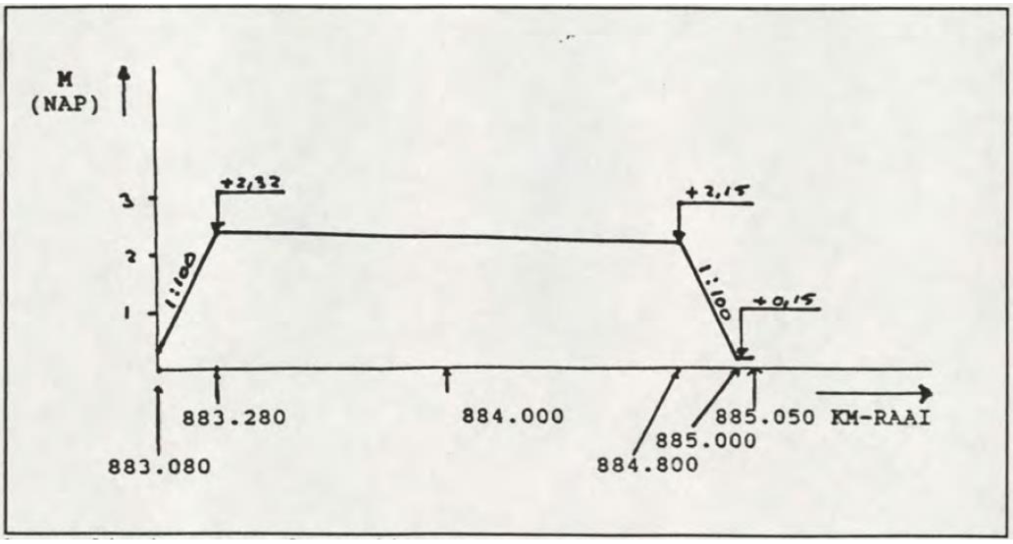

FIGURE 2 - LOCATION AND ELEVATION LEVEL OF FIXED LAYER AT CONSTRUCTION (IMAGE FROM FRANSSEN, 1995)

2.2 Research questions

To answer the main research question of this research, this report makes use of several sub-questions as defined in the preliminary report. These sub-questions are outlined in this section. The main research question along with the research aim are already described in the introduction. The following sub-questions help answering these research questions (van Oostrum, 2019):

- What are the dynamics of the fixed layer in the Waal river?
- How can the 1D model of the Riverlab be used for the project?
- What are possible solutions that decrease the problems for navigation in the river bend at Nijmegen?
- What are the effects of possible solutions on the morphology, water levels and discharge partitioning at Pannerden?
- How does the 1D model perform compared to expected results and results of 2D calculations?

2.2.1 What are the dynamics of the fixed layer in the Waal river?

The first sub-question focusses on answering why the fixed layer was constructed and how it works. To answer the question, the fixed layer's contributions to current erosion and sedimentation patterns are discussed. This sub-question enables an understanding of the current issues around the fixed layer and is answered in chapter 4.

2.2.2 How can the 1D model of the Riverlab be used for the project?

This purpose of this sub-question is to gain a solid understanding of the model. Therefore, the model is studied and analyzed. Key parameters are identified and the relevance of the model output is discussed. Possible limitations of the model are also outlined to answer this research question.

2.2.3 What are possible solutions that decrease the problems for navigation in the river bend at Nijmegen?

The third sub-question answers which possible solutions mitigate the issues that are being experienced around the fixed layer. Hence, the theoretical consequences of these measures are described as well.

2.2.4 What are the effects of possible solutions on morphology, water levels and discharge partitioning at Pannerden?

This sub-question focusses on exploring the effects of the measures found in answering the previous sub-question. These measures are modeled in the 1D model of the Riverlab and based on the output of the model, the effects on the morphology, water levels and discharge partitioning at Pannerden are studied.

2.2.5 How does the 1D model perform compared to expected results and results of 2D calculations?

The final sub-question assesses the usability of the 1D model in this research. Therefore, the results of the model are compared with the expected effects of measures and with results of 2D calculations. This is then used to reflect on the applicability of the 1D model on a practical problem, such as the fixed layer at Nijmegen.

3 THEORETICAL FRAMEWORK

In this chapter the theoretical framework of the research is discussed. To fully understand the problem, it is important to gain insight in the degradation issues of the Waal river. Furthermore flow patterns and resulting erosion and sedimentation in river bends should be understood.

3.1 Degradation of the Waal river

The Waal river is experiencing both degradation and aggradation along its longitudinal profile. Near Nijmegen the Waal river is degrading with 2-3 cm per year. Further downstream, degradation and aggradation is almost completely absent, whereas even further downstream effects sedimentation can be observed (Blom, 2016). These effects could have a big impact on the long term if no mitigating measures are taken. The results of these effects over the next 100 years can be seen in Figure 3, assuming continuous degradation of 2 cm per year at the upstream boundary. Inside the blue ellipses, no effects of erosion and sedimentation are seen as at these locations the bed is fixed by human interventions, one of them being the fixed layer near Nijmegen. It becomes clear that the issues of the fixed layer in the bend near Nijmegen will only become bigger if no measures are taken.

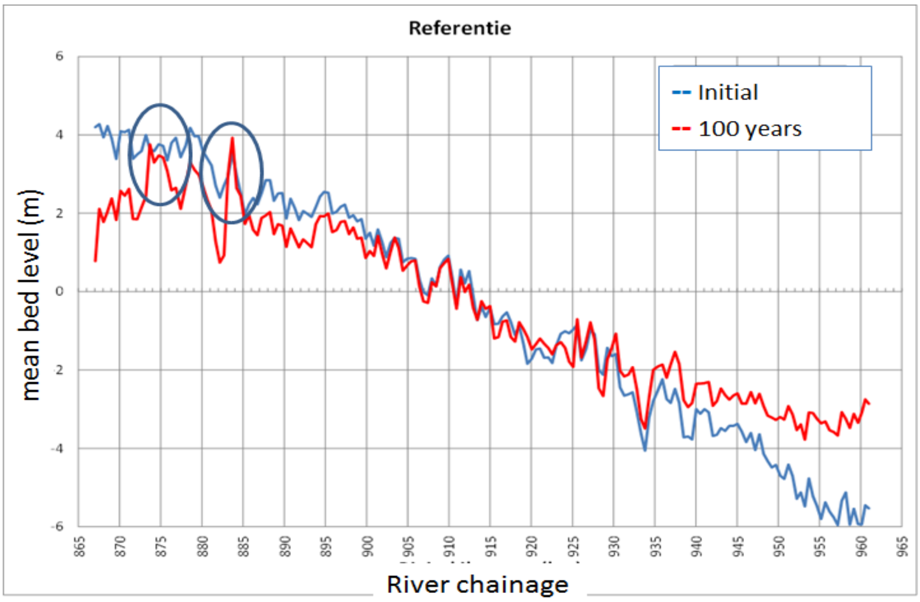

FIGURE 3 - INITIAL STATE AND MEAN BED LEVEL OVER 100 YEARS OF THE WAAL RIVER IF NO MITIGATING MEASURES ARE TAKEN, ASSUMING A DEGRADATION OF 2 CM PER YEAR AT THE U;STREAM BOUNDARY (FIGURE FROM SCHIELEN ET AL., 2019)

Erosion and sedimentation in rivers happen if the sediment transport capacity of the river and the sediment supply are imbalanced. In case the sediment supply is larger than the sediment transport capacity, sedimentation will occur. Opposite, if the sediment supply is smaller than the transport capacity, erosion will occur. If the transport capacity and the sediment supply are equal, the system is in balance and no erosion or sedimentation will occur (Alekseevskiy et al., 2008). Behavior of this system can be altered by human interventions. The supply can be changed, for example by adding sediment (Schielen et al., 2019). The transport capacity of a river depends on the channel bed gradient, width of the river, properties of the sediment and the flow speed (Alekseevskiy et al., 2008). Therefore, these characteristics could be changed to counteract erosion or sedimentation.

In case of the river Waal, the hypothesis is that degradation is mainly resulting from training works in the Rhine river, constructed in the 19th and 20th centuries. Constructions of levees and groynes narrowed the river, while cutting off bends led to a shorter river. Both resulted in an increase of the flow velocity, which increased the sediment transport capacity. Upstream sediment supply from Germany did not increase, therefore the river adjusts to a new equilibrium state, resulting in degradation of the upper part of the Waal. This problem of bed degradation is not limited to the river Waal, but also occurs in the Dutch and German Rhine, Elbe and Danube (Blom, 2016).

3.2 Erosion and flow patterns in river bends

In meandering rivers, the form of the river and shape of the riverbed change continuously. Nowadays, rivers are usually fixed such that meandering is prevented. However, specific erosion and sedimentation processes still occur in river bends. In river bends, typically the outside of the bend is at a lower level than the inside of the bend, which creates a slope in transversal direction. This is caused by sediment transport from the outside of the bend to the inside of the bend, which is an effect of spiral flow.

Spiral flow is caused by several effects, which will be explained next. The centrifugal force in the river bend presses the water to the outside of the bend. This leads to the water level ascending towards the outside of the river bend. The difference in water level results in a difference in hydrostatic pressure in the bend, the hydrostatic pressure in the outside of the bend is larger than in the inside of the bend. The difference of the hydrostatic pressure is uniform over the river depth. Besides, the centrifugal force is not uniform but depends on the flow velocity. Therefore, the centrifugal force is zero at the river bed and maximum at the water level. Combining the centrifugal force, which is directed to the outside of the bend, and the hydrostatic pressure, which is directed to the inside of the bend, results in a non-uniform pressure distribution. This resulting pressure distribution is directed towards the outside of the bend at the water level and is directed towards the inside of the bend at the bed level. This creates a secondary, circular flow in transverse direction. This secondary flow together with the primary flow through the river bend, results in the phenomenon of spiral flow (Robert, 2003). Figure 4 shows this process schematically.

This spiral flow in the center of the river cross section is well-known in literature. Aside from this central spiral flow, another circular flow was discovered near the outer-bank by Graf and Blanckaert. This flow has a circular motion opposite to the direction of the central spiral flow and is less turbulent. The presence of this less turbulent flow serves as a protection of the outer bank, as it keeps the maximum velocity in the center of the river cross section away from the bank and decreases the turbulent activity near the outer bank (Graf & Blanckaert, 2002).

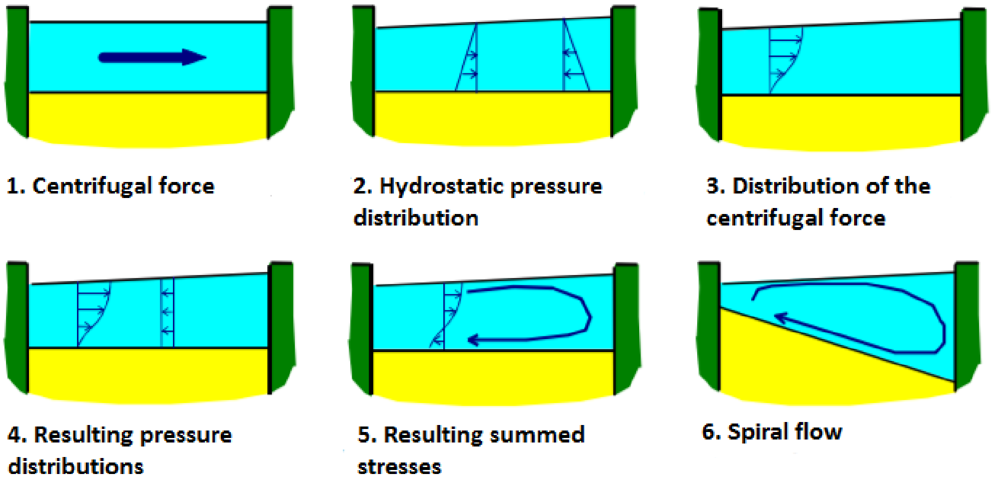

FIGURE 4 - SCHEMATIZATION OF EFFECTS RESULTING IN SPIRAL FLOW IN A CHANNEL CROSS-SECTION (IMAGE FROM VAN REEN, 2002)

3.3 Models

Mathematical models can be a representation or abstraction of reality and are often used to describe behavior of a system. Usually, a model is built after a problem is identified in a system, the model would then be a representation or abstraction of that system. Then, the goal of a modelling study is to obtain an acceptable solution to this problem (Birta & Arbez, 2013). In general models are used to get a better understanding of a phenomenon, or to understand what happens after a certain action.

This is also the case in river engineering, where 3D, 2D and 1D models are used to describe the behavior of rivers. In this case, 3D models are the most comprehensive and precise, they aim to give an accurate representation of a river system and its small scale processes. A lower dimension model is a tradeoff with accuracy and calculation times. A reduction in accuracy leads to improved calculation times, this is beneficial when for example quick results for measures are needed. 3D models are usually used for complex river systems and other scenarios where 3D calculations are important, such as flow around objects or when flow velocities vary over depth (Swift, 2014).

2D models usually use depth averaged equations and therefore are a simplification of 3D models. 2D models are mainly used for instances where floodplains are relevant, such as shallow floodplain flow. They are also used for split flow conditions and situations where flow velocities have little variation over depth (Swift, 2014). 2D models are also used when the needed data for calibration and validation of a 3D model is not present or insufficient (Pasternack et al., 2004).

1D models are a further simplification compared to 2D and 3D models. 1D models usually use a calculation grid on which cross-sections of a river are defined. They are mainly used in cases where flow primarily has one direction and the effects of small scale processes are minimal. (Swift, 2014). When looking at a small scale, the effects of processes can be relatively large. However, when the scale becomes larger and the same process happens, its effects become less significant compared to the situation on the smaller scale. This is used at 1D modelling. The main advantage of 1D models are short calculation times, this makes 1D models useful for calculation on, for example, long term effects over 50 to 100 years. 2D or 3D models are unpractical for these kind of calculations, as their calculation times would be too long (Swift, 2014).

4 PROBLEM DEFINITION

This section discusses the problem by answering the first sub-question of the main research question. It discusses why the fixed layer was constructed, what its consequences are and why this situation is currently unwanted. These issues with the fixed layer can be divided in local issues, which occur around the fixed layer in specific, and issues in the bigger picture, which mostly occur in the (Upper-)Waal river.

4.1 Local issues

As described before, the fixed layer was constructed between 1985 and 1988 in the bend of the river Waal near Nijmegen, because sedimentation at the inside of the bend caused the navigable width to be insufficient at multiple locations in the bend. During construction of the fixed layer the navigable width first increased sufficiently at all locations in the bend in 1986, but a drawback occurred in the years afterwards, where multiple locations fell again below or close to the required navigable width. This was caused by sedimentation at the inside of the bend, downstream of the fixed layer (Franssen, 1995). Also an erosion pit has formed just downstream of the fixed layer at the outside of the bend (van Reen, 2002).

To explain these phenomena, the characteristics of the fixed layer are discussed first. The fixed layer fixes the depth of the outer bend and prevents erosion of the outer bend. Preventing erosion of the outer bend leads to an imbalance of sediment transport and sediment supply, which leads to erosion of the inside of the bend. The fixed layer also has a higher roughness compared to the river bed. Consequently, the stream velocity at the outside of the bend is lower than at the inside of the bend. Summarizing, the fixed layer has the following characteristics (van Reen, 2002):

- Fix the river bed at the outside of the bend
- Prevent erosion at the outside of the bend
- Increase the roughness at the outside of the bend

These characteristics have led to several erosion and sedimentation patterns around the fixed layer. As already mentioned, preventing erosion at the outside of the bend leads to erosion at the inside of the bend. (van Reen, 2002). However, as erosion at the inside of the bend was the initial goal of the fixed layer, this is not necessarily unwanted.

Another phenomenon is the erosion pit downstream of the fixed layer. This can also be explained by an imbalance in sediment transport and sediment supply. As in the outer bend, no sediment is available, the sediment transport capacity at the outside of the bend is higher than the sediment transported in the stream. Downstream the fixed layer sediment can be picked up again, which leads to erosion. Overtime, this has led to an erosion pit downstream of the fixed layer (van Reen, 2002). The erosion pit leads to the fixed layer being protrusive for ships coming from Rotterdam. Ships coming from upstream the fixed layer are being pulled down when sailing above the erosion pit, caused by the squat effect (Van Vuren, 2019).

Furthermore, at the inside of the bend sediment is transported. The erosion pit at the outside of the bend attracts a larger part of the discharge. Consequently, downstream of the fixed layer the stream velocity at the inside of the bend reduces and sedimentation occurs (van Reen, 2002). This sedimentation is mainly located around the columns of one of the bridges across the Waal river. Around these columns dredging is not allowed, causing the sediment accumulation around the columns to continue growing.

Other effects of the fixed layer are the backwater effect. As the fixed layer has a larger roughness than the river bed, the flow velocity is reduced upstream of the fixed layer. This causes a higher water level and reduces erosion upstream of the fixed layer. The backwater effect does not impact the discharge partitioning at the bifurcation point at Pannerden (van Reen, 2002).

Currently, the top of the fixed layer is not as smooth anymore compared to after the construction of the fixed layer. Some rocks in the fixed layer are more protrusive than others. During periods of low water ships can collide with these protrusive rocks (Van Vuren, 2019). Moreover, some of the rocks are setting loose, these rocks can damage the propeller of ships.

The aforementioned effects of the fixed layer could be unwanted. The erosion of the inside of the bend was the initial goal of the fixed layer. However, if the erosion continues and too much erosion occurs, the stability of the fixed layer could be in danger. Moreover, the sedimentation at the inside of the bend downstream of the fixed layer could form a point bar, which could limit the navigational width at that location.

4.2 Issues in the bigger picture of the Waal

When taking a look at the bigger picture, other issues occurring in the Waal stand out. During periods of low water the fixed layer forms an obstacle to the shipping industry. Ships have to be loaded less heavy, in order to pass the fixed layer without colliding with it. The fixed layer is not the only obstacle in the river Waal during periods of low water. On multiple locations at the river Waal underpasses of cables pipes are present. At these locations dredging is not allowed and therefore local shallow water can occur, creating more small obstacles for shipping in periods of low water. The underlying cause of these obstacles is the degradation of the Upper-Waal. Without the erosion in the Upper-Waal with 2-3 cm per year, these obstacles would likely not have arisen (Van Vuren, 2019).

5 MODEL

The model used in this research is the 1D model of the Waal from the Numerical River Laboratory. To run this model the D-Flow FM software is used. The model is developed by Deltares, the general steps taken by them are described in this paragraph. The FM-1D model of the Waal river is based on the SOBEK3-model of the Rhine branches and describes the geometry of approximately 2017 (Deltares, 2019). The model was edited to only contain the river Waal and was exported to a configuration which can be used to run the model in D-Flow FM. Boundary conditions were added separately, as these could not be imported from the SOBEK3 model. For the modelling of morphological processes, settings of the SOBEK-RE model were taken over . These boundary conditions are further discussed in section 5.1.

The 1D model has not been calibrated, both hydrodynamically as well as morphologically, therefore its results lack accuracy. Water levels resulting from the FM model are much higher than water levels resulting from the SOBEK-RE model. The differences reach up to 60 cm (Spruyt, 2018). The morphological results also show differences between the FM model and the SOBEK-RE model. The general trends of the models are quite similar, but differences occur locally. However, conclusions from the SOBEK-RE model can also be obtained with results of the D-Flow FM model (Spruyt, 2018).

5.1 Boundary conditions

To make sure the model represents reality as accurate as possible, several boundary conditions are imposed. These can be divided in hydrodynamic boundary conditions and morphological boundary conditions.

5.1.1 Hydrodynamic boundary conditions

Upstream at Pannerdensche Kop and downstream at Hardinxveld hydrodynamic boundary conditions are imposed. At Pannerdensche Kop a discharge is imposed, whereas at Hardinxveld a waterlevel is imposed with a Q/h-relationship. An average discharge hydrograph is imposed. The shape of the hydrograph can be seen in Figure 5. The discharge levels together with its amount of days per year can be found in Table 1.

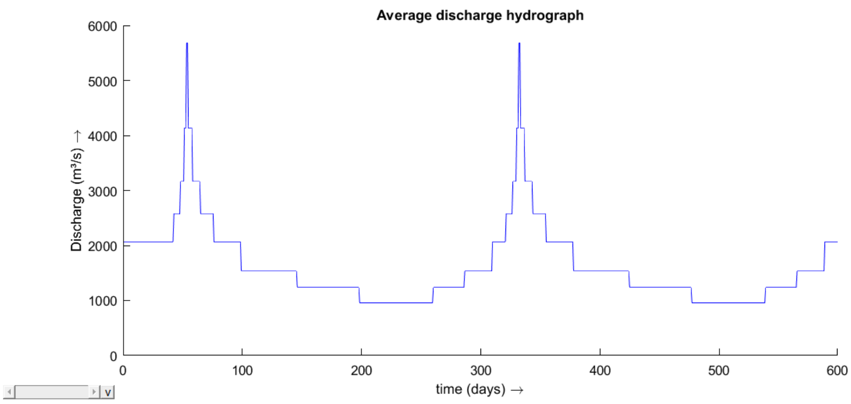

FIGURE 5 - AVERAGE DISCHARGE HYDROGRAPH IMPOSED AT PANNERDENSCHE KOP

TABLE 1 - DISCHARGE LEVELS AND THEIR AMOUNT OF DAYS PER YEAR IN THE AVERAGE DISCHARGE HYDROGRAPH (SPRUYT, 2018)

Discharge (m^3/s)	Amount of days
957	81
1237	103
1533	92
2066	45
2580	22
3163	13
4137	7
5678	2

5.1.2 Morphological boundary conditions

Besides hydrodynamic boundary conditions, also morphological boundary conditions are imposed at Pannerdensche Kop and Hardinxveld. At Pannerdensche Kop a bed level change is prescribed. The model is setup for a change of 1 cm per year at Pannerdensche Kop, as in reality 1 cm erosion per year is observed at Pannerdensche Kop. Downstream at Hardinxveld no boundary condition is imposed to the bed level.

As the upstream boundary condition is located at Pannerdensche Kop, changes to the water levels at the bifurcation point in Pannerden cannot be reliably concluded. Changes to the water level are for a relatively big part induced by changes to the bed level. Therefore changes to the water level are also party prescribed by the morphological boundary condition.

5.2 Initial bed level

The initial bed level in the model is the bed level of the Waal of approximately 2017 (Spruyt, 2018). This can be seen in Figure 6.

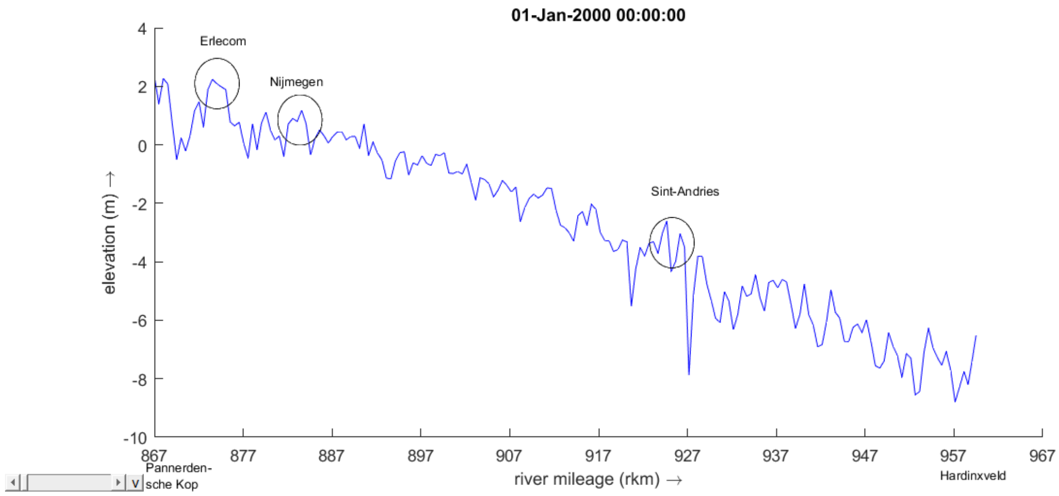

FIGURE 6 - INITIAL BED LEVEL (BOTTOM LEVEL) IN MODEL OF APPROXIMATELY 2017, INCLUDING INDICATION OF THE LOCATION OF BOTTOM GROYNES AND FIXED LAYERS

The location of bottom groynes and fixed layers are indicated in the ellipses, from left to right these are the bottom groynes at Erlecom, the fixed layer at Nijmegen and the fixed layer at Sint-Andries. The bed level shown in the figure is the averaged bottom level of the cross-sections.

The bed level is defined by cross-sections, which are defined approximately each 500 meters. The cross-sections originate from the SOBEK3 model of the Rhine branches and are a 2D approximation of the real river bed. The cross-sections are vertically symmetrical and are defined by relatively little data points. Therefore, the cross-sections are an abstraction of reality, such that it best approximates the flow area and dimensions of the real river.

5.3 Morphological updating

The sediment and morphological modelling processes enable updating of the bed level over time. The sediment transport formula used in this model is the general sediment transport formula. This formula is similar to the Meyer-Peter-Muller transport formula, but in the general formula all coefficients and powers can be adjusted to suit the requirements. The general transport formula reads (Deltares, 2019):

$$S = \alpha D_{50}\sqrt{\Delta g D_{50}}\theta^b(\mu\theta - \xi\theta_{cr})^c$$

where ξ is the hiding and exposure factor for the sediment and

$$\theta = \left(\frac{q}{C^2}\right)\frac{1}{\Delta D_{50}}$$

where q is the magnitude of the flow velocity. The hiding and exposure factor from Ashida & Michiue is used. This formulation looks as follows (Spruyt, 2018):

$$\xi = \begin{cases} 0.8429\frac{D_m}{D_i} & \text{if } D_i/D_m < 0.38889 \\ \left(\frac{\log_{10} 19}{\log_{10} 19 + \log_{10}(D_i/D_m)}\right)^2 & \text{otherwise} \end{cases}$$

The coefficients and powers which are applied in the general transport formula can be found in Table 2.

TABLE 2 - APPLIED COEFFICIENTS AND POWERS IN GENERAL SEDIMENT TRANSPORT FORMULA IN THE MODEL (DELTARES, 2019)

Parameter	Description	Value
α	Calibration coefficient	0.4
b	Power b in the general transport formula	0
c	Power c in the general transport formula	1.5
μ	Ripple factor or efficiency factor	0.7
θ_c	Critical mobility factor	0.025

The general transport formula then gives the sediment transport rate, imposed as bedload transport. Changes to the bed level are dynamically updated at each computation timestep. The change in the mass of the bed material is calculated. Then the change in mass is translated into bed level change based on the dry bed densities. The bed levels at the cell centers (the bottom bed levels) as well as the cell interfaces, all other data points corresponding with the river bed, are updated (Deltares, 2019).

6 MEASURES

There are several measures which could mitigate the issues around the fixed layer and improve the navigable depth for the shipping industry. In general, the measures can be divided into 'hard' measures and 'soft' measures (Berkhof et al., 2018).

Soft measures are measures which are reversible and easy to adjust. Soft measures usually aim to decrease the sediment deficit of the supply from Germany by sediment supplementations. This sediment can be obtained from downstream dredging or other sources as the digging of secondary channels or materials from outside the area (Berkhof et al., 2018).

Hard measures are measures which are more permanent and costly to reverse. These measures usually focus on delaying the sediment transport process. Examples of hard measures are the lowering of groynes or the implementation of longitudinal dams. In the river Waal these hard measures are possible, due to the relatively large dimensions of the cross-sections of the Waal river (Berkhof et al.,2018).

Hard measures related to the fixed layer are measures which involve editing of the fixed layer. Several hard measures could potentially improve the current situation. These are listed below (Berkhof et al., 2018).

- Removal of the fixed layer
- Lowering of the fixed layer
- Smoothening the fixed layer
- Lengthening of the fixed layer
- Reducing the slope of the fixed layer with respect to the river bed

Soft measures related to the issues with the fixed layer are sediment related. Possible soft measures are listed below.

- Filling the erosion pit downstream of the fixed layer
- Sediment nourishment

The effects of these measures are described in the following sections.

6.1 Hard measures

In this section the potential effects of hard measures to morphology and hydrology are described. Hereby the focus is on the hydrological effects near the fixed layer and upstream of the fixed layer, where it could potentially have effects on the discharge partitioning at Pannerden.

6.1.1 Removal of the fixed layer

Removal of the fixed layer would lower the bed with about 70 cm. This would increase the navigable depth significantly. However, the river bed at the bend would no longer be protected, which could lead to sedimentation of the inside of the river bend. Eventually, this could lead back to the situation of before 1985. Back then the fixed layer was not constructed yet and a point bar at the inside of the bend caused the navigational width to be insufficient. Therefore, the removal of the fixed layer could solve the issues for shipping on the short-term, but could bring back issues on the long-term (Berkhof et al., 2018).

6.1.2 Lowering of the fixed layer

Lowering the fixed layer would lower the river bed and could thereby increase the navigable depth. The river bed at the bend would still be protected, therefore morphology at the river bend would not change any further. However, if the degradation of the upper-Waal continues, the fixed layer could form an obstacle for shipping again in the future (Berkhof et al, 2018).

6.1.3 Smoothening the fixed layer

Smoothening of the fixed layer would reduce local difference in depth at the fixed layer. During periods of low water this would reduce the chance of ships colliding with protruding rocks of the fixed layer. Smoothening the fixed layer also decreases the roughness of the river bed at the fixed layer. However, it would not have any significant effects to the water levels or morphology, as it is only a minor change to the fixed layer and altitude of the fixed layer. Therefore, smoothening the fixed layer would only slightly improve the situation, but not solve the current issues for shipping.

6.1.4 Lengthening the fixed layer

Lengthening the fixed layer would remove the erosion pit downstream of the fixed layer and prevent the forming of a new erosion pit on that location. This would increase the water levels at the fixed layer. The fixed layer would also be located differently in the outside of the river bend, which decreases the development of a downstream erosion pit. Furthermore, sedimentation at the inside of the bend would no longer be located in an area where dredging is not allowed. The sedimentation could thus be dredged, which increases the navigational width. However, another erosion pit would still be forming downstream of the lengthened fixed layer. Overtime, this erosion pit could lead to a reduction of the water levels at the fixed layer, which could endanger the navigable depth again. Moreover, continuous degradation of the Upper-Waal could mean the fixed layer would be increasingly sticking out of the river bed.

6.1.5 Reducing the slope of the fixed layer with the river bed

Reducing the slope of the fixed layer with the river bed would reduce the sudden transition of relatively deep water to less deep water. This would improve the navigability in the bend. Ships from Rotterdam would benefit from the increased navigability. However, in case the degradation of the Upper-Waal continuous in the future, the fixed layer could become increasingly protrusive again compared to the surrounding river bed. Therefore, reduction of the slope of the fixed layer with the river bed is likely to be only a short-term solution.

6.2 Soft measures

In this section the potential effects of soft measures to hydrology and morphology are described. The focus is on hydrological and morphological effects of the measures near the fixed layer and upstream of the fixed layer.

6.2.1 Filling the erosion pit

Filling the erosion pit would increase the water levels at the fixed layer. This improves the navigable depth in the river bend. However, filling the erosion pit does not change the sediment shortage in the river bend. Therefore, the erosion pit is prone to be formed again, which would return the issues for navigability in the future. Thus, filling the erosion pit needs to happen periodically in order to continuously improve the situation. Another option is to cover the erosion pit with gravel after filling it, this would reduce erosion. However, also in this case the continuous degradation of the Waal could increase the issues with the fixed layer in the future.

6.2.2 Sediment nourishment

Sediment nourishment can be used to decrease the sediment shortage in a part of the river. When the sediment is transported downstream by the river, it can reduce erosion of the river bed if the sediment shortage is decreased. When the sediment nourishment causes a sediment surplus, sedimentation occurs. Therefore, sediment nourishments could be used to increase the bed level of the Upper-Waal. Increasing the bed level of the Upper-Waal increases the water levels and therefore reduces the issues of the navigability at fixed layer (Berkhof, 2018). In case nourishments are done periodically and the bed level of the Upper-Waal increases sufficiently, issues with the fixed layer could be solved completely.

6.3 Selection of measures

A selection of measures is made, these measures are modeled and their results are studied. The selection is based on the modelled measures in a similar study and variations on these measures.

Variant	Description
1	Filling the erosion pit downstream of the fixed layer
2	Lowering of the fixed layer
3	Filling the erosion pit + lengthening the fixed layer
4	Filling the erosion pit + lengthening the fixed layer + lowering the fixed layer
5	Increasing the bed level of the Upper-Waal

Variant 1 and 3 are also modeled in a similar study, this enables comparing of the results. Variant 2 and 4 are selected as a variation on variant 1 and 3. Variant 5 is selected as the analysis of the measures in section 6.2.2 showed an increased bed level of the Upper-Waal is beneficial Therefore, it is interesting to see the results of that measure.

7 MODELLING OF MEASURES

The reference situation has to be established and the selected variants have to be modelled. Some changes have been made to the model initially, to have a reference which better describes reality. Moreover, changes have been made to the model to represent the variants. This chapter describes the changes that have been made to the model to reach the results.

7.1 Reference

The initial model results without any modifications showed erosion at the fixed layers of Nijmegen and Sint-Andries and the bottom groynes at Erlecom. This was caused by the maximum amount of erosion that was set in the model. The maximum amount of erosion was 0.4 m at the fixed layers and bottom groynes, at all other locations the maximum amount of erosion set was 4 m. Moreover, at the erosion pit downstream of the fixed layer, the maximum amount of erosion was set on 0.4 m.

To give more realistic results the maximum amount of erosion at the erosion pit is set to 4 meters, similar to other locations. The maximum amount of erosion at the fixed layers and bottom groynes was set to 0.00001 meter, a value close to 0, as 0 itself may cause troubles for the model.

7.2 Variant 1: Filling the erosion pit

Filling the erosion pit in the model is done by increasing the bed level of the cross-sections which correspond with the erosion pit. The lowest bed level of these cross-sections are increased, such that the erosion pit is filled and together with surrounding bed levels a smooth gradient is created. The changed cross-sections of the model in SOBEK3 can be seen in Appendix 1.

7.3 Variant 2: Lowering the fixed layer

Lowering of the fixed layer is done in the same way as filling the erosion pit. The fixed layer is lowered by 35 cm, as this is roughly half of the height that the fixed layer raises above the river bed. This is done by decreasing the bottom bed levels of the cross-sections corresponding with the fixed layer. The changed cross-sections of the fixed layer in SOBEK3 can be seen in Appendix

7.4 Variant 3: Filling the erosion pit and lengthening the fixed layer

For this variant the erosion pit was filled similar to variant 1, as described in section 7.2. The fixed layer was lengthened with 1 km. To lengthen the fixed layer, the maximum amount of erosion at the corresponding locations was set to 0.00001 meter, similar to other locations with fixed layers or bottom groynes.

7.5 Variant 4: Filling the erosion pit and lengthening & lowering the fixed layer

All steps required to fill the erosion pit and lengthen & lower the fixed layer have been undertaken at the previous variants already. Lengthening the fixed layer together with filling the erosion pit has been done at variant 3, as described in section 7.4. Lowering of the fixed layer has been done at variant 2, as described in section 7.3. Variant 4 is modelled the same way as variant 2 and 3 combined, therefore, the corresponding SOBEK3 cross-sections can be found in Appendix 1 and 2.

7.6 Variant 5: Increasing the bed level

In variant 5 the bed level of the Upper-Waal is returned to its state of approximately 2012. In the 5 years between 2012 and 2017 the bed level has eroded with roughly 10 cm. The Waal is prone to erosion between Pannerdensche Kop and river kilometer 902, which is roughly 10 km upstream of Tiel. The summer bed of the corresponding SOBEK3 cross-sections have been increased by 10 cm. The levels of the bottom groynes at Erlecom and the fixed layer at Nijmegen have not been increased. This creates a bed level of the Upper-Waal which coincides roughly with the situation of 2012.

8 RESULTS

The results of the different variants can be analyzed. The variants are analyzed on changes to morphology and water levels. As the upstream boundary conditions are located at Pannerdensche Kop, changes to the discharge partitioning have not been taken into account. The boundary conditions would have too much of an impact on the results. First the reference situation is analyzed, thereafter the variants are compared with the reference situation.

8.1 Reference situation

In this section the reference situation is described. To determine the reference situation the model was ran for 100 years. The reference situation is the situation where no measures are applied. This means the fixed layer is unedited and the bed level of 2017 is applied. The change of the riverbed level over 100 years, as well as changes to the water levels over 100 years are taken into account.

8.1.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation can be seen in Figure 7. It can be observed that upstream between Pannerdensche Kop and Nijmegen erosion of 4 to 5 meters occurs in 100 years. Downstream of Nijmegen this reduces to 2 meters. Only 80 km downstream of Pannerdensche Kop sedimentation occurs. These results are not in line with the behavior of the river Waal and the imposed boundary conditions. The Waal shows erosion of around 2 cm per year between 0 and 35 km. Whereas between 35 and 65 the bed level remains constant and downstream of 65 km sedimentation occurs up to 3 meter in 100 years. **Fout! Verwijzingsbron niet gevonden.** is not in line with these trends of the river Waal.

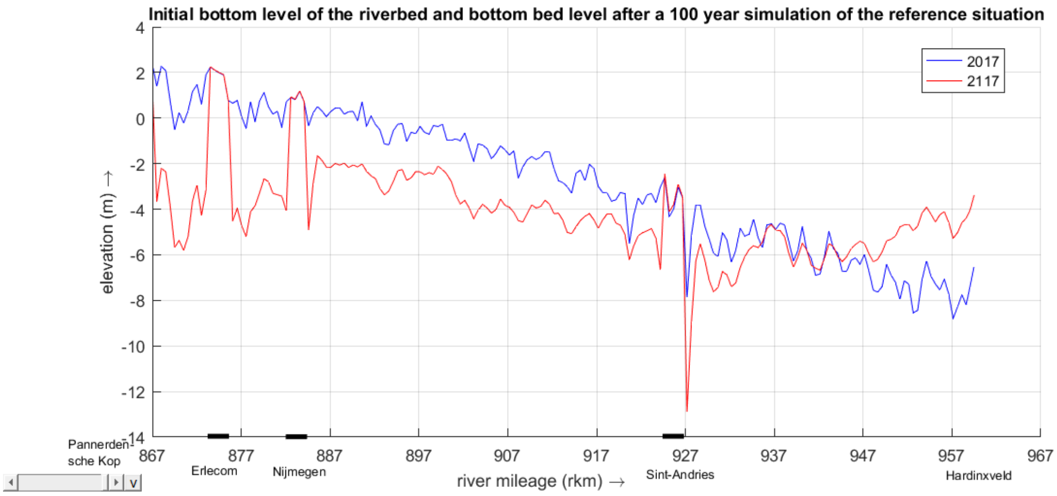

FIGURE 7 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF THE REFERENCE SITUATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.1.2 Water levels

The water levels of interest to this study are water levels during periods of low water. As during these periods the fixed layer is an obstacle to the shipping industry. The lowest input discharge in the model is 957 m^3/s. Therefore, water levels during periods of that specific discharge are used in the reference situation. For the initial water level the water levels of model time 11 March 2000 is used. This compares with late 2018/early 2019, when the initial bed level and morphological acceleration factor are taken into account. For the effects in 100 years the results of 19 December 2009 model time are used, this corresponds with December 2116, when corrected with the date of the initial bed level and morphological acceleration factor. For these water levels, the initial water depth in the reference situation and the water depth after a simulation of 100 years is given in Figure 8.

It can be observed that the water depth between Pannerdensche Kop and Erlecom increases with around 4 meter over 100 years. The water depth between Erlecom and Nijmegen increases with around 3 meter over 100 years. At the bottom groynes at Erlecom and the fixed layer at Nijmegen de water depth decreases with around 20 cm. Downstream of Nijmegen the water depth increases with around 1 to 1.5 meter. Between river kilometer 937 and 947 the water depth increases slightly with around 0 to 10 cm over a 100 year simulation. Downstream of river kilometer 947 the water depth decreases with up to 3.5 meter after 100 years. When comparing this change in water depth with the bed level change, the results are quite similar. At locations where erosion occurs, the water depth increases with roughly the same amount as the reduction in bed level. Whereas at locations where sedimentation occurs, the water depth decreases with roughly the same amount as the increase in bed level.

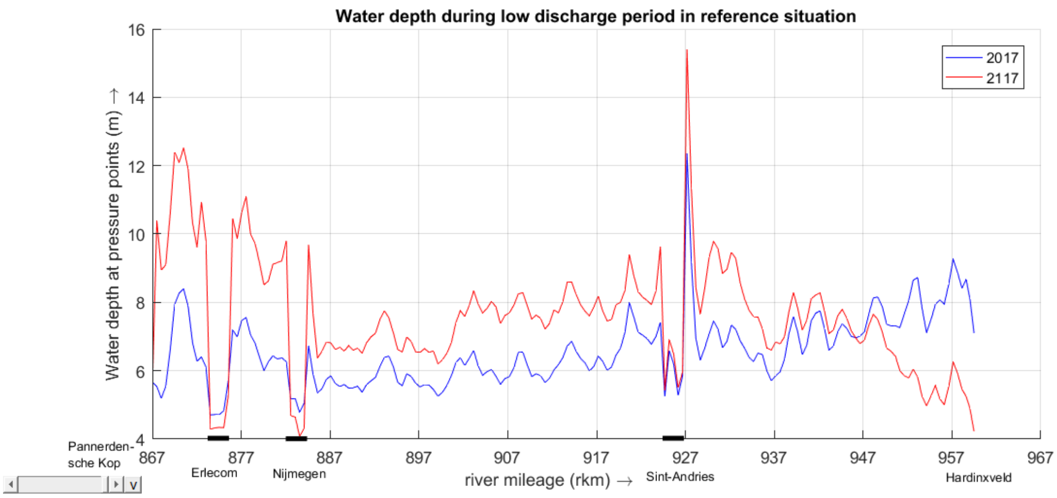

FIGURE 8 - WATER DEPTH DURING PERIODS OF LOW DISCHARGE IN 2017 AND 2117 IN THE REFERENCE SITUATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.2 Variant 1: Filling the erosion pit

In this section the model results of variant 1 are analyzed. The changes to the bed level and water levels over 100 years are assessed in respectively section 8.2.1 and 8.2.2.

8.2.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation of variant 1 can be seen in Figure 9. The figure shows similar patterns of erosion and sedimentation as the reference situation. It can be observed that the erosion pit has been formed again after a simulation of 100 years. However, the erosion pit is 120 cm less deep compared to the reference situation. This can be seen in Figure 10, where the difference in bottom bed level between the reference situation and variant 1 can be seen after a 100 year simulation. The figure also shows a slight increase of erosion just upstream of the fixed layer.

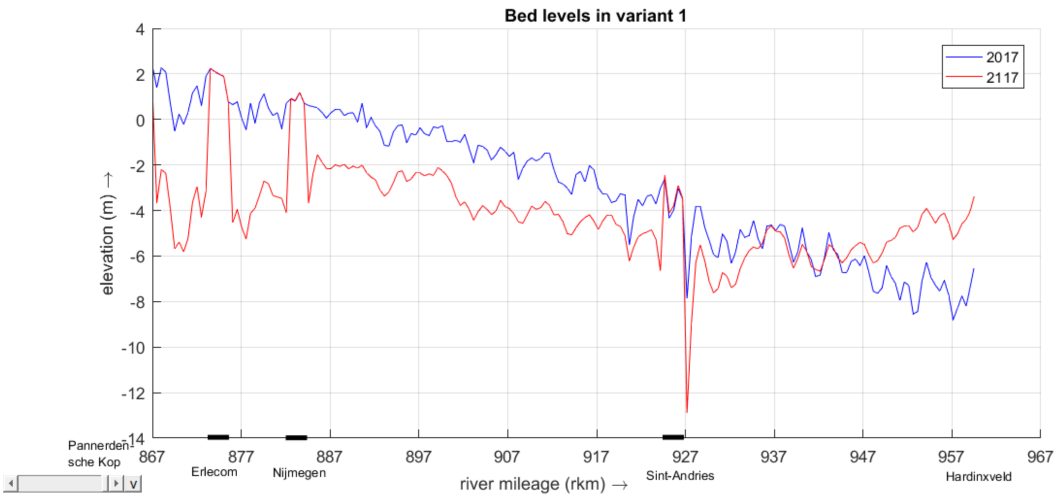

FIGURE 9 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF VARIANT 1, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

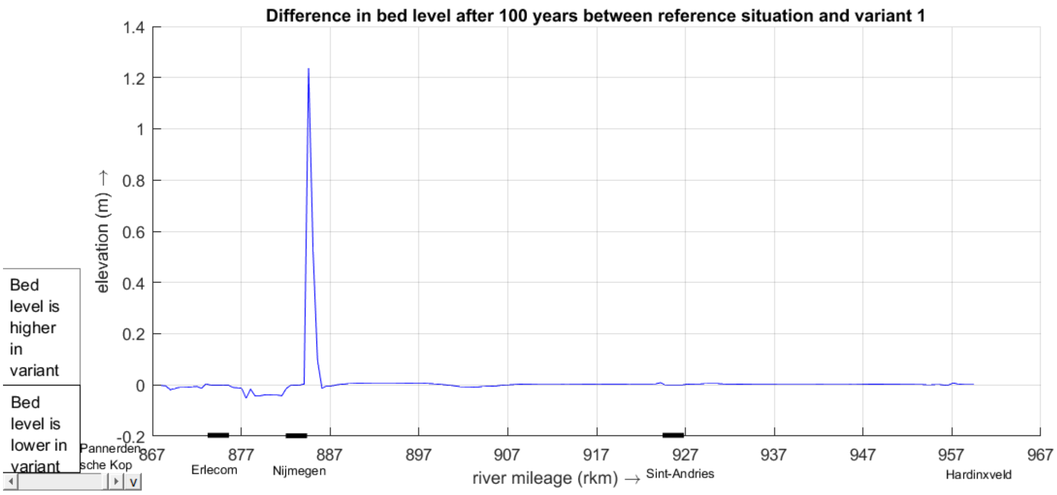

FIGURE 10 - DIFFERENCE BETWEEN REFERENCE SITUATION AND VARIANT 1 IN BOTTOM BED LEVEL OF THE RIVER AFTER A 100 YEAR SIMULATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.2.2 Water levels

The difference in water depth during low discharge periods between the reference situation and variant 1 is demonstrated in Figure 11. The figure shows an initial decrease of the water depth at the erosion pit of 60 cm. This is in line with the bed level change caused by filling the erosion pit. After a 100 year simulation a decrease of the water depth of 1.2 meter can be seen at the erosion pit. This is the same as the increase in bed level at the erosion pit after 100 years, as illustrated in section 8.2.1. At the fixed layer a reduction in water depth of up to 10 cm can be observed after 100 years. At the bottom groynes at Erlecom a reduction of the water depth of around 1-2 cm can be observed after 100 years.

This result is not in line with the expected result, which is described in section 6.2.1. The backwater effect cannot be seen in the results. A similar study of HKV does show a backwater effect when the erosion pit is filled (HKV, 2019). The reduction of the water depth at the fixed layer at Nijmegen and the bottom groynes at Erlecom cannot be explained by the changes of the bed level.

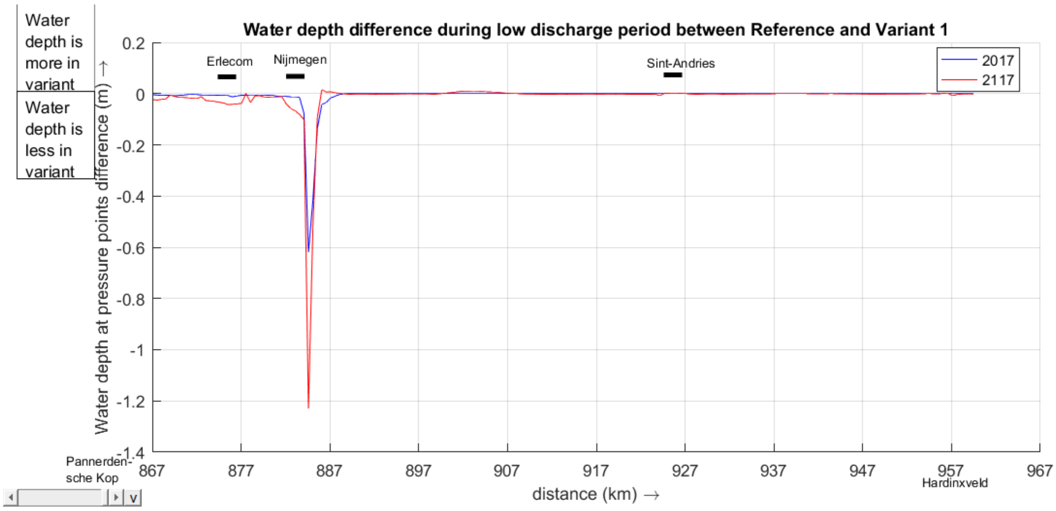

FIGURE 11 - DIFFERENCE IN WATER DEPTH DURING PERIODS OF LOW DISCHARGE (Q = 957 M³/S) IN 2017 AND 2117 BETWEEN REFERENCE SITUATION AND VARIANT 1, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.3 Variant 2: Lowering the fixed layer

In this section the model results of variant 2 are analyzed. The changes to the bed level and water levels over 100 years are assessed in respectively section 8.3.1 and 8.3.2.

8.3.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation of variant 2 can be seen in Figure 12. Similar patterns of erosion and sedimentation can be seen in the figure, compared to the reference situation. The difference in bottom bed level between the reference situation and variant 1 after a 100 year simulation can be seen in Figure 13. The figure shows increased erosion of around 7-8 cm upstream of the fixed layer. Also upstream of the bottom groynes at Erlecom a slight increase of erosion can be observed. The trajectory downstream of the fixed layer at Nijmegen shows an increase in bed level of around 3 cm. Moreover, the figure shows the erosion pit downstream of the fixed layer erodes less. This effect is about 5 cm, which is not a significant effect, as the model results show almost 5 meter erosion over 100 years.

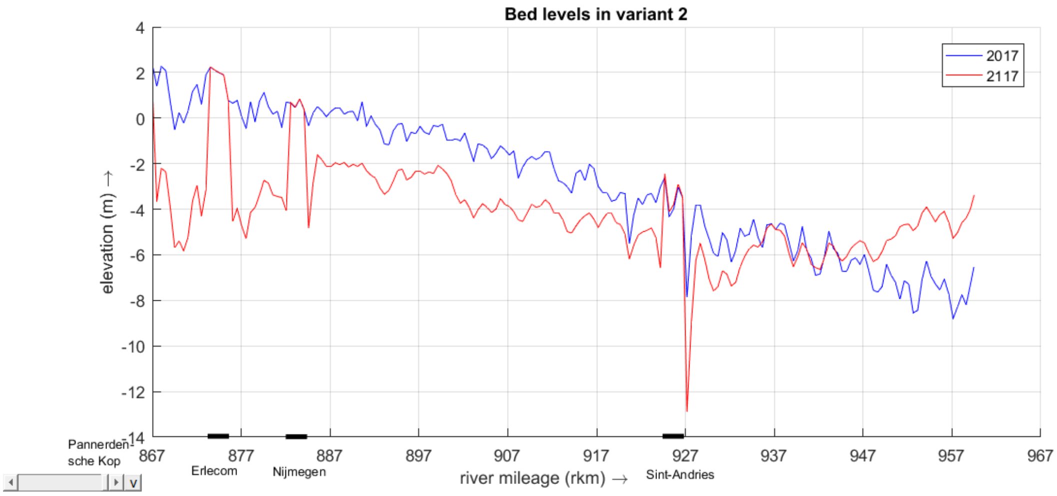

FIGURE 12 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF VARIANT 2, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

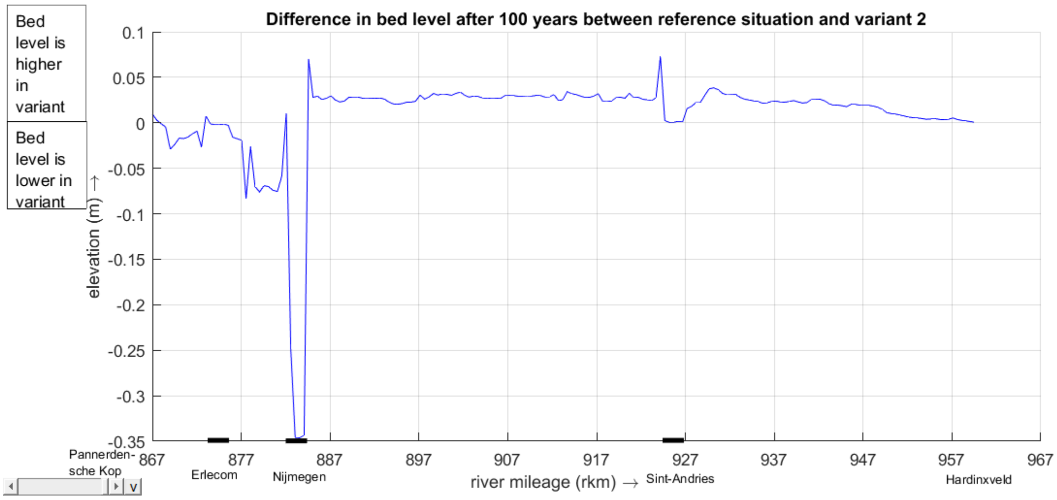

FIGURE 13 - DIFFERENCE BETWEEN REFERENCE SITUATION AND VARIANT 2 IN BOTTOM BED LEVEL OF THE RIVER AFTER A 100 YEAR SIMULATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.3.2 Water levels

The difference in water depth during low discharge periods between the reference situation and variant 2 is demonstrated in Figure 14. A lot of variations can be seen in the initial change of the water depth. The most important ones are the increase of the water depth above the bottom groynes at Erlecom and the fixed layer at Nijmegen including the erosion pit of 60 cm at Erlecom and the erosion pit and 30 cm at the fixed layer at Nijmegen. After a 100 year simulation, an increase in water depth can be observed at the fixed layer of around 30 cm. Upstream of the fixed layer the water depth reduces with about 10 cm after 100 years. After 100 years the fluctuations in water depth change are gone and downstream of Nijmegen a slight decrease in water depth can be seen. This can be explained by the increased bed level downstream of the fixed layer.

There is no apparent explanation for the initial fluctuations in the change of the water depth. The decrease in water depth upstream of the fixed layer can be explained by the backwater effect. Although the water depth increases at the fixed layer, the water level is reduced. The backwater effects causes a reduction in water level upstream if the fixed layer. As erosion upstream of the fixed layer is less than the reduction of the water level, a reduction of the water depth can be observed.

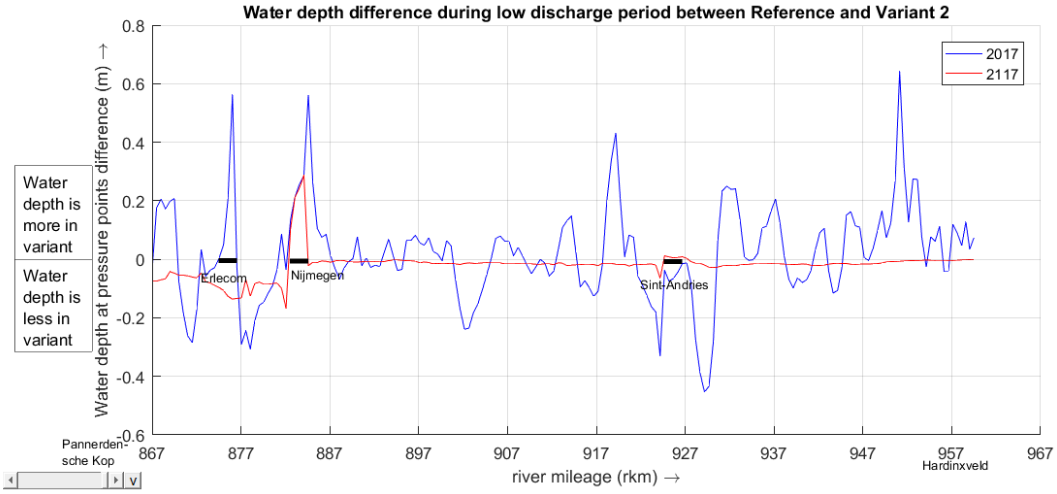

FIGURE 14 - DIFFERENCE IN WATER DEPTH DURING PERIODS OF LOW DISCHARGE (Q = 957 M³/S) IN 2017 AND 2117 BETWEEN REFERENCE SITUATION AND VARIANT 2, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.4 Variant 3: Filling the erosion pit and lengthening the fixed layer

In this section the model results of variant 3 are analyzed. The changes to the bed level and water levels over 100 years are assessed in respectively section 8.4.1 and 8.4.2.

8.4.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation of variant 3 can be seen in Figure 15. The figure shows similar patterns of erosion and sedimentation as the reference situation. It can be seen that downstream the lengthened fixed layer a new erosion pit has formed after a 100 year simulation. This erosion pit is, however, not as deep compared to the erosion pit in the reference situation after a simulation of 100 years. The difference of the bottom bed level between the reference situation and variant 3 after a simulation of 100 years is shown in Figure 16. The peaks in this figure align with the filling of the erosion pit and fixing the bed level at that location and the newly formed erosion pit. Aside from these peaks, no significant change of the bottom bed level after 100 years can be seen.

FIGURE 15 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF VARIANT 3, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

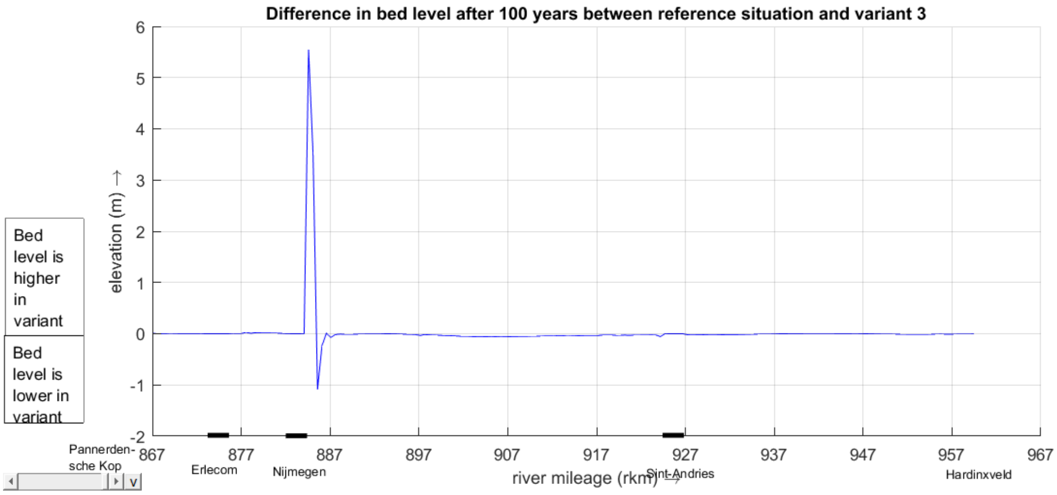

FIGURE 16 - DIFFERENCE BETWEEN REFERENCE SITUATION AND VARIANT 3 IN BOTTOM BED LEVEL OF THE RIVER AFTER A 100 YEAR SIMULATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.4.2 Water levels

The difference in water depth during low discharge periods between the reference situation and variant 3 is demonstrated in Figure 17. It can be observed that the initial water depth at the erosion pit has decreased with about 1.80 meter. This is more than the increase in bed level caused by filling the erosion pit. An initial increase in water depth can be seen just downstream of the fixed layer of around 1 meter. Upstream and downstream of the fixed layer at Nijmegen the same initial effects can be seen as in variant 2. These effects and their explanations are given in section 8.3.2. After a 100 year simulation these effects cannot be seen anymore and the only significant change in water depth is at the filled erosion pit and below the filled erosion pit. This is not in line with the research from HKV, where the backwater effect was present (HKV, 2019). At the erosion pit a reduction in water depth of 5.5 meter can be seen after 100 year, this is in line with the change in bed level after 100 years. Downstream of the filled erosion pit an increase in water depth of 1.1 meter can be seen after 100 years. This is in line with the newly formed erosion pit.

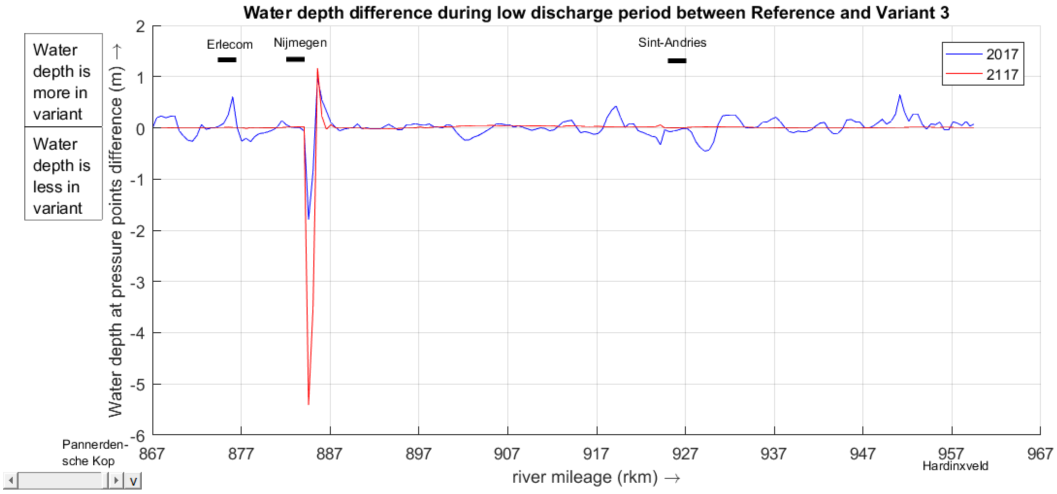

FIGURE 17 - DIFFERENCE IN WATER DEPTH DURING PERIODS OF LOW DISCHARGE (Q = 957 M³/S) IN 2017 AND 2117 BETWEEN REFERENCE SITUATION AND VARIANT 3, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.5 Variant 4: Filling the erosion pit and lengthening & lowering the fixed layer

In this section the model results of variant 4 are analyzed. The changes to the bed level and water levels over 100 years are assessed in respectively section 8.5.1 and 8.5.2.

8.5.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation of variant 3 can be seen in Figure 18. The figure shows similar trends of erosion and sedimentation as the reference situation. It stands out that below the lengthened fixed layer a new erosion pit barely forms. This is in line with the results from variant 2 and 3. In variant 2, the lowering of the fixed layer also caused a slight reduction of the depth of the erosion pit. Similarly, variant 3 showed a significantly slower forming erosion pit. In Figure 19 the difference in bottom bed level between the reference situation and variant 1 after a 100 year simulation can be seen. The figure shows the newly formed erosion pit only eroded with 50 cm in 100 years. The other peaks correspond with the lowering of the fixed layer and the filling of the erosion pit.

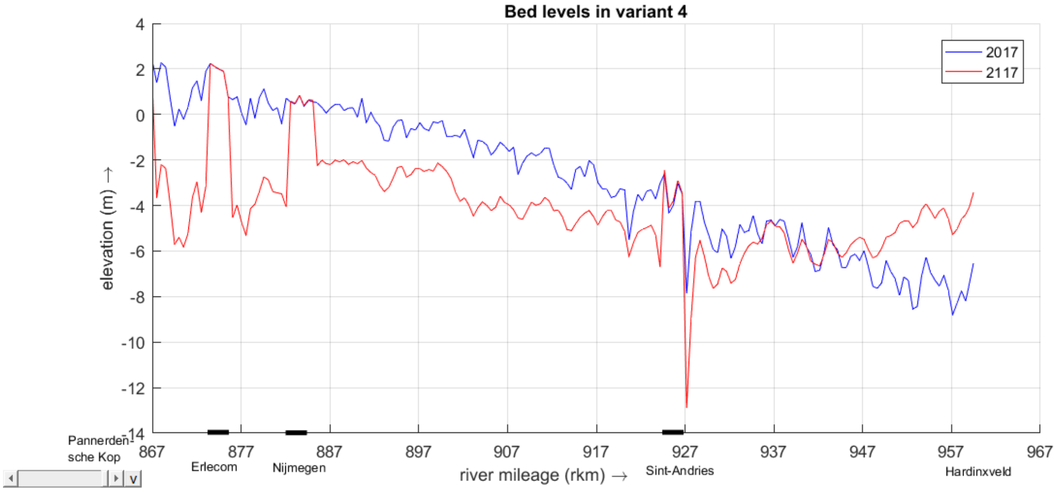

FIGURE 18 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF VARIANT 4, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

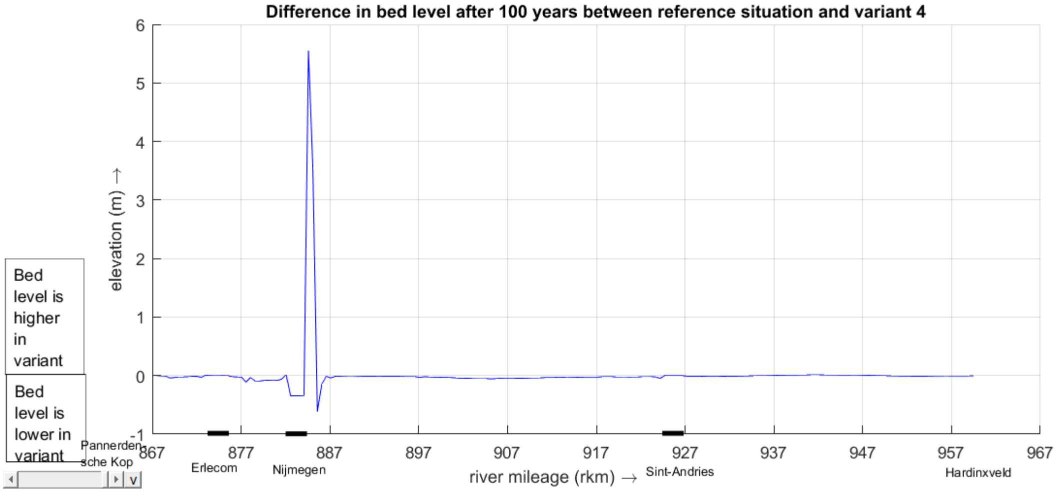

FIGURE 19 - DIFFERENCE BETWEEN REFERENCE SITUATION AND VARIANT 4 IN BOTTOM BED LEVEL OF THE RIVER AFTER A 100 YEAR SIMULATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.5.2 Water levels

The difference in water depth during low discharge periods between the reference situation and variant 4 is demonstrated in Figure 20. The results are very similar to the results of variant 2 and variant 3, described in section 8.3.2 and 8.4.2 respectively. Upstream of the fixed layer the same changes of the water depth over 100 years can be seen as in variant 2. The changes in the water depth downstream of the fixed layer and above the former erosion pit are similar to those of variant 3. Therefore, it seems that lowering the fixed layer induces lower water depths upstream of the fixed layer, while lengthening the fixed layer slightly increases the water depth downstream of the fixed.

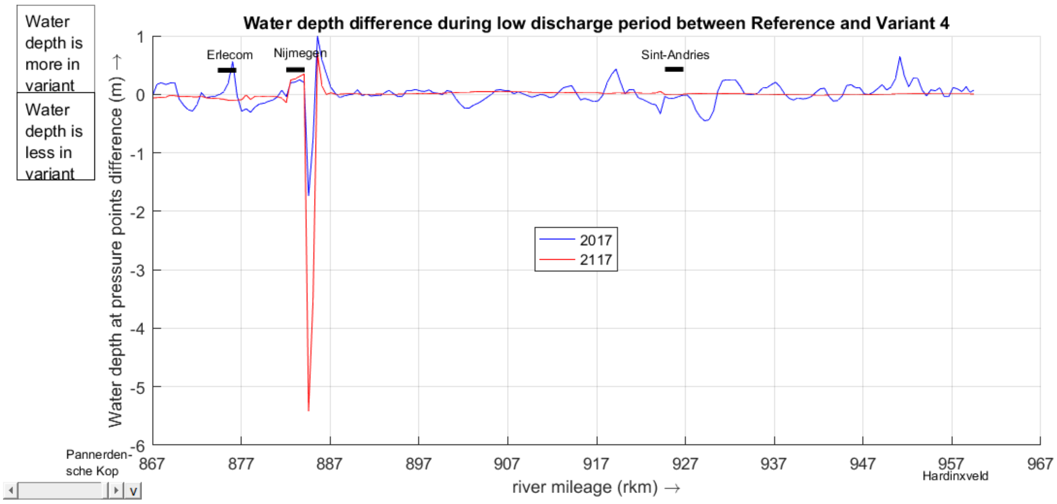

FIGURE 20 - DIFFERENCE IN WATER DEPTH DURING PERIODS OF LOW DISCHARGE (Q = 957 M³/S) IN 2017 AND 2117 BETWEEN REFERENCE SITUATION AND VARIANT 4, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.6 Increasing the bed level

In this section the model results of variant 5 are analyzed. The changes to the bed level and water levels over 100 years are assessed in respectively section 8.6.1 and 8.6.2.

8.6.1 Bed level

The initial bottom level of the riverbed and the bottom bed level after a 100 year simulation of variant 3 can be seen in Figure 21. The figure shows similar patterns of erosion and sedimentation compared to the reference situation. To see if the increased bed level in the Upper-Waal still holds after a 100 year simulation, Figure 22 can be observed. The figure shows that upstream of the fixed layer differences in bed level after a 100 year simulation vary strongly compared to the reference situation. The differences vary between a decrease of 15 cm to an increase of 10 centimeters. The figure also shows an increase of the bottom bed level downstream of the fixed layer.

FIGURE 21 - INITIAL BOTTOM LEVEL OF THE RIVERBED AND THE BOTTOM BED LEVEL AFTER A 100 YEAR SIMULATION OF VARIANT 5, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

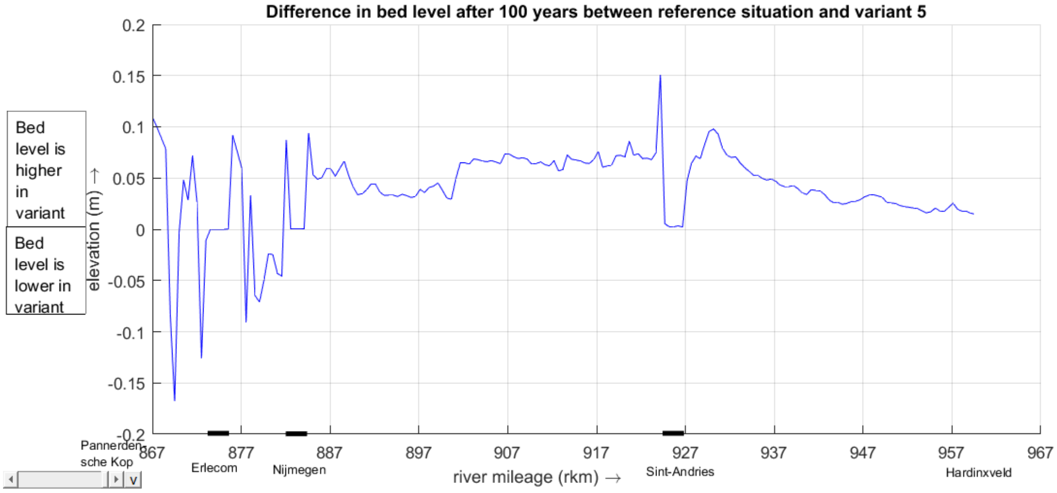

FIGURE 22 - DIFFERENCE BETWEEN REFERENCE SITUATION AND VARIANT 5 IN BOTTOM BED LEVEL OF THE RIVER AFTER A 100 YEAR SIMULATION, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.6.2 Water levels

The difference in water depth during low discharge periods between the reference situation and variant 5 is demonstrated in Figure 23. The initial change in water depths shows a lot of variation. At the bottom groynes at Erlecom an initial increase of 60 cm is observed. At the erosion pit downstream of the fixed layer an initial increase of about 40 cm can be seen. Above the fixed layer the initial increase of the water depth is about 5 cm. Upstream of the fixed layer at Nijmegen and the bottom groynes at Erlecom an initial reduction of the water depth with 25-30 cm is observed. Over a 100 year simulation, the fluctuations in the changes to the water depth are reduced. At the fixed layer an increase in water depth of around 2 cm can be seen after 100 years. Upstream of Nijmegen the water depth is reduced with up to 5 cm after 100 years, with a slight exception just upstream of Sint-Andries, where a reduction of 10 cm can be observed. Upstream of the fixed layer the water depth is increased with about 5-10 cm. Upstream of Erlecom local increases of the water depth of up to 20 cm can be seen.

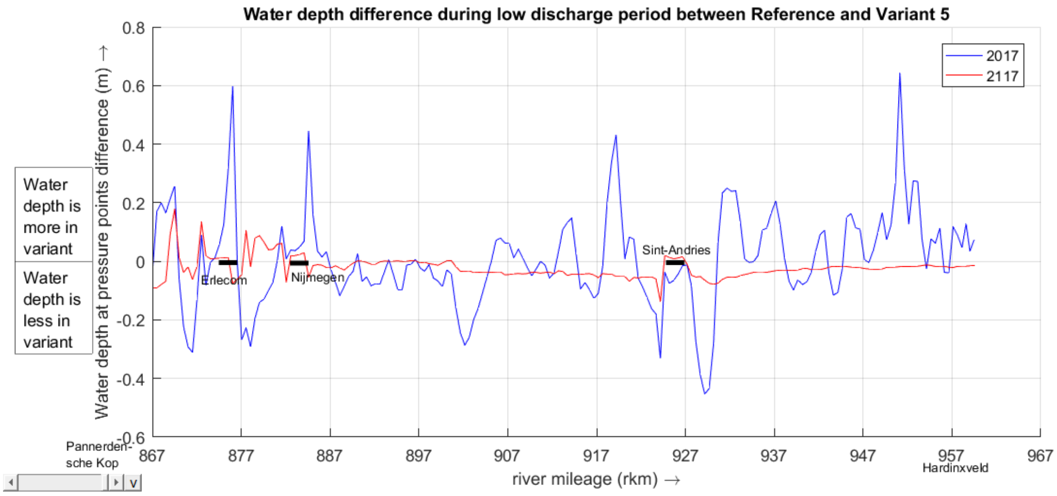

FIGURE 23 - DIFFERENCE IN WATER DEPTH DURING PERIODS OF LOW DISCHARGE (Q = 957 M³/S) IN 2017 AND 2117 BETWEEN REFERENCE SITUATION AND VARIANT 5, THE LOCATION OF THE FIXED LAYERS AT NIJMEGEN AND SINT-ANDRIES AND THE BOTTOM GROYNES AT ERLECOM ARE INDICATED WITH A BLACK LINE

8.7 Comparison of the variants

In this section the results of the variants are compared. In table XX the results on morphology and hydrology are summarized.

TABLE 3 - COMPARISON OF THE RESULTS TO BED LEVEL AND WATER LEVELS

Variant	Results to bed level	Results to water levels
1) Filling the erosion pit downstream of the fixed layer	Erosion pit forms again	Reduction of water depth at fixed layer of 0-10 cm
2) Lowering of the fixed layer	Erosion occurs upstream of the fixed layer and sedimentation occurs downstream of the fixed layer	Increase of the water depth at the fixed layer with ca. 30 cm. However, at Erlecom a reduction of 10 cm can be observed.
3) Filling the erosion pit + lengthening the fixed layer	A new erosion pit forms downstream of the lengthened fixed layer, but forms much slower than the 'old' erosion pit.	The water depth at the fixed layer remains similar.
4) Filling the erosion pit + lengthening the fixed layer + lowering the fixed layer	A new erosion pit forms downstream of the lengthened fixed layer, but forms much slower than the 'old' erosion pit.	Increase of the water depth at the fixed layer with ca. 30 cm. However, at Erlecom a reduction of 5-10 cm can be observed.
5) Increasing the bed level of the Upper-Waal	Increases the bed level downstream the fixed layer over 100 years	Increase of water depth at the fixed layer with ca. 2 cm. Downstream of the fixed layer

The results show that lowering of the fixed layer creates the largest increase in water depth at the fixed layer. Therefore, lowering of the fixed layer is the most beneficial way to improve the navigability in the river bend at Nijmegen. However, this does create a reduction of the water depth at the bottom groynes at Erlecom, which could have a negative effects on the navigability at Erlecom. Increasing the bed level does appear to lead to an increase of the water depth at the fixed layer. A further increase of the bed level could lead to a more beneficial increase of the water depth.

9 DISCUSSION

During the research several issues have been encountered which reduce the reliability of the results. These issues are discussed in this chapter. To start, the model is not validated, which means that model results do not accurately represent the reality. Therefore, the model results are not reliable in general.

Furthermore, the reference situation shows way more erosion in the Upper-Waal than it should, given the boundary conditions. Consequently, the bed levels after 100 year simulation do not correspond with reality.

This research looks as differences between the reference and variants, which minimizes the unreliability of the results, as unreliability's are distracted from each other. However, in the reference situation as well as the variants, the maximum amount of erosion occurs between Pannerdensche Kop and Nijmegen. This limit is reached before the end of the simulation, meaning more erosion should occur according to the calculation of the models. Therefore, even the differences in bed level after 100 year between the reference and variants in this section of the Waal are not reliable. This also impacts the water levels, as these are depending on the bed level. Consequently, the mentioned issues with the model results mean the results of this research are unreliable.

Besides, the model output is recorded every 100 days, as recording more data would create bigger output files. However, with less available output times, it is harder to obtain results from certain discharges, as large discharges occur significantly less in the model than small discharges. With model output every 100 days, no results could be found where the same large discharge occurred about 100 years apart from each other. Recording the model output every 10 days would be sufficient for this goal, however, the model output files would then be larger than a gigabyte. Therefore, only water levels during periods of low discharge have been taken into account in this research.

10 CONCLUSION

Five variants have been modelled and analyzed. In general, increasing the bed level seems to be an effective measure towards increasing the water levels at the fixed layer. The 10 cm increase Also lowering of the fixed layer contributes towards a better navigability of the fixed layer. Moreover, lengthening the fixed layer could potentially cause a slower development of an erosion pit.

However, given the unreliability of the model, the morphological results and hydrodynamic results are unreliable. The high unreliability of the morphology upstream of the fixed layer induce an increased unreliability of the hydrodynamic results. Therefore, no trustworthy conclusion can be tied to the results of the research. As some of the results are not in line with similar research from HKV, the model should first, for the model to be useful in similar research.

11 RECOMMENDATIONS

Some recommendations can be made for future studies, these are discussed pointwise below.

- Validate the model. The used model is not validated, which results in unreliable model output. It is recommendable to use a validated model for further research.
- It would be interesting to see if lengthening and lowering of the fixed layer really contribute to the erosion pit developing much slower. More research could be done into this subject.
- Look into larger scale measures. This research has mainly looked into measures which only adapt the fixed layer and the erosion pit. A 1D model is more suitable to look at larger scale measures, instead of the small scale adaptions to the fixed layer and erosion pit.
- Look into the results of the variants at multiple discharges. In this research, only results during low discharges are taken into account. It would be useful to look at the results during higher discharges.

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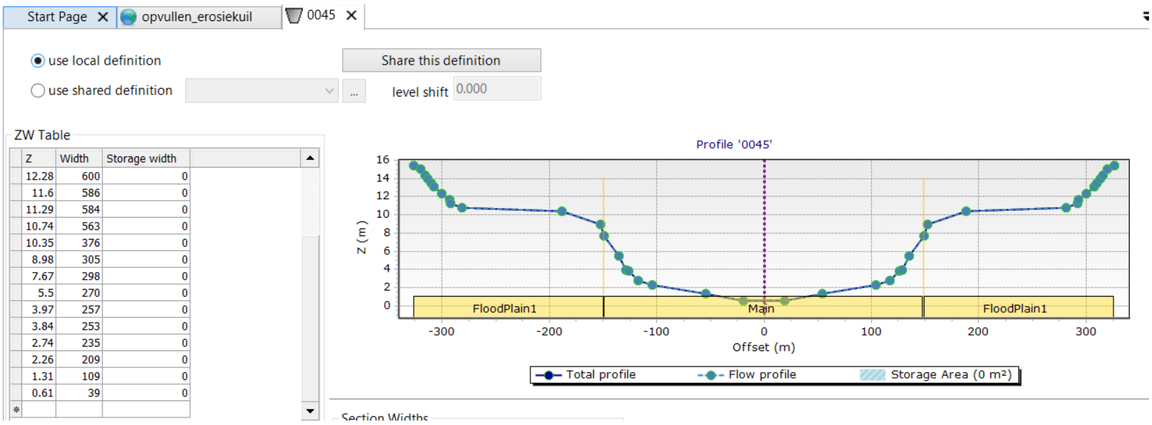
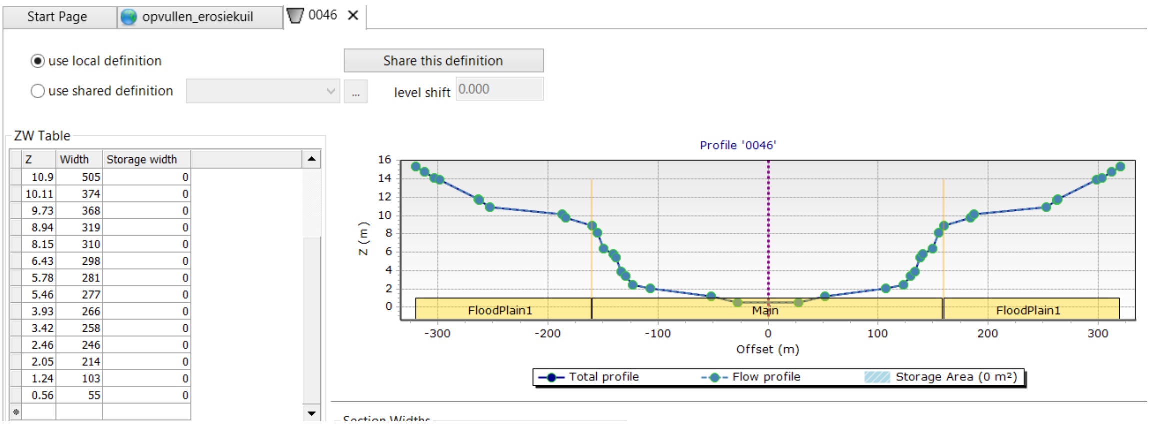
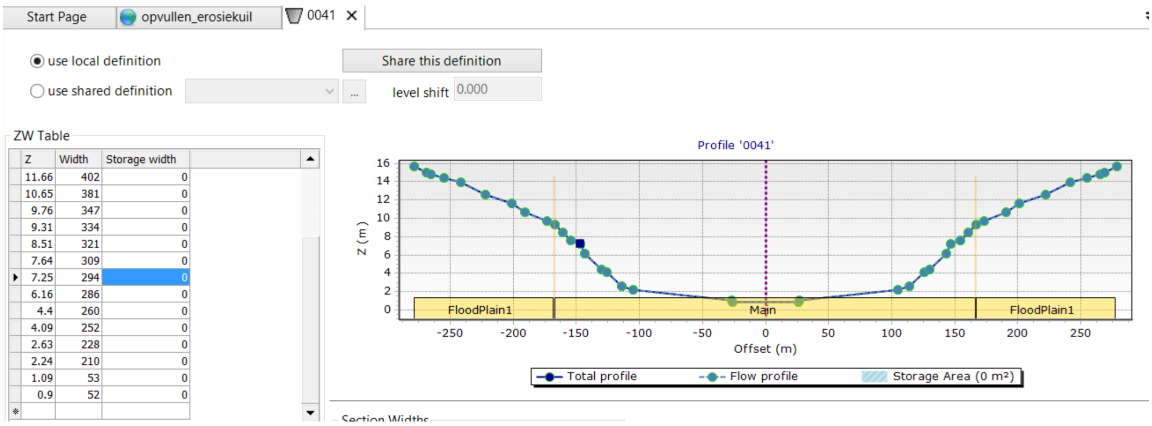
APPENDICES

1 APPENDIX 1: SOBEK3 CROSS-SECTIONS OF FILLED EROSION PIT





2 APPENDIX 2: SOBEK3 CROSS-SECTIONS OF LOWERED FIXED LAYER



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8.51	321	0
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7.25	294	0
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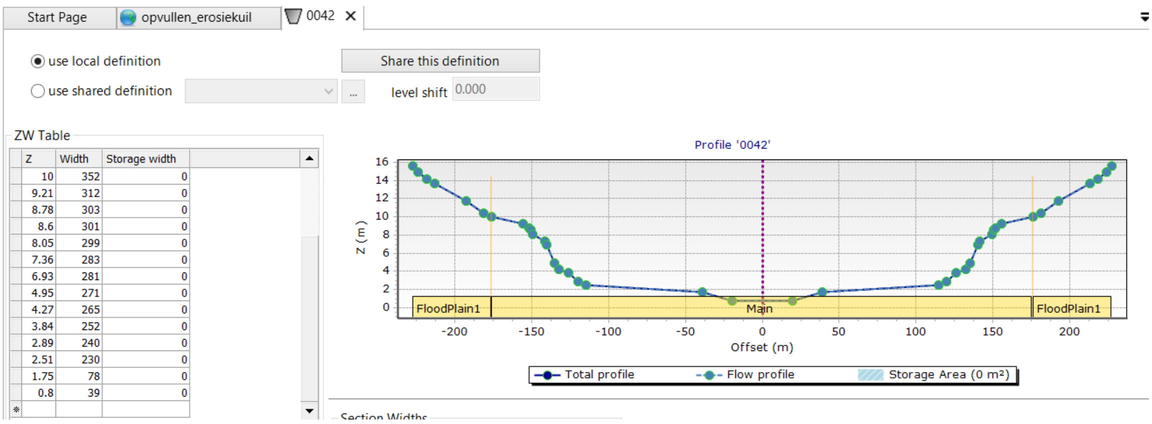
1.09	53	0
0.9	52	0



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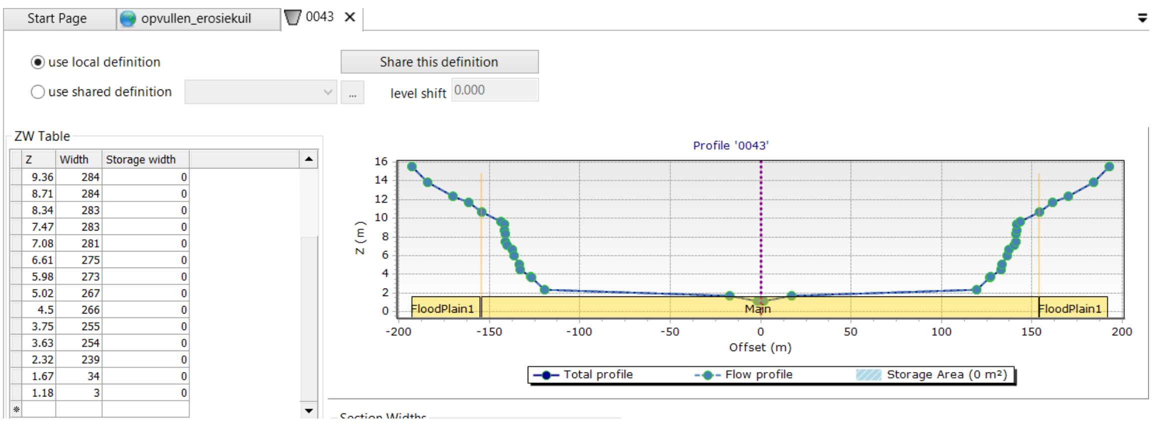
0.8	39	0



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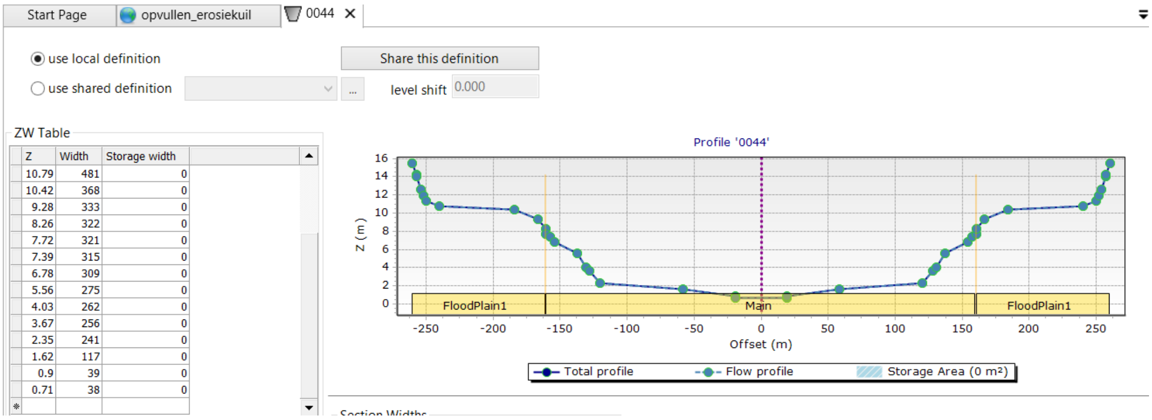
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use shared definition
Share this definition
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0.000
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Offset (m)
FloodPlain1
Main
FloodPlain1
Total profile
Flow profile
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Section Widths