Effects of fixed beds on large scale morphodynamics

Roeland Heitkönig

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Roeland Heitkönig
4585798
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Personal information

Name:	R. R. P. (Roeland) Heitkönig
Institution:	Delft University of Technology
Student number:	4585798
MSc:	Hydraulic Engineering
Specialization:	River Engineering
Faculty:	Civil Engineering and Geosciences

Graduation committee

Name:	Dr. ir. A. (Astrid) Blom
Organization:	Delft University of Technology
Faculty:	Civil Engineering and Geosciences
Section:	Rivers, Ports, Waterways and Dredging Engineering
Name:	Dr. C. (Clàudia) Ylla Arbós
Organization:	Delft University of Technology
Faculty:	Civil Engineering of Technology
Section:	Rivers, Ports, Waterways and Dredging Engineering
Name:	Dr. ir. (C.J.) Kees Sloff
Organization:	Delft University of Technology, Deltares
Faculty:	Civil Engineering of Technology
Section:	Rivers, Ports, Waterways and Dredging Engineering
Name:	Dr. J.E.A. (Joep) Storms
Organization:	Delft University of Technology
Faculty:	Civil Engineering and Geosciences
Section:	Applied Geology

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This report marks the final milestone in achieving my Master’s degree in Civil Engineering, while specializing in River Engineering. The entire journey was not without challenges, since it has its ups and downs. But all together, I look back at it with satisfaction. I have gained a lot of interesting insights throughout this process, both on the subject itself and beyond that.

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Abstract

Rivers are essential for sustaining human life, preserving ecosystems, providing clean water, supporting energy production, offering recreation, and enabling transportation. Human interventions have led to the creation of so called 'engineered rivers', such as the Dutch Rhine, which has undergone significant interventions over the past two centuries. These interventions include straightening, dam construction, and the addition of fixed beds.

Fixed beds are unique features that can be found in the Dutch Rhine, namely in Nijmegen, at St. Andries and in Spijk. They are composed of non-erodible materials and are strategically placed on the bottom of the outer bends of a river to enhance navigation. They cause erosion in the inner bend, which widens the river and improves navigability. Similar features in the world are sediment nourishments, where sediment is deposited on the riverbed. This also creates a manmade layer of large rocks that are hardly erodible and spans part of the river width. Also, bedrock reaches occur across the world, which are natural hard riverbeds. These bedrock reaches contain rocks that are hardly or non-erodible. The remaining part of the river is alluvial.

When the alluvial riverbed around the fixed bed erodes, the fixed bed can protrude from the riverbed. While there is knowledge of the small-scale effects of fixed beds, which are mainly erosion pits downstream of the fixed beds and alluviation on top of the fixed bed itself, their possible protrusion in combination with the non-erodibility may have potential large-scale consequences. This study aims to investigate the morphodynamic effects of a fixed bed on the large scale, which is an area with limited knowledge.

This research begins by examining the initial response of a fixed bed. A fixed bed results in (1) a sill-effect, (2) increased roughness, and (3) decreased mobility, and these effects are separated and treated individually. Conceptual models based on river dynamics theory are used to understand and predict how these effects contribute differently to the morphodynamic responses.

Following that, the study continues by looking into the transient and long-term response of a fixed bed using both conceptual and numerical models. These numerical models are created using the model system SOBEK-RE. The fixed bed-related effects are still considered separately with reference models created first and the effects integrated after. The reference model focuses on the transient state due to narrowing, where the slope decreases and the bed level increases. By doing this a comparison can be made of the fixed bed related effects with and without it. A similar process is repeated for a model run where the effects are all combined to assess their relative importance and the overall combined effect. The models reveal that all three effects contribute significantly to the fixed bed.

The main results of the model show that when the river is only affected by narrowing from the past, the slope decreases by 4% when looking at a total duration of 50 years. When introducing a fixed bed and combining the fixed bed related effects the upstream slope decreases by only 3% and the downstream slope decreases by 7%. From this it follows that the fixed bed influences the riverbed's slope. It reduces the downstream slope while it increases the upstream slope. At the upstream side of the fixed bed, it traps sediment caused by an M1-backwater curve. The height up to which this upstream sediment trapping continues is determined by two important parameters: the sill length and the sill height. The choices that are made in this study introduce various uncertainties and limitations such as the dimension of the model system, the uniformity of sediment grains and discharge, and the

parameter choices. In reality, the slope changing effects depend on the width of the fixed bed, the length and the amount of protrusion relative to the water level.

It is vital for water management authorities to recognize the importance of fixed bed structures, especially in extensively engineered rivers. This is because the fixed beds can result in significant and long-lasting changes to the riverbed. Successful management requires continuously monitoring and measuring the height of the riverbed over time.

Table of contents

1. Introduction

1.1 Context

Rivers play a vital role in supporting the livelihood of people, maintaining natural ecosystems, providing a source of clean drinking water, enabling energy production, offering recreational opportunities, and facilitating navigation. As a result of human interventions, rivers have been adapted to better serve these various purposes. These human-modified rivers are often referred to as engineered rivers. In the Netherlands it is the task of Rijkswaterstaat, which is the Dutch water management authority, to manage the Dutch Rivers. They monitor water levels, water quality, and ensure the safe flow of shipping. Rijkswaterstaat also plays a crucial role in flood protection, infrastructure maintenance, and environmental conservation, collaborating for optimized traffic flow and effective emergency response.

One notable example of an engineered river is the Dutch Rhine River which has undergone numerous interventions over the past two centuries. Due to all the interventions, the river has experienced significant adjustments in its overall structure. The narrowing of its channel has led to incision of the riverbed. When a channel is narrowed, it results in increased transport capacity and a decrease in the equilibrium channel slope, leading to an eroding riverbed. Examples of modifications that the Dutch Rhine River has undergone include straightening (by cutting off the meanders), the construction of dams, dikes, groynes and the construction of fixed beds (Cioc, 2002).

These fixed beds are particularly used in the Dutch Rhine. The specific design and construction method of the fixed beds in the Netherlands have so far not been adopted in other countries. In the Rhine, a fixed bed is a riverbed composed of sand and gravel over which a layer is placed with large rocks in it, which makes it non-erodible. These fixed beds are strategically positioned in the relatively sharp outer bend of a river to improve the navigability. Due to the complex hydrodynamics within the riverbend, characterized by phenomena such as spiral flow and complex sediment transport patterns, the presence of a fixed bed causes the inner bend to erode. This erosion, in turn, contributes to the widening of the navigable channel, thus increasing its width. The large roughness of the fixed bed in the outer bend enhances this process. In the equilibrium situation there will be no sedimentation in the outer bend and the sediment transport primarily occurs through the inner bend (Sloff et al., 2006). The consequence of the eroding inner bend due to the fixed bed is a larger navigable width of the river, improving the navigability of the river in the sharp bend. Figure 1.1 shows what such a Dutch fixed bed looks like.

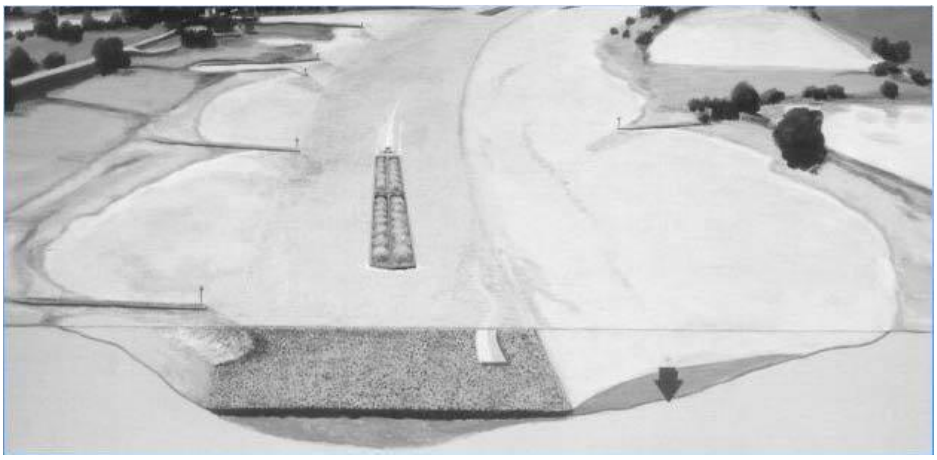

Figure 1.1: Schematic of a fixed bed in The Netherlands (Nuyten, 2006).

Three examples of fixed beds in the Dutch Rhine are at St. Andries, implemented in 1988, at Nijmegen, implemented in 1998 (White & Blom, 2020), and at Spijk, implemented in 2014 (Havinga, 2020). The fixed beds at St. Andries and Nijmegen consist of a riverbed composed of sand and gravel, onto which an upper layer is added, incorporating large rocks. Figure 1.2 shows an example of such large rocks. This upper layer is non-erodible and contains a filter which prevents sand from passing through (Havinga, 2020). In Figure 1.3 two schematics show the fixed beds at Nijmegen and at St. Andries. At Spijk the deep outer bend of the river is filled with coarse sediment, ranging from 45 to 125 mm in grainsize and reaching thicknesses of up to 5 meters in some areas. The fixed bed, spanning approximately 4 km, varies in width from 30 to 100 meters (Decker, 2014). Another location in The Netherlands where the navigable width had to be increased was Erlecom. In Erlecom less additional width was needed and less budget was available, so they installed bendway weirs. These are partial dams consisting of coarse sediment and installed perpendicular to the river flow, causing erosion in the inner bend and potentially widening the river width for navigation purposes. Just like fixed beds, they are also installed in the outer bend of the river. Bendway weirs are not treated in this research. In this report, a 'fixed bed' is defined as a non-erodible and manmade layer of large stones on the bed of a river. Figure 1.4 shows the fixed bed locations in the Dutch Rhine.

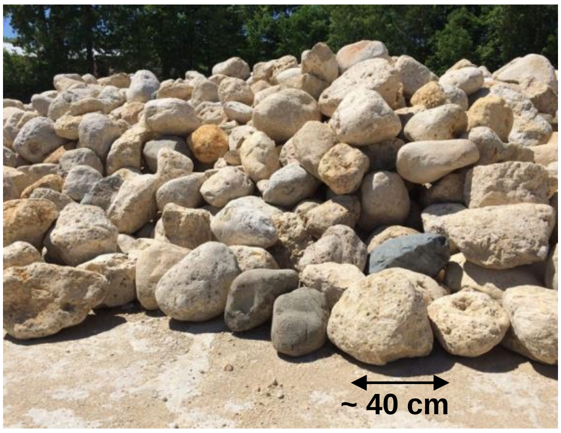

Figure 1.2: Cobblestone & Boulders (Lemke Stone, n.d.).

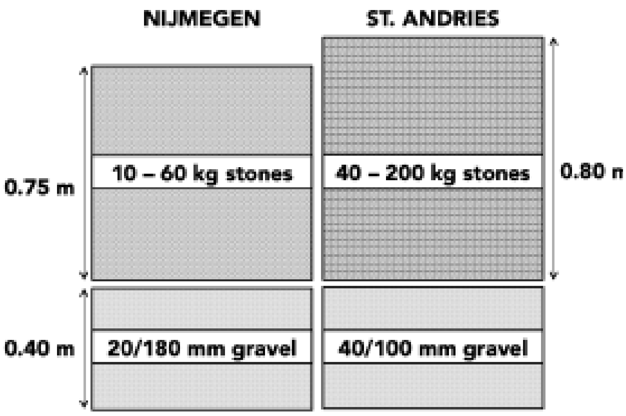

Figure 1.3: Schematics of the fixed beds at Nijmegen and St. Andries (White & Blom, 2020).

Figure 1.4: Locations of the Dutch fixed beds at Nijmegen, St. Andries and Spijk (White & Blom, 2020).

There are river interventions around the world with characteristics similar to fixed beds, such as sediment nourishments and bedrock reaches. Over the past five decades, sediment nourishments have been used in parts of the German Rhine to mitigate the channel bed erosion caused by channel narrowing. These nourishments are relevant since they share some properties with the fixed beds in the Dutch Rhine. Both nourishments and fixed beds provide a manmade riverbed that is difficult to erode. The sediment nourishments in Germany typically do not protrude from the riverbed. Czapiga et al. (2022) studied the large-scale effects of sediment nourishments. They focused on the grainsize distribution, volume, dumping frequency and the dumping location. They used a 1D model to determine how the channels respond to adding nourishments. Multiple effects of the nourishments were analysed including the protruding effect and the roughness that is increased, compared to the surrounding alluvial riverbed. In their study they found that channel bed erosion can be mitigated by nourishing sediment, but only when the imposed change in the sediment flux increases the equilibrium channel slope. This is done through coarsening the sediment flux, increasing the magnitude of the sediment flux, or by doing both. Consequently, coarse sediment nourishments should be designed to coarsen the sediment flux, promoting an increase in the equilibrium channel slope. In contrast, careful design of fine sediment nourishments is essential to prevent increased erosion due to fines, which may refine the sediment flux and lead to a decreased equilibrium channel slope and enhanced erosion."

There are more things that have similar properties as fixed beds. Another example of this is bedrock layers. Bedrock layers are natural layers of the riverbed that consist of non-erodible rock. This is the opposite of an alluvial riverbed, which is made of sediment transported by the river itself. In comparison with fixed layers, bedrock layers have a natural origin and are not man-made. On engineering time scale, bedrock can be considered to be non-erodible. There is a difference in the roughness of the layers. In general, the roughness of fixed layers is larger than the roughness of bedrock layers (Jafarinik & Viparelli, 2020). While fixed layers are less common, particularly in the Dutch context, there have been numerous studies on bedrock layers, offering valuable insights into the behaviour of fixed layers due to their similarities in fixed behaviour. Figure 1.5 shows a schematic of the Lower Rhine River with bedrock reaches in it (Ylla Arbós et al., 2021). It is important to note that the bedrock surface level can vary significantly over the cross-section, influencing erosion rates and flow dynamics. Bed incision can weaken flood protection foundations and increase flood risk.

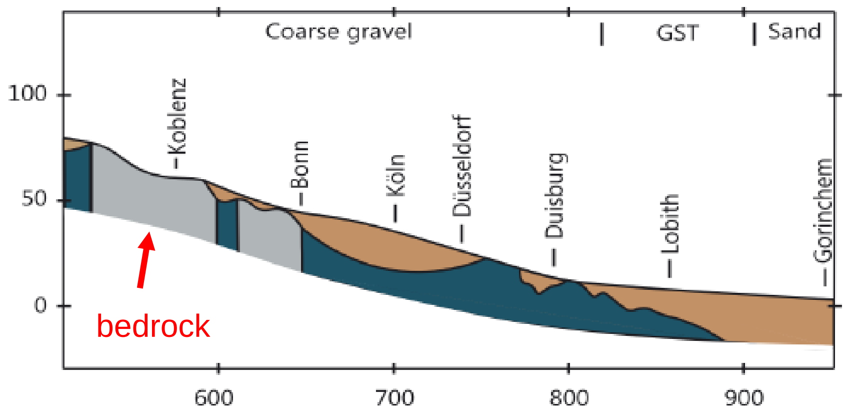

Figure 1.5: Sketch of the Lower Rhine River with bedrock (Ylla Arbós et al., 2021).

While fixed beds can have benefits, such as widening the river bend for navigation, studies have found out that they also have drawbacks. Over the past centuries, the reach of the Rhine from Bonn to Gorinchem, has experienced degradation. The fixed beds however do not erode since they are non-erodible. Therefore, they can protrude from the degrading alluvial riverbed, causing multiple problems.

The protrusion of a fixed bed can occur due to degradation of the surrounding alluvial riverbed or immediate protrusion of the nourishment upon placement (Czapiga et al., 2022). This protrusion, similar to a sill-like obstacle, along with the higher roughness of the fixed bed, can induce a backwater curve. A backwater curve refers to the rise in water level cause by a hydraulic control, such as a dam or obstruction. This results in results in a temporary rise in water elevation upstream. This phenomenon disrupts the linear water level profile, also reducing the vessels' maximum draft during dry periods with low water levels. If there is a very strong backwater curve, this may impact the bifurcation in the Rhine at the Pannerdense Kop, where the river splits into the Waal and Pannerden Canal. This bifurcation plays a crucial role in determining water flow ratios between the branches, affecting decisions on dike heights. Extended backwater curves reaching this bifurcation could potentially disrupt this water flow ratio. White & Blom (2020) conducted a field study on the impact of fixed beds in the Netherlands (Nijmegen and St. Andries) on local morphology and flow dynamics, as depicted in Figure 1.6. The plot suggests that upstream of the fixed bed sediment trapping has occurred, likely as a result of a backwater, with the sediment trapping subsequently following and eliminating the backwater. The elimination of the backwater through sediment trapping diminishes its prominence, thereby reducing the expectation of its magnitude and potential upstream issues. Ylla Arbós et al. found that there is an increasing water discharge to the Waal at the expense of the discharge to the Pannerdensch Kanaal (Ylla Arbós et al., 2023). Additionally, the relative erosion in the Waal is greater than that in the Pannerdensch Kanaal. These changes suggest a shift in water flow dynamics, potentially influencing sediment transport patterns in the region. However, since the fixed beds in the Dutch Rhine do not show a distinct backwater, it is assumed that this change in water flow ratio is not caused by the fixed beds.

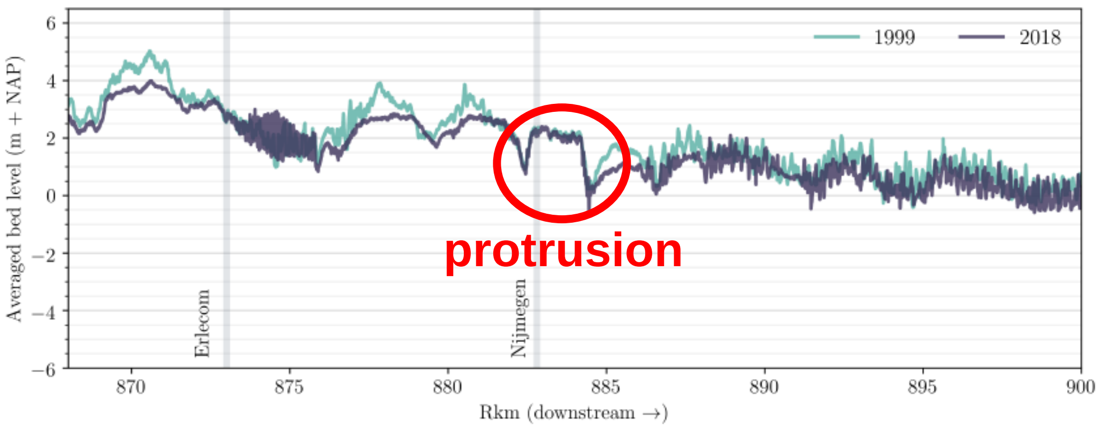

Figure 1.6: Streamwise profiles of bed level, obtained by averaging three parallel profile lines (White & Blom, 2020).

In their field data study White & Blom (2020) also found out that right downstream of the fixed beds there is the formation of erosion pits and also sediment deposition in the inner bend right downstream from the fixed bed. If the erosion pits keep increasing in size, they may affect the stability of the fixed bed. The sediment deposition is a bottle neck for navigation as it reduces the navigable river width, and thus has to be dredged periodically. Figure 1.7 shows this erosion pit and sedimentation right downstream of the fixed bed at Nijmegen (Sloff, 2010). It can be safely assumed that the fixed beds play a role in the formation of the erosion pits and sediment deposition downstream of the fixed beds.

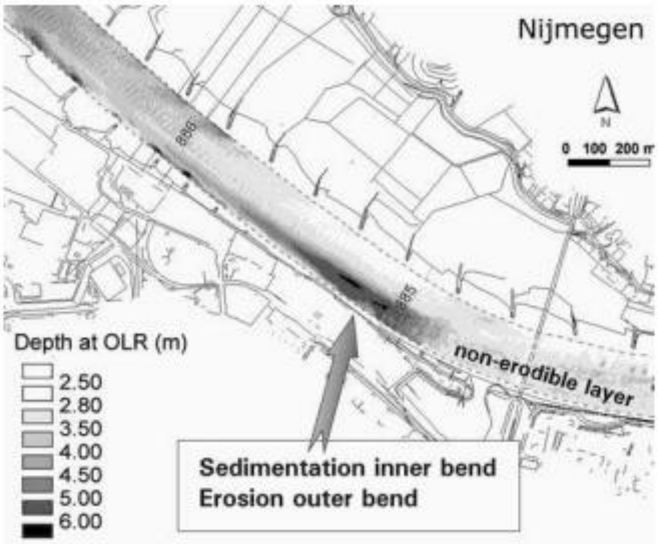

Figure 1.7: Multibeam sounding of bed level at Nijmegen, showing the fixed bed, erosion pit and sedimentation (Sloff, 2010).

Besides the local effects, White & Blom also looked into the bed elevation change on the large-scale dynamics of the Dutch fixed beds. They did this using 2-D bathymetric plots. They observed that at Nijmegen, the fixed bed was visibly rough and there was a ridge formation on top of the fixed bed. At St. Andries the surface was smooth, and significant erosion was observed throughout the inner bend. A selection of these morphological observations at St. Andries is shown in Figure 1.8.

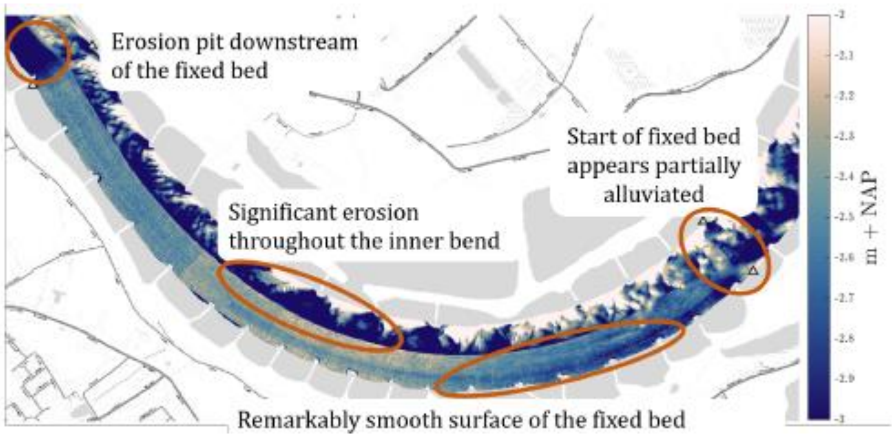

Figure 1.8: Morphological observations of the fixed bed at St. Andries (White & Blom, 2020).

Sloff et al. (2006) conducted a study on the effectiveness of fixed beds in the Dutch Rhine. They used a 2D-morphological model capable of simulating the scour hole downstream of the fixed bed. The model facilitated the computation of depth-averaged flow and sediment transport in 2D. In their study they concluded that in most cases the fixed bed is effective in eroding the inner bends of the river. However, in certain cases, such as when the river was narrow, the erosion of the inner bend did not occur due to flow redistribution. Here there will be aggradation instead of degradation in the inner bend. The river width thus has an influence on the effectiveness of the fixed bed. They also concluded that it is needed to extend the length of the fixed bed past the bend, to make sure that there is no problem for navigation due to the sedimentation and scour hole downstream.

The studies described in this paragraph mainly focussed on the local effects of the morphodynamic effects of the fixed beds. They highlighted that fixed beds fulfil their intended purpose, increasing the river width and mitigating channel bed erosion, but that there are locally negative consequences.

However, less is known about the effects of fixed beds on the large scale morphodynamics. There are no studies to the general large scale morphodynamic response to fixed beds on the bed level and bed slope. For example, if the fixed beds would change the slope or the bed level of a river, this could increase the risk of flooding or ships getting stuck. Given that there are multiple fixed beds in the river system, understanding their large-scale morphodynamic effects is of great importance due to the potential far-reaching impacts of their consequences.

1.2 Research question

This study aims to provide insight on the large-scale effects of fixed beds and the factors that influence these effects to fill this research gap. Therefore, the following main research question will be answered:

What are the large-scale morphodynamic effects of fixed beds?

To answer this research question, two sub-questions have been formulated which are shown below. Since this research is about the large scale morphodynamics, the sub-questions focus on locations downstream and upstream of the fixed bed. For all sub-questions the river mentioned is subject to degradation.

1. *What is the initial morphodynamic response to the construction of a single fixed bed?*

2. *What is the large-scale transient and long-term morphodynamic response to the construction of a single fixed bed in terms of bed level change and bed slope?*

1.3 Methodology

Three different stages of a river that is out of its equilibrium are distinguished, namely the initial, transient and long-term response. First, there is the quick “initial response” where only the river hydraulics has time to adjust to new conditions. After that, there is the so called “transient response”, which is the transition period between the initial response and the final equilibrium state. In this period the morphology also has time to adjust and the riverbed is trying to find a new balance. This transient phase often takes a considerable amount of time, until the river reaches its equilibrium state, which is also called the “long-term response”. This is when the river profile has found a stable state where the water is flowing without significant morphodynamic changes, the hydraulics and morphology remain unchanged.

Sub-Question 1: Understanding the initial response

The first sub-question is answered by first examining the initial response of a fixed bed. For this the different effects that a fixed bed has are distinguished from each other. To analyse each effect separately, sketches were made based on the principles of river dynamics theory to capture the initial response. This theory includes the study of how the river responds morphologically and hydraulically to adaptations at the initial state where the bed is starting to adjust but has had no time to adjust yet. These 1D conceptual models will give some first insight in the initial behaviour of a fixed bed. These 1D models are idealized cases meaning that it is a simplified version of a river. For each of the separate effects, plots are made of the discharge, water depth, flow velocity, sediment transport rate and variations of the sediment transport and initial bed level.

Sub-Question 2: Investigating the transient and long-term responses

After gaining insights in the initial response, the examination of the transient and long-term responses of a single fixed bed is continued through multiple model runs. These model runs look at the fixed bed related effects separately. Conceptual models are first developed for these different fixed bed related effects using schematics based on the underlying theory behind riverbed response.

Subsequently, 1D numerical models are developed using SOBEK-RE, a modelling suite initially developed by Delft Hydraulics and Rijkswaterstaat RIZA (now Deltares) around 1995 of last century (Deltares, n.d.). These numerical models specifically address the individual effects associated with fixed beds. The starting point of these model runs is a river in a transient state caused by narrowing, leading to degradation. This so-called reference model is utilized to generate the model runs for the various effects. No other modifications have been made to this reference model.

The erosive conditions play a crucial role as they facilitate the lowering of the alluvial bed surrounding the fixed beds. This, in turn, causes the fixed beds themselves to protrude. Therefore, by introducing narrowing to the reference case, a river scenario is created where both the riverbed and slope experience lowering. This strategic implementation of narrowing ensures the generation of erosive conditions necessary for the protrusion of the fixed beds.

The outcomes of the numerical model runs are then compared with the conceptual models to see whether they match and to assess the extent to which the numerical models accurately capture the underlying physics.

Furthermore, an additional model will be developed to integrate the combined effects, aiming to simulate a more comprehensive representation of a fixed bed. However, it's important to note that this model remains highly schematic and does not fully replicate the complexity of a real fixed bed. The model outcomes are compared with the reference model. This comparison is based on changes in bed level and bed level slope. This will finally lead to a conclusion about the large-scale morphodynamic effects of a river with a single fixed bed.

1.4 Structure

In chapter 2, the initial response to the construction of a single fixed bed is treated, understanding the separate effects that a fixed bed comprises: the sill-effect, increased roughness and decreased mobility. This is done by using conceptual models. Chapter 3 provides an in-depth explanation of the model setup, explains the 3D effects in a river bend, specifies the model details, the modelling plan, as well as the initial conditions, boundary conditions and numerical parameters. In chapter 4, the transient and long-term morphodynamic river response of a single fixed bed is investigated. Here the fixed bed related effects are still separated. This is done using conceptual and numerical models. Chapter 5 extends this by examining the transient and long-term morphodynamic river response of a single fixed bed by combining the effects. Subsequently, chapter 6 is dedicated to the numerical comparison with field data and the 2D analysis. Chapter 7 is about discussion of the results. Finally, chapter 8 concludes the research by summarizing the key findings, discussing their implications. This final chapter answers the (sub-)research questions.

2. Initial response of a single fixed bed

There are multiple effects that come into play when considering fixed beds. One of them is the Bernoulli effect, a small-scale hydraulic effect influencing the flow over a sill. This effect arises from the conservation of energy along a streamline and often predicts changes in the free surface of water. The Bernoulli equation, which assumes constant energy along the streamline, is utilized to analyse flow over a sill-like obstruction while neglecting frictional forces. For example, for subcritical flow, the Bernoulli effect can lead to a decrease in water surface elevation, accompanied by an increase in flow depth and velocity on top of the fixed bed. Following from the field data study of White & Blom (2020), this Bernoulli effect is neglected. The fixed bed is initially level with the riverbed, any potential Bernoulli effects are minimized before protrusion occurs. The relatively small height of the fixed bed upon placement is expected to limit its influence on flow dynamics. Therefore, given these factors, the Bernoulli effect is deemed negligible in this scenario. The other three fixed-bed related effects are treated here, which are he sill-effect, increased roughness and decreased mobility. The sill-effect and increased roughness are alluvial cases and the decreased mobility is about non-erodibility.

2.1 Sill-effect

The first effect is the sill-effect, which is due to the protrusion height of a fixed bed. For this sill-effect a 1D conceptual model is made of the water level, water depth and sediment transport shown in Figure 2.1. In the initial response plots, there are hydraulic changes and initial rates of changes of bed level, because the riverbed did not have time to adjust yet and is just about to start adapting to a new state.

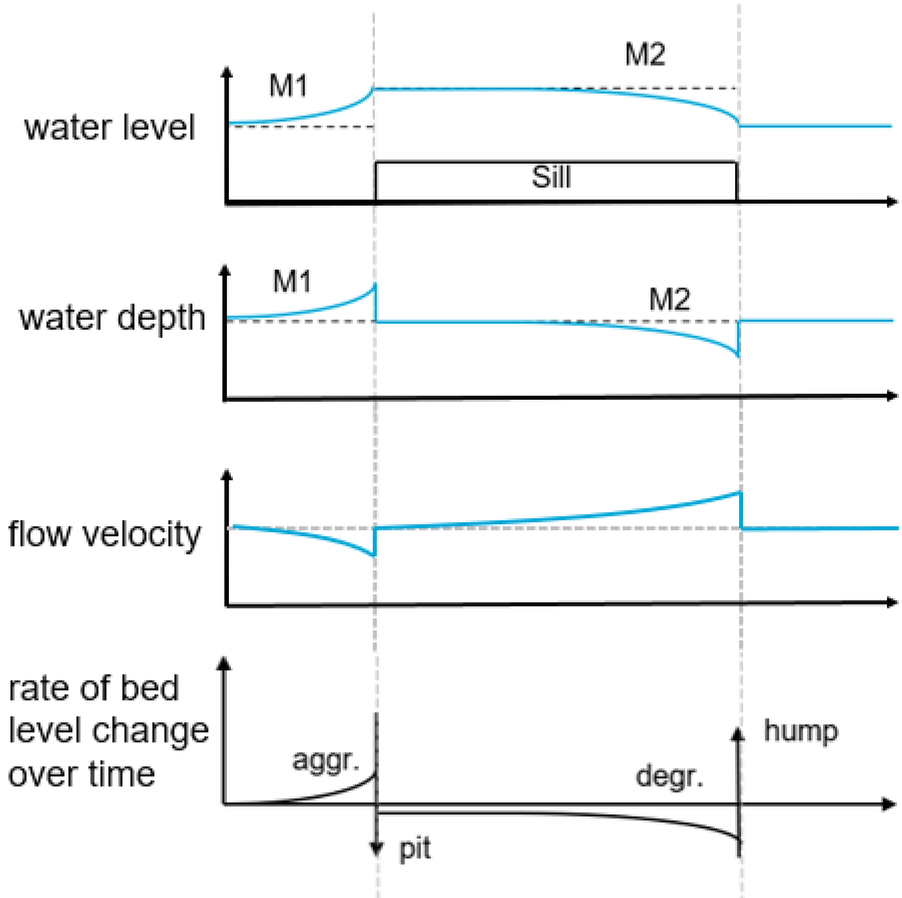

Figure 2.1: 1D conceptual model of the initial response of the sill-effect, the flow direction is from left to right. The vertical dashed lines indicate the boundaries of the location where the fixed bed would be located, and the horizontal dashed lines indicate the equilibrium water level (first plot), equilibrium water depth (second plot) and equilibrium flow velocity (third plot).

It can be seen that for the sill-effect an M2-backwater curve occurs on top of the fixed bed. This is caused by the difference in water level between the location immediately downstream of the sill and the most downstream point of the sill. Upstream of the fixed bed, an M1-backwater curve is present, which is a result of the protrusion.

The hydraulic responses result in an initial morphological response, shown in Figure 2.1. Upstream of the fixed bed there is accumulation of sediment. This is caused by the increased water depth, which causes the velocity to decrease, resulting in reduced sediment transport with streamwise position and therefore the bed level to increase. Figure 2.1 also shows an expected erosion pit at the upstream end of the fixed bed, resulting from the abrupt change in sediment transport caused by a sudden increase in velocity. The pit and the hump are shown by the arrows in Figure 2.1. In reality this erosion pit cannot be observed because it is a fixed bed.

These figures are only accurate if the sill is also made of sand. If it is a solid layer, then the pit and degradation will not occur, and due to a lack of sand supply from the solid layer, theoretically a depression may form downstream of the solid layer instead of a hump and a pit. Additionally, it is important to note that the duration of this process in this theoretical scenario depends on the length of the fixed layer. In practice, it will naturally take some time before such a layer is deposited, and the theoretical scenario may not completely apply.

2.2 Increased roughness

The second effect that is looked into is the increased roughness. The roughness on top of the fixed bed is larger than the roughness of the surrounding natural riverbed because the grainsize of the rocks that make up the fixed bed is larger. On top of a fixed bed there can also be the presence of dunes and ripples. If this holds, this generally increases the overall resistance in the flow. It will disrupt the movement of water and cause additional friction, resulting in an overall increase in resistance. Therefore, dunes on a fixed bed with high resistance would further increase the resistance in the flow (Tuijnder et al., 2009). As a result of the increased roughness the equilibrium water depth on top of the fixed bed is larger. This causes the water level to rise to attain the new equilibrium water depth as shown in Figure 2.2. The increased roughness leads to an M2-backwater curve. Similar to the sill-effect an M1-backwater curve is present at the upstream end of the fixed bed. Due to these differences in the water level there are morphological effects which are graphically described in the last graph of Figure 2.2. Upstream of the fixed bed location aggradation is expected and at the location of the fixed bed itself degradation is expected due to the same effects as described previously for the sill-effect. The amount of aggradation and degradation is influenced by the degree of roughness increase. Additionally, it's important to note that there is no abrupt transition in flow velocity; hence, no hump or erosion pit is expected.

In the 1D conceptual model, an erosion pit forms at the location where roughness increases. This pit is attributed to the larger grain size of sediment found at the fixed bed location, leading to enhanced grain roughness. At the downstream end of the fixed bed location the grain roughness abruptly decreases, leading to a sediment hump where the larger grains naturally transition into smaller particles, as depicted in Figure 2.2.

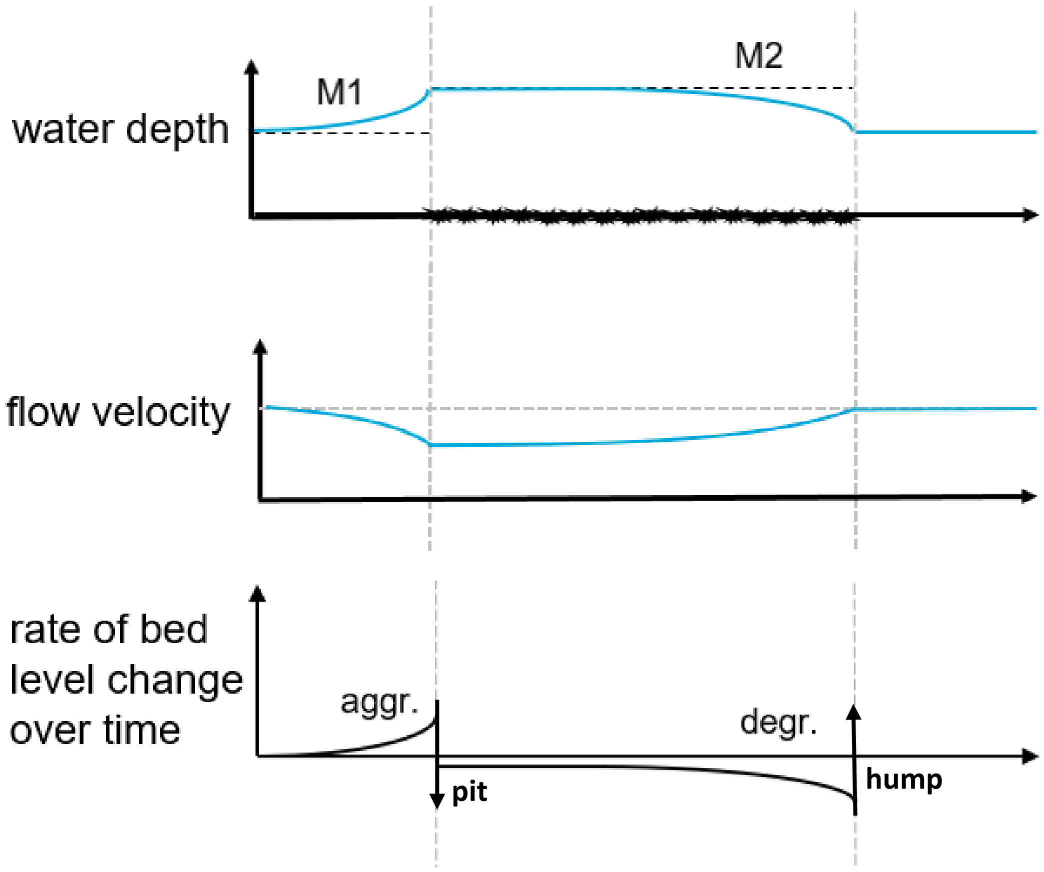

Figure 2.2: 1D conceptual model of the initial response of the increased roughness. The vertical dashed lines indicate the boundaries of the location where the fixed bed would be located, and the horizontal dashed lines indicate the equilibrium water level (first plot), and equilibrium flow velocity (second plot). The pit and hump are caused by the larger grain roughness.

2.3 Decreased mobility

The third and final effect that is considered is the decreased mobility. As the fixed bed is non-erodible, it remains stationary. Hence, the mobility is smaller than the surrounding alluvial riverbed. In Figure 2.3 the 1D conceptual initial response shows a water level that is equal on the whole river section; so there are no initial hydraulic changes due to the decreased mobility. However, due to the immobile layer there are morphological changes. The decreased mobility implies that sediment transport is smaller at this location leading to a reduced sediment transport. This sudden transition causes a sharp transition point in the sediment transport so the slope of this line, representing the change in sediment transport, is infinite. This large local sediment transport change, located on the outer sides of the fixed bed location, will cause aggradation upstream and degradation downstream of the fixed bed. This morphological initial response differs from the two preceding fixed bed related effects.

In the measured field data there is not enough density in time to analyse the initial response. Since the field data is already in the transient regime, a comparison between the initial response and the existing real life state would be off.

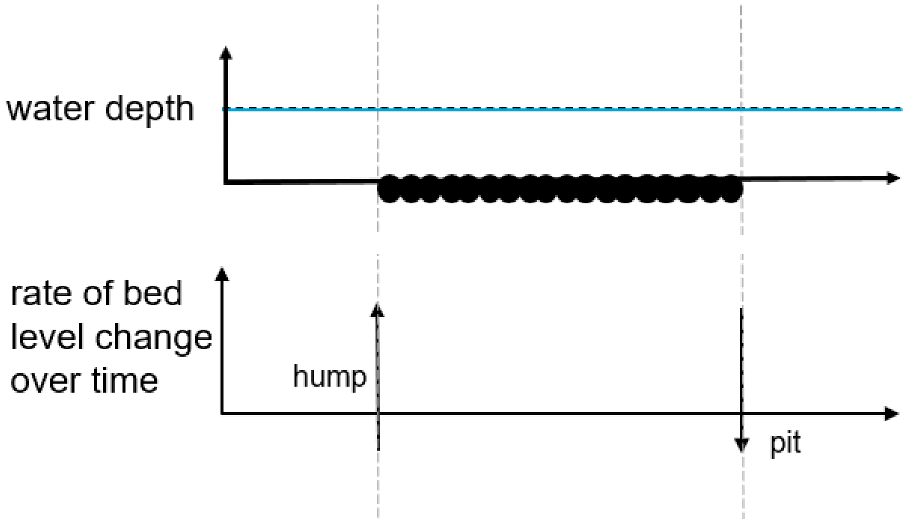

Figure 2.3: 1D conceptual model of the initial response of the decreased mobility. The vertical dashed lines indicate the boundaries of the location where the fixed bed would be located.

2.4 Reflection and comparison to measured data

The shift from conceptual 1D initial responses to observed 2D field data in the context of fixed beds in the Rhine River reveals notable distinctions. In a 1D framework, hydraulic and morphological effects are oriented along the river's flow, emphasizing dynamics in the longitudinal dimension while neglecting lateral complexities. Integrating 2D field data into an analysis originally based on 1D responses is not straightforward, as it required accounting for responses influenced by 2D effects. The 2D field data considers the actual spatial variability of fixed-bed behaviour, involving interactions in both the length and width directions. This variability is particularly significant when the fixed bed is located in the outer bend of the river (2D), where interactions differ from those in the entire width of the river (1D). The downstream erosion pit near the fixed bed seems to be influenced by 2D effects, emphasizing the need for a more nuanced 2D perspective to accurately capture the 2D complexities.

The three separate mechanisms (i.e., the sill-effect, increased roughness and decreased mobility) each yield a distinct initial morphodynamic response, differing from one another in their respective outcomes. Right upstream of the fixed bed, it is expected that aggradation will occur, while at the location of the fixed bed itself, degradation is expected. These initial responses are primarily caused by the sill-effect and increased roughness. It is important to note that these effects are considered separately from each other, even though in reality, a fixed bed cannot erode since it is fixed. The relative contributions of the sill-effect and the decreased mobility determine whether there will also be a hump and/or a pit right downstream and upstream of the fixed bed location. In the field data clear erosion pits were observed downstream of the fixed bed. The decreased mobility only leads to a temporary effect while field observations show that it lasts. This means that the downstream erosion pits are caused by 2D effects or upstream trapping of sediment due to backwater effects.

These relative contributions may also shape the overall behaviour of the river on a larger scale. For instance, if the river is undergoing significant incision, the degree of degradation can vary accordingly. This relationship highlights the importance of understanding how the interactions between the sill-effect, increased roughness, and decreased mobility influence morphodynamic processes in river systems.

All the initial morphological responses described above occur at the small scale, so focussing on the fixed bed itself and its immediate surroundings. In the phase of initial response the riverbed does not have the time yet to adapt. These initial hydraulic and morphodynamic responses are important to get an idea of what is happening with the fixed bed.

It's very important to pay attention to the bed level and bed of the riverbed because changes can bring big risks for the surrounding area where people live. If the level of the ground around the river starts changing it can affect many things. When the ground near the river changes it may create an erosion pit. This can make the fixed bed and riverbed unstable, which could lead to damage or even losing the riverbed. Not only does this decrease the stability of the riverbed, but it can make navigation through the river difficult. Also, if these erosion pits downstream get bigger and bigger, they could put the banks of the river in danger.

In reality, as also mentioned in the previous paragraph, there is indeed erosion going on at the fixed beds in the Netherlands. This erosion however is not uniform over the width and length of the river. In particular the edges of the fixed bed are highly eroded (White & Blom, 2020). It is expected that this erosion is due to a combination of effects, of which the increased roughness is one of them. For both the sill-effect and the increased roughness, reason for the degradation of the alluvial cover upstream and downstream of the fixed bed is the narrowing in the past. In reality, there is a huge erosion pit right downstream of the fixed beds in both Nijmegen and St. Andries. However, neither the sill-effect nor the increased roughness models account for such a substantial erosion pit.

3. Numerical model setup and runs

This chapter provides a description of the numerical model, the modelling plan is discussed including the model runs, and the initial conditions, boundary conditions and the numerical parameters are treated.

3.1 Model specifications

A model will be set up using the model system SOBEK-RE, a modelling suite made by Deltares (Deltares, n.d.). SOBEK-RE is a software program used for one-dimensional modelling of open-channel networks. It simulates unsteady and steady flow, uniform and mixed-size sediment transport, morphology.

The equations for water motion solved by SOBEK-RE originate from the St. Venant equations for flow, specifically equations (3.1) and (3.2). These equations describe unsteady flow, where the flow changes with time.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{3.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(a_B \frac{Q^2}{A_f}\right) + gA_f \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} = 0 \tag{3.2}$$

Here, A represents the cross-sectional area of the flow, Q is the flow rate, a_B is a coefficient that accounts for the influence of channel width variations on flow, h stands for the flow depth, g is the acceleration due to gravity, R is the hydraulic radius, and C is the Chézy resistance coefficient. The A_f stands for the floodplain area, which is the flat land adjacent to the river that gets inundated during periods of high discharge.

The equations that SOBEK-RE solves are the one-dimensional mass balance, averaged over the width and the height of the water column, and the momentum balance equation. These equations are derived from the St. Venant equations and are used to model flow in open channels. The steady flow assumption is made, implying that the flow does not change with time so that the partial derivatives with respect to time are zero. These equations are used to analyse flow in open channels when the flow velocity, depth, and other parameters remain constant over time. Density and wind differences are neglected. The assumptions lead to the steady-state solutions of the St. Venant equations:

$$\frac{\partial Q}{\partial x} = 0 \tag{3.3}$$

$$\frac{\partial}{\partial x}\left(a_B \frac{Q^2}{A_f}\right) + gA_f \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} = 0 \tag{3.4}$$

To describe how bed level changes over time because of erosion and deposition, there is the Exner equation. The Exner equation, a mass conservation equation, shows that a spatial change in the sediment transport rate results in a change in bed elevation. For a constant width:

$$\frac{1}{1-\varepsilon_p} \frac{\partial z_b}{\partial t} + \frac{\partial s}{\partial x} = 0 \tag{3.5}$$

This change of bed level is dependent on the grainsize of the sediment, which plays a crucial role in the sediment transport of a river. The grainsizes of the bed material determine how sediment is transported, deposited and eroded in the river system. When using a model with multiple grainsizes, the Hirano equation is used (Hirano, 1971). The Hirano equation is often referred to as the 'active layer model'. The active layer represents the portion of the sediment bed that actively interacts with the flow.

The layer below this active layer is not actively involved in sediment transport. The sediment transport relation incorporates the critical shear stress and the distribution of different sediment sizes. To be able to model changes of the bed level over time and solve for the mass conservation numerically, a sediment transport relation is needed. The sediment transport relation is often called a 'closure relation' and helps to solve for the mass conservation.

In this research the chosen sediment transport formula that is needed for the modelling is the Meyer-Peter-Müller formula. This is since it is valid for grainsizes larger than 0.4 mm, which will become useful later on and it is also useful for the decreased mobility effect. Meyer-Peter-Müller SOBEK-RE has a mixed-size sediment option with and without hiding and exposure, which is needed and used in this research. The hiding and exposure means it can describe how sediment particles interact, either clustering together to cover one another or dispersing and spreading out while remaining individually visible.

3.2 Modelling plan

To address the second sub-question about the transient and long-term response of a single fixed bed, multiple model runs will be made. For this the fixed bed related effects are both treated separately from each other and will be combined.

The numerical model runs have a simulation time of 100 years, from which both the transient and long-term response can be obtained. All the numerical model runs are starting from a reference model. These reference models do not have a fixed bed. Table 3.1 shows all numerical model runs that have been made and their parameters.

Table 3.1: Overview of all numerical model runs with their varying parameters.

Run	Name	River width of the main channel (m)	Sill height (m)	Chézy-coefficient ($\sqrt{m}$/s)	Grainsize(s) of bed sediment (mm)	Simulation time (years)
1	RM1	200	0	50	10	1,000
2	RM2	150	0	50	10	100
3	Sill1	150	0.5	50	10	100
4	Incr1	150	0	40	10	100
5	Decr1	150	0	50	10 & 250	100
6	Sill2	150	1.0	50	10	100
7	Sill3	150	1.5	50	10	100
8	Incr2	150	0	35	10	100
9	Incr3	150	0	30	10	100
10	Decr2	150	0	50	10 & 125	100
11	Decr3	150	0	50	10 & 62.5	100
12	Com1	150	0.5	40	10 & 250	50

The first model is reference model 1, referred to as RM1 in Table 3.1. This reference model is in a state of equilibrium, meaning that there are no changes in the hydraulics or morphodynamics. The chosen criterion for which a river is considered to be in the long-term state is when no variations are observed anymore. It is important to note that the river system comprises two main components: the main channel, indicated as a red B in Figure 3.3, and the floodplains, indicated as a black P in Figure 3.3. The main channel represents the central watercourse where the majority of the flow is confined, while the floodplains refer to the adjacent low-lying areas that periodically flood during high water events. Subsequent to reference model 1, the width of the main channel of the river is reduced, leading to an expansion of the floodplain's width. As a result of this, the newly created (engineered) river will strive to reach a new equilibrium state. This will be achieved by reducing its channel slope and lowering the bed level of the main channel, a consequence of the increased transport capacity resulting from the narrowing. The floodplains, however, do not lower, which can result in a significant difference in bed level between the floodplains and the main channel. The moment when the bed level change is at maximum 2 cm per year is the chosen criterion for considering the river to be in a transient state due to narrowing. This moment is the initial condition for reference model 2 (RM2), as shown in Figure 3.4. The red arrows show the decreasing slope and degrading bed, while the blue line shows the water level of the new reference model 2. At the downstream end of this model, the water level is constant, simulating a lake or a sea.

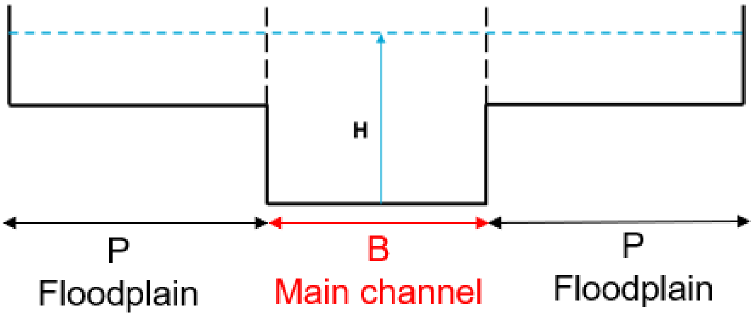

Figure 3.3: Schematic of the cross-section of the river including the main channel and floodplains.

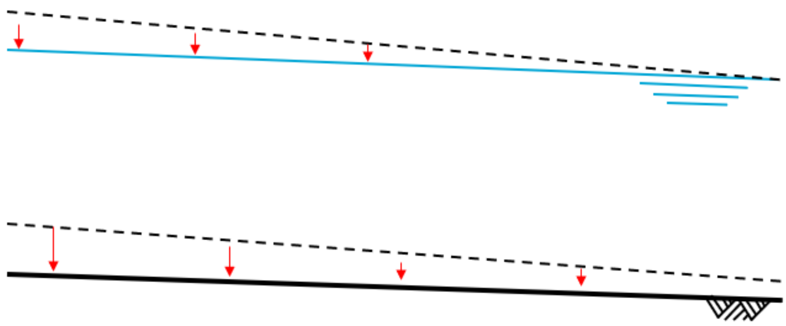

Figure 3.4: Longitudinal profile of reference model 1 (RM1) and reference model 2 (RM2). The dashed lines represent the water level and bed level of RM1, and the solid lines represent the water level and bed level of RM2 when the bed level change over time is at maximum 2 cm per year.

Consequently, reference model 2 represents a river in a transient state due to narrowing, meaning that it is subject to degradation. This reference model is chosen as the initial condition for the model runs related to the separate effects (runs 3 – 11 in Table 3.1). Each of the three fixed bed related effects is starts from the same starting point, which is reference model 2 (RM2), corresponding to run 3, 4 and 5. From these model runs, the transient and long-term response will be obtained. To simulate the sill-effect, a 3 km long and 0.5 m high sill is placed in the middle of the model to mimic a protruding bed (run 3). The increased roughness effect involves lowering the Chézy value from 50 to 40 $\sqrt{m}$/s (run 4), so a decrease of 20%. The larger the Chézy-coefficient is, the smoother the bed surface is. In the case of the decreased mobility effect, the grainsize of the fixed bed location is increased from 10 mm to 250 mm (run 5) to make a layer that is immobile. For this the mixed-size sediment option in SOBEK-RE is used. The only two sediment fractions used here are the 10 mm of the alluvial bed and 250 mm of the decreased mobility region. The results of the transient and long-term responses of these numerical models will be compared with the corresponding conceptual models. The numerical models will verify whether the conceptual models accurately represent the expected physics.

Next, six other model runs are conducted (runs 6 - 11), resembling runs 3, 4 and 5 but with different parameters for sill height, Chézy-coefficient and grainsize of the bed sediment. By doing this for every effect there are 3 different model runs, which will be used for a sensitivity analysis.

Following this, model runs 3, 4 and 5 conducted earlier are combined together, labelled as Com1 in Table 3.1. This reference model is very important as it combines the three effects of a fixed bed. With this reference model changes in bed slope and bed level will be evaluated. This is done by comparing and assessing the results with reference model 2 in which the river is only subjected to narrowing. The comparison of the numerical model results will assess the magnitude of the large-scale morphodynamic effects of the fixed bed.

3.3 Reference models: Initial conditions

The reference models RM1 and RM2 each have their own initial conditions, while the river's length, which remains consistent across all models, measures 150 km. The shared initial conditions between both reference models are the discharge and grainsize. For the discharge a value of 2,000 m^3/s is used, based on the average discharge of the Rhine, which is about 2,200 m^3/s. The Rhine's actual discharge of the Rhine varies between 600 to 16,000 m^3/s (Helpdesk Water, n.d.). The sediment in the alluvial riverbed has a D_{50} grainsize of 10 mm, which remains constant. Additionally, the sediment composition remains constant along the length of the river, with no downstream fining or other variations observed. While the grain size used may not precisely reflect that of the Rhine, it's important to note that the Rhine river is not being replicated in a one-to-one manner, ensuring that the modelling approach remains appropriate for its intended purpose with a homogeneous sediment composition where all fractions are uniformly distributed.

In the first reference model (RM1), which represents an equilibrium state, the main channel width, denoted as B in Figure 3.3, is 200 m, and the width of the floodplains, denoted as P in Figure 3.3, is 300 m. Important to note is that to get to the slope value of RM1 boundary conditions have been used. These boundary conditions will be explained in section 3.4, but since reference model 1 is needed to create reference model 2, the outcomes of these models is already mentioned here. The equilibrium slope is $2.61 * 10^{-4}$ m/m. It has to be kept in mind that real rivers do not have a linear longitudinal profile making it harder and less realistic to compare the slopes. Also, the grainsize used here is 10 mm, which is not comparable to the Dutch Rhine. When comparing the slope to the Rhine River this slope is somewhat steeper, which is to be expected due to the larger grainsize. While this slope is representative for the German segment of the Rhine, the average slope in the Dutch part of the Rhine is on average approximately $1.2 * 10^{-4}$ m/m (Ylla Arbós et al., 2021). Compared to the world-average river-reach slope, which is $2.60 * 10^{-3}$ m/m (Cohen et al., 2018), the slope used in this research is relatively small. It is important to consider that the Rhine in the Netherlands is situated near its estuary leading to a gentler slope compared to its upper reaches. The initial condition for the downstream flow depth level that corresponds to the equilibrium river is 6.25 m. This downstream end of the river simulates a lake or a sea, so the water level is constant for all runs in this research.

As mentioned earlier, to transition to reference model 2, the width of the main channel in reference model 1 is reduced from 200 m to 150 m marking a 25% reduction in width. The total width of the whole river is 500 m. Due to this reduction in the width of the main channel, the floodplain's width, see Figure 3.3, now measures 350 m. This transformation creates an engineered river in a state of degradation, causing the bed level and channel slope both to decrease. The conditions of the river when the maximum bed level change over time is 2 mm per year form the starting conditions for reference model 2. These include the river's slope, which is now 2.43 * 10^{-4} m/m, and the downstream flow depth, which is now 6.88 m. The water level at the downstream boundary is the same as for reference model 1, since it simulated a lake or sea with a constant water level. Figure 3.5 illustrates a schematic cross-section of the rivers, showing the conditions for reference model 1 and 2. The B stands for the width of the main channel and the i stands for the bed slope.

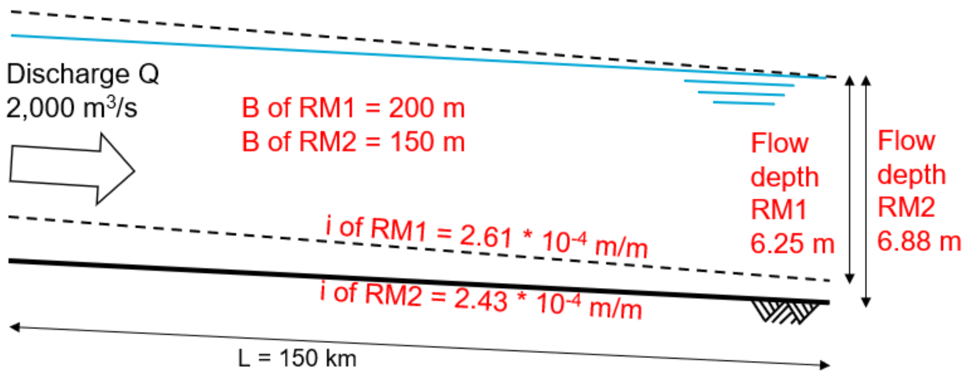

Figure 3.5: Longitudinal profile with the initial conditions of the reference models.

3.4 Reference models: Boundary conditions

The reference models also have their boundary conditions. The boundary conditions that both models have in common are the discharge and the sediment load. In both reference models, the upstream discharge remains constant at 2,000 m^3/s. The upstream sediment load is 1.4 * 10^{-1} m^3/s. The downstream water level is constant over all runs and equals 6.25 m relative to mean sea level. The downstream water level simulates a sea or a lake where the water level is fixed. Figure 3.6 shows the boundary conditions for reference model 1 and 2.

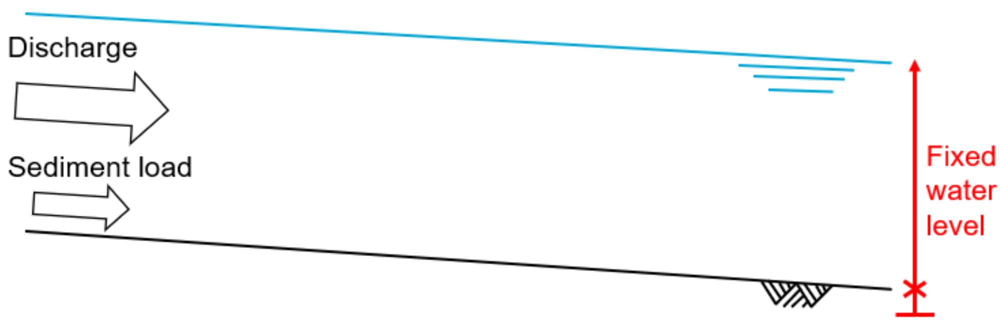

Figure 3.6: Longitudinal profile with the boundary conditions of the reference models.

3.6 Numerical parameters

Appendix A provides an overview of the parameters and values used, which remain consistent throughout all numerical model runs. The gravitational acceleration equals 9.81 m/s^2, in line with Earth's conditions, and the density of freshwater is standardized at 1,000 kg/m^3. Water flow calculations are steady state, indicating that short-term flow or water level fluctuations are of secondary importance.

4. Transient and long-term morphodynamic river response of a single fixed bed with separate effects

For the three fixed bed-related effects multiple models have been made involving both conceptual and numerical models. All model runs incorporate the transient river response as well as the long-term river response to each fixed bed related effect. The conceptual models illustrate the expected response to fixed bed-related effects and they show four distinct moments in time. The initial state, Time 0, signifies the starting point where no changes have occurred yet. The next two moments, Time 1 and Time 2, represent the transient response, allowing the river morphology to adapt. During these periods, the riverbed is in the process of finding a new equilibrium. The final timestep, Time 3, shows the long-term response. The transient response to narrowing is not included in the conceptual models.

4.1 Sill-effect

In Figure 4.1 the conceptual model is shown for the response to the sill-effect. The dark blue lines indicate the water level for the different moments in time, which are needed to explain the upstream backwater effect with sediment trapping. It can be seen that the sill is expected to decrease in height and to move downstream. The discharge remains constant. As water flows over a sill, the water depth at the top of the sill decreases. Due to this, the water flowing over the sill will accelerate. The increased flow velocities and turbulence generated here lead to an increased sediment transport. The sediment particles of the sill will be picked up and transported in downstream direction. As a result, the sill will lower in height and propagate downstream. At the upstream end of the sill, there is an M1-backwater curve. This backwater curve is trapping sediment as long as the sill is present. The more the sill decreases in height, the smaller the backwater curve, thus the smaller the trapping of sediment. In the long-term state the sill is expected to be disappeared completely.

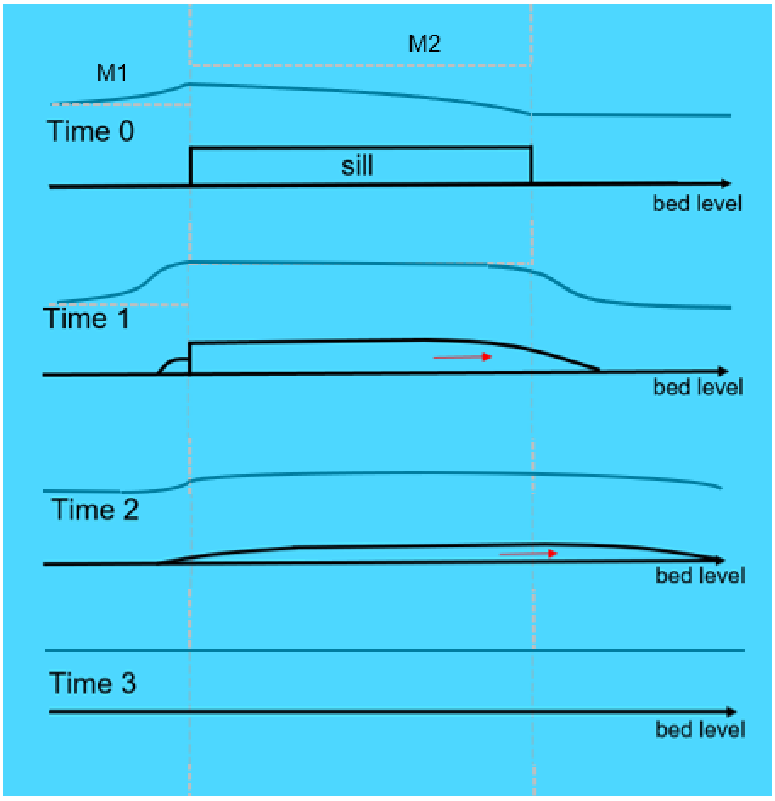

Figure 4.1: Conceptual model of the expected response to the sill-effect. The dark blue line indicates the water level. The transient response to channel narrowing has not been included in these schematics. The water level in these schematics is exaggerated for clarity, emphasizing the effect more prominently than it will appear in actual conditions.

Figure 4.2 shows the numerical model results on the response of the sill-effect and clearly depicts the downstream movement and height reduction of the sill within a few months. The average rate of downstream movement is approximately 3.5 km/y. However, this process is not completely linear since it varies with time. At the beginning the transport rate is the largest. Here the sill itself is not immobile as it has the same grain size as the surrounding bed (10 mm). After the sill has migrated downstream and disappeared the bed continues to erode in response to the channel narrowing. The aggradation that was expected at the upstream end of the sill is non-existent. Right at the upstream end the bottom of the river adjusts itself to the streamline, causing there to be no effect due to the M1 backwater. The upstream backwater effect is negligible here because the sill is only 0.5 m in height and 3 km in length. It can be concluded that the conceptual and numerical models show the same physical mechanisms, and the numerical model enables comparison of the relative effects. The total domain of the model run is 150 km long, so the sill is located directly in the middle of the domain. The red line in Figure 4.3 represents the initial state of the model, which holds for all the following plots of numerical model runs.

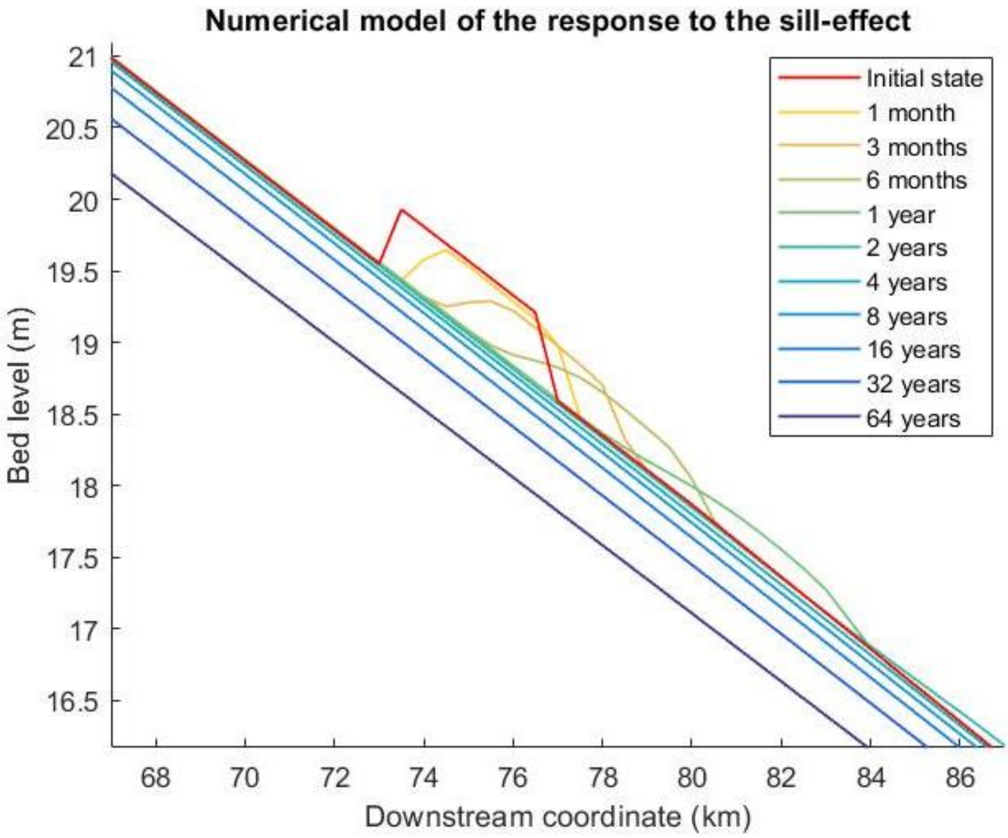

Figure 4.2: Numerical model outcome of the response to the sill-effect.

4.2 Increased roughness

For the second fixed bed related effect, which is the increased roughness, a conceptual and numerical model are also made. Figure 4.3 shows the conceptual model. It can be seen that the upstream aggradation is expected to move upstream and decrease in size. The upstream movement is explained by the fact that the aggradation is trapping sediment due to the M1-backwater curve being present at that location. In Figure 2.2 is can be seen that at the location of the fixed bed there is degradation expected for this effect. Since there is an M2-backwater curve present on top of this location, the velocity and sediment transport increases. This increased sediment transport will induce degradation, which is the largest at the downstream end, so it is expected to start eroding from the downstream end to the upstream end. The downstream hump and upstream pit are caused by the increase in grain roughness. The downstream sediment hump will move downstream like a sill-like obstacle. The erosion pit at the upstream part of the fixed bed location will grow in downstream direction. This is explained by the fact that the whole fixed bed location is subject to degradation according to Figure 2.2. Therefore this erosion pit will grow and cause an erosion pit over the whole length. In the equilibrium state there is only an erosion pit left at the location of the increased roughness. This is because the equilibrium depth is larger when the roughness is larger.

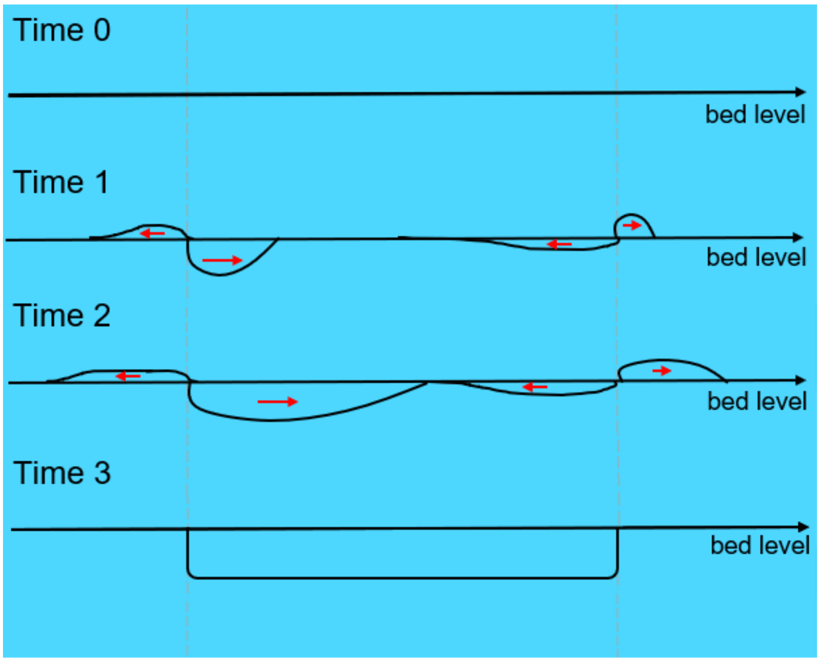

Figure 4.3: Conceptual model of the expected response to the increased roughness.

Figure 4.4 does not clearly show the upstream aggradation that was discussed in the conceptual model. This is because the aggradation is caused by the M1-backwater curve. If this backwater curve is small, which is the case here, then also the aggradation will be small. The erosion pit at the location of the increased roughness is observed very well, caused by the downstream migrating erosion waves. This erosion pit is created in the downstream direction due to the fact that the sediment transport relation also depends on the grain roughness. The Meyer-Peter-Müller relation, which is used here, considers the grainsize when predicting sediment transport. The higher roughness leads to a higher sediment transport rate at the upstream end of the region with increased roughness. This leads to the formation of an erosion pit upstream of this location. Since the erosion of the location propagates from upstream to downstream, it is assumed that the influence of the increase grain roughness dominates the influence of the degradation area at the downstream side. The creation of the erosion pit goes quite gradual during the first year. In the long-term response, after the erosion pit is fully grown in size and the aggradation and hump are vanished, the whole river shows degradation due to the narrowing in the past. Important to note here is that in reality the roughness is only increased on the part of the fixed bed itself, the top layer of the bed, and not on the whole ground layer. This makes the model more inaccurate since the erosion pit would erode all the sediment with an increased roughness and expose the other, smoother, sediment. This is not the case in the SOBEK-RE model.

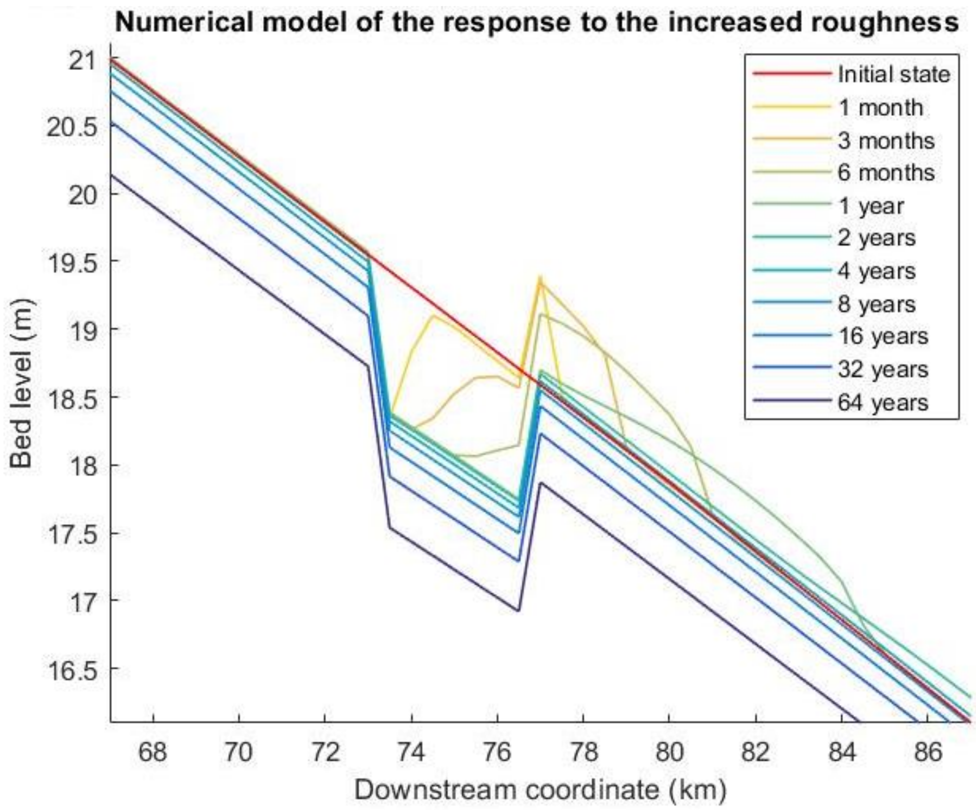

Figure 4.4: Numerical model outcome of the response to the increase roughness effect.

4.3 Decreased mobility

For the last fixed bed related effect, the decreased mobility, a conceptual and numerical model are also made. For creating this effect within SOBEK-RE, the D_{50} grainsize of the sediment at the fixed bed location is set to 250 mm to create an immobile layer. This 250 mm has to do with the fact that the SOBEK-RE model faced issues handling larger sediment sizes. This likely occurred due to the significant difference in grain sizes, leading to potential computational challenges or model instability. The D_{50} grainsize of the surrounding alluvial bed is 10 mm again. A multi-fraction approach is used for this.

The non-erodible layer prevents the underlying layers to be eroded. In Figure 4.5 the conceptual model of the expected response to the decreased mobility is shown without an eroding surrounding bed. The sediment hump formed upstream of the reduced mobility location results from the reduced sediment transport. Due to this sudden transition in sediment transport the change in sediment transport is infinite. This will cause aggradation upstream and degradation downstream of the immobile layer. An increase in skin friction due to the larger grains is not accounted for and the Chézy roughness is unchanged for this model run. The hump is expected to move downstream and disappear like a sill. The downstream erosion pit experiences a reduction in height and is moving downstream just like the hump. In the equilibrium state there is no long term effect as long as the surrounding riverbed is not eroding.

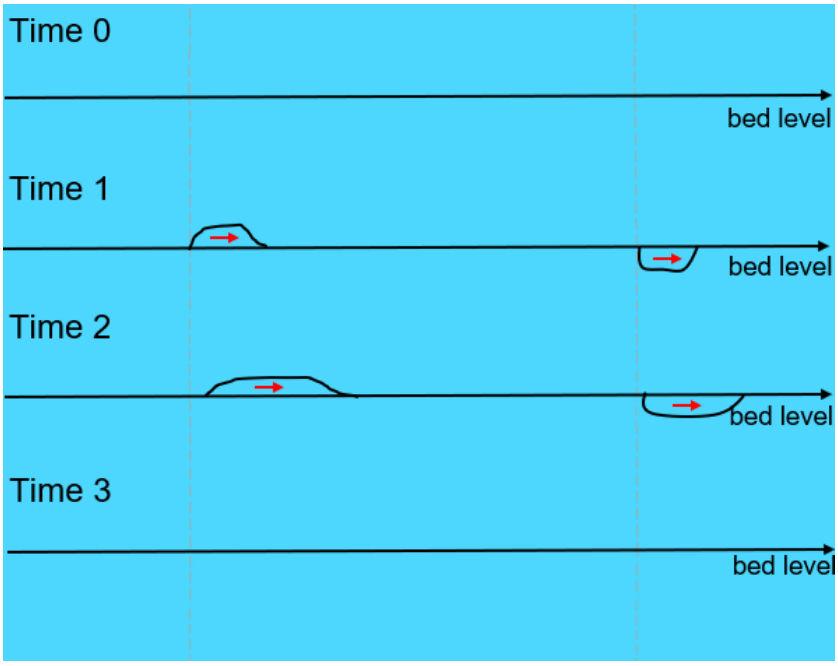

Figure 4.5: Conceptual model of the expected response to the decreased mobility. Without an eroding surrounding bed.

In Figure 4.6 the same response from Figure 4.5 is shown, but now for an eroding surrounding bed. The bed level upstream and downstream of the immobile layer is degrading. At the upstream end there is an M1 backwater that fills up the eroding part again. However, the upstream height of the bed level that is filled up again is dependent on the length of the fixed bed, which determines to which extent the M2 backwater curve reaches its equilibrium water depth. This is the exact same story as for the sill-effect. As the upstream end is getting filled up, the backwater moves upstream, continuing this process until the whole upstream part of the river is back at its original bed level. Downstream of the immobile layer there is degradation due to the narrowing from the past. Assuming that the backwater curve reaches the equilibrium water level this will stabilise in the final state when there is no effect of degradation due to narrowing anymore. If the backwater curve does not reach the equilibrium water level, then upstream the bed level would not be of the same level as the fixed bed location.

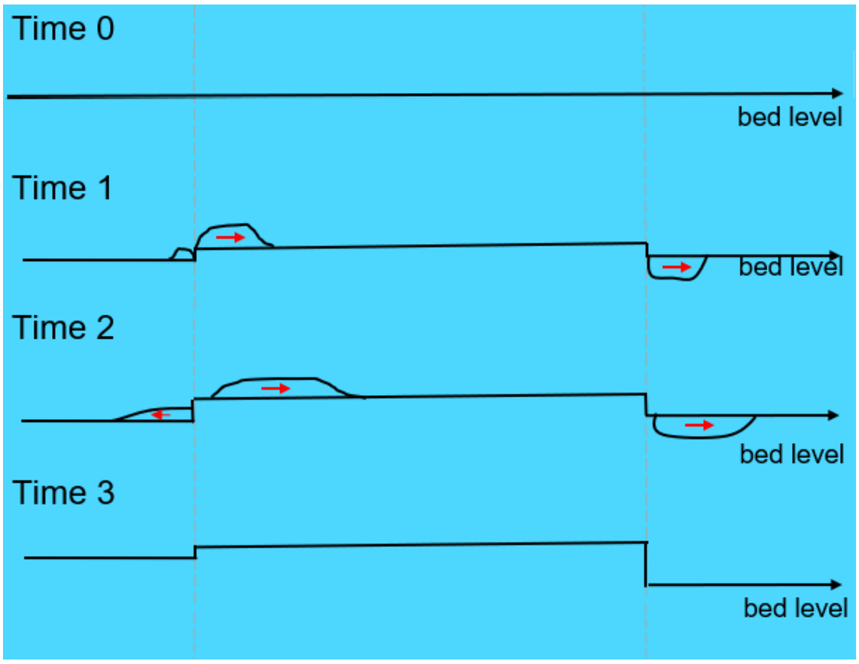

Figure 4.6: Conceptual model of the expected response to the decreased mobility. With an eroding surrounding bed.

In the numerical model, the 'hiding and exposure option' is employed. In this context, 'hiding' denotes the shielding of small sediment particles by a non-erodible, immobile layer, preventing their transport. Figure 4.7 shows the numerical model outcome of the response to the decreased mobility. It can be seen that the coarse fraction is not transported, and only the fine fraction moves. However, due to hiding and exposure, the transport of fine sediment is also reduced on the coarse grains, leading to some of it begin captured by the fixed layer. The layer fills up with fine sediment to the active-layer thickness in the multi-fraction model. It is important to note that this trapping of sediment is artificial and depending on the settings for the active layer thickness and the hiding and exposure settings. Also the grainsizes that are used determine the amount of sediment trapping. This in its turn also determines the downstream erosion, because until the entire immobile layer is covered with fine sediment there will be a shortage of sediment supply downstream of the immobile layer resulting in erosion. The fact that the fixed layer is covered with a layer of fine sediment is a model artifact. Figure 4.5 shows that in the transient response especially in the beginning of the run there is a large erosion pit right downstream of the fixed bed location that is growing in size in the first couple of months. After the immobile layer is completely filled with sediment to create the active layer, the erosion pit is refilled. The pit is therefore replenished as the sediment transport over the immobile layer commences. So in other words the pit gradually diminishes. The downstream erosion that is left is caused by the large-scale degradation due to the narrowing. The 250 mm stones that are used as a fixed layer take up the entire depth of the riverbed. This however is not an issue, as the coarse sediment is fixed and thus it does not matter what is underneath it. In the final response state there is an immobile layer over which finer sediment is aggraded and only the surrounding riverbed is degrading due to the narrowing in the past. Upstream of the immobile layer sediment is being trapped due to the presence of an M1 backwater curve.

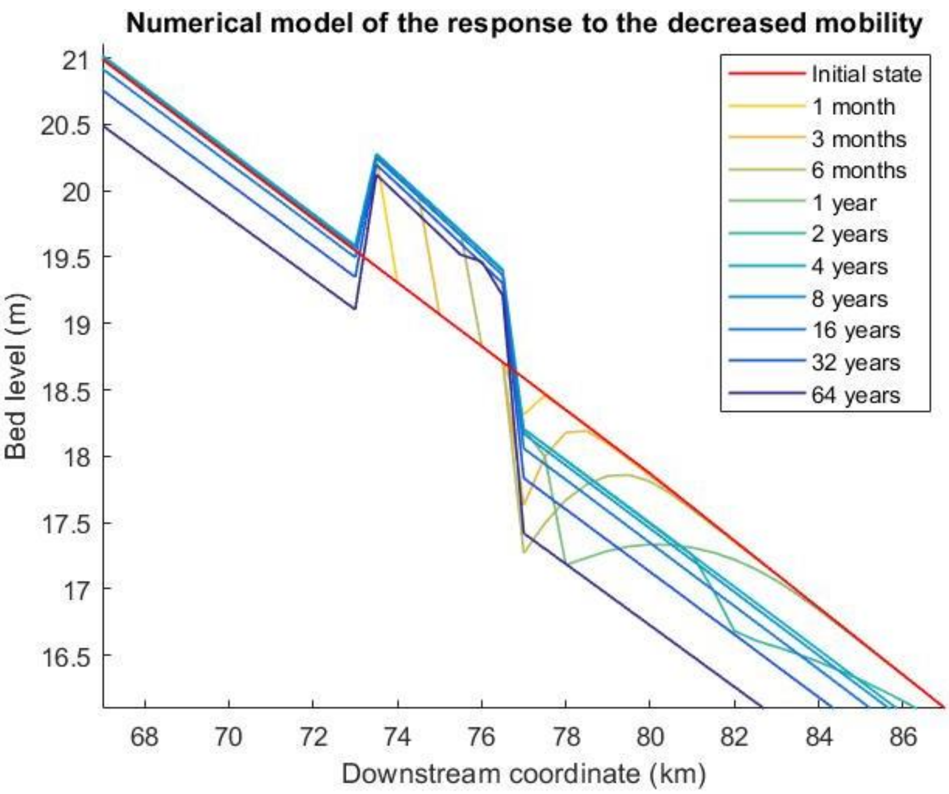

Figure 4.7: Numerical model outcome of the response to the decreased mobility effect.

4.4: Sensitivity analyses of the separate effects

As shown in Table 3.1 before, three different model runs relate to the sill-effect. In each model run only the height of the sill was changed. The three different sill heights are 0.5 m, 1.0 m and 1.5 m. By making these model runs, it can be investigated whether or not the height of the sill has an influence on the speed at which the sill is disappearing. The moment at which the sill is considered to be disappeared is when locally only 5% of its original height remains. In Figure 4.6 it can be seen that an increase in sill height, which means a larger sediment volume, leads to an increase in the time that is needed for the sill to disappear. This relation is not completely linear, but it levels off as sill height increases, meaning that the rate of increase gradually diminishes. This can be explained in a simple way, since Q = u * B * h. So h_{new} = 0.9 * h, then u_{new} = u/0.9. When considering sediment transport, these are typically represented by equations with exponents greater than 3 (for example, n = 5), indicating a non-linear relationship between flow velocity and sediment transport. This explains the results from Figure 4.8.

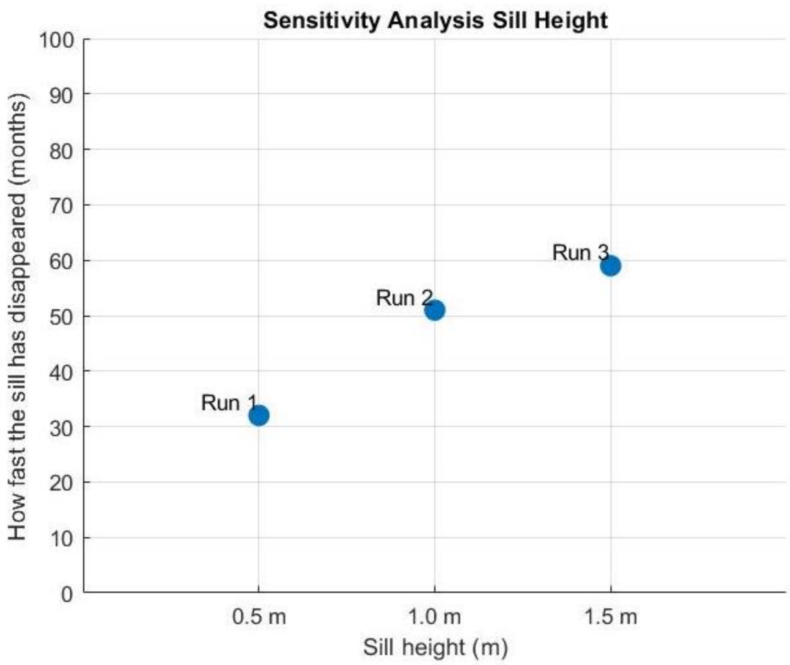

Figure 4.8: Graph showing the relationship between sill height and the rate at which the sill disappears, represented by blue dots.

For the increased roughness effect also three different model runs are made. The values of the Chézy-coefficient are 40, 35 and 30 $\sqrt{m}$/s. It follows that the amount of roughness does not influence the time it takes for the erosion pit to form. The depth of the erosion pit that is formed, however, does depend on the Chézy-coefficient. To explain this, equation 4.1 and 4.2 show the equilibrium water depth d_e and the Chézy value. A smaller Chézy roughness value corresponds to a larger roughness value c_f, which leads to a larger equilibrium depth d_e, and thus a deeper erosion pit. Therefore, while the roughness value does not affect the rate at which the erosion pit forms, it significantly impacts the depth of the erosion pit.

$$d_e = \left(\frac{c_f q^2}{i_b g}\right)^{\frac{1}{3}} \tag{4.1}$$

$$C = \sqrt{\frac{g}{c_f}} \tag{4.2}$$

In Figure 4.9 the relation between the Chézy coefficient and the depth of the erosion pit at the final response state is shown. It can be seen that there is a relation, which is not linear as expected, but slightly parabolic.

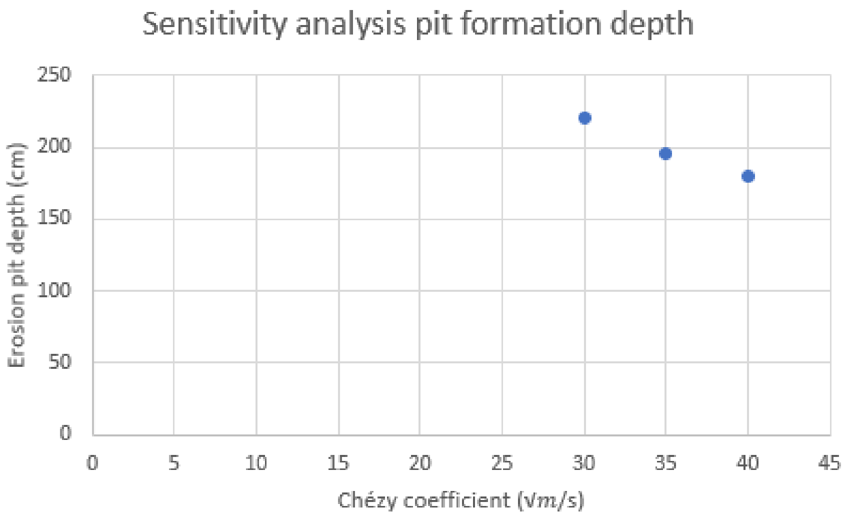

Figure 4.9: Graph showing the relationship between erosion pit depth and the Chézy coefficient, represented by blue dots.

The grainsize related to the decreased mobility only affects the results when the less mobile sediment is mobile (and not immobile). In Figure 4.10 it can be seen that when the grainsize of the immobile layer is 60 mm or larger there is no difference in the time it takes for the erosion pit to form. However, when decreasing the grainsize to a value such that the sediment is less mobile but not immobile this time decreases compared to when the grainsize is 60 mm or larger. Important to note is that also the depth of the erosion pit decreases in this case. When the grainsize is 10 mm, the bed is mobile and there is no formation of an erosion pit.

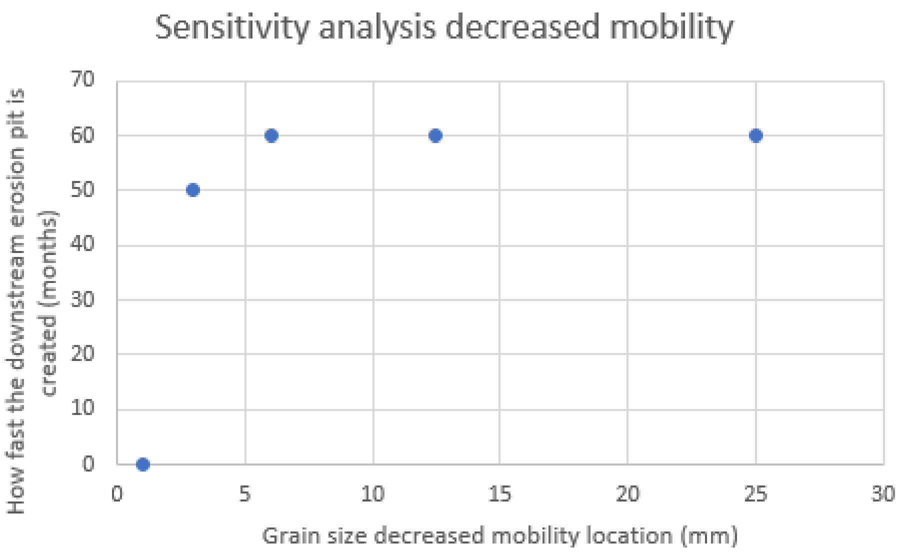

Figure 4.10: Graph showing the sensitivity analysis of grainsize in relation to the time of downstream erosion pit formation for the decreased mobility case, represented by blue dots.

5. Transient and long-term morphodynamic river response of a single fixed bed with combined effects

5.1 Combined effects

As mentioned earlier, here the model combines the three fixed bed related effects. Because a fixed bed can be distinguished in multiple effects, it is difficult to create a conceptual model for it. First the upper part of Figure 5.1 shows a fixed bed which is protruding like a sill, has a higher roughness and is immobile, so it is a combination of the three effects. Due to the sill, there is a mismatch between the water level related to equilibrium flow depths at the downstream end of the fixed bed. The equilibrium water depth of the fixed bed is increased by the height of the sill, illustrated by the two small black arrows in Figure 5.1. This leads to an M2-backwater curve over the sill and an M1-backwater curve upstream of the sill. The length of the sill determines to which extent the M2-backwater curve can reach the higher equilibrium water level as shown by the small red arrow. This, in turn, determines to which extent the M1-backwater curve will aggrade sediment to reach the equilibrium water level upstream of the fixed bed as shown in the lower part of Figure 5.1. Following this, the fixed bed leads to upstream aggradation and moreover, the sill height and length determine to which height this aggradation will take place.

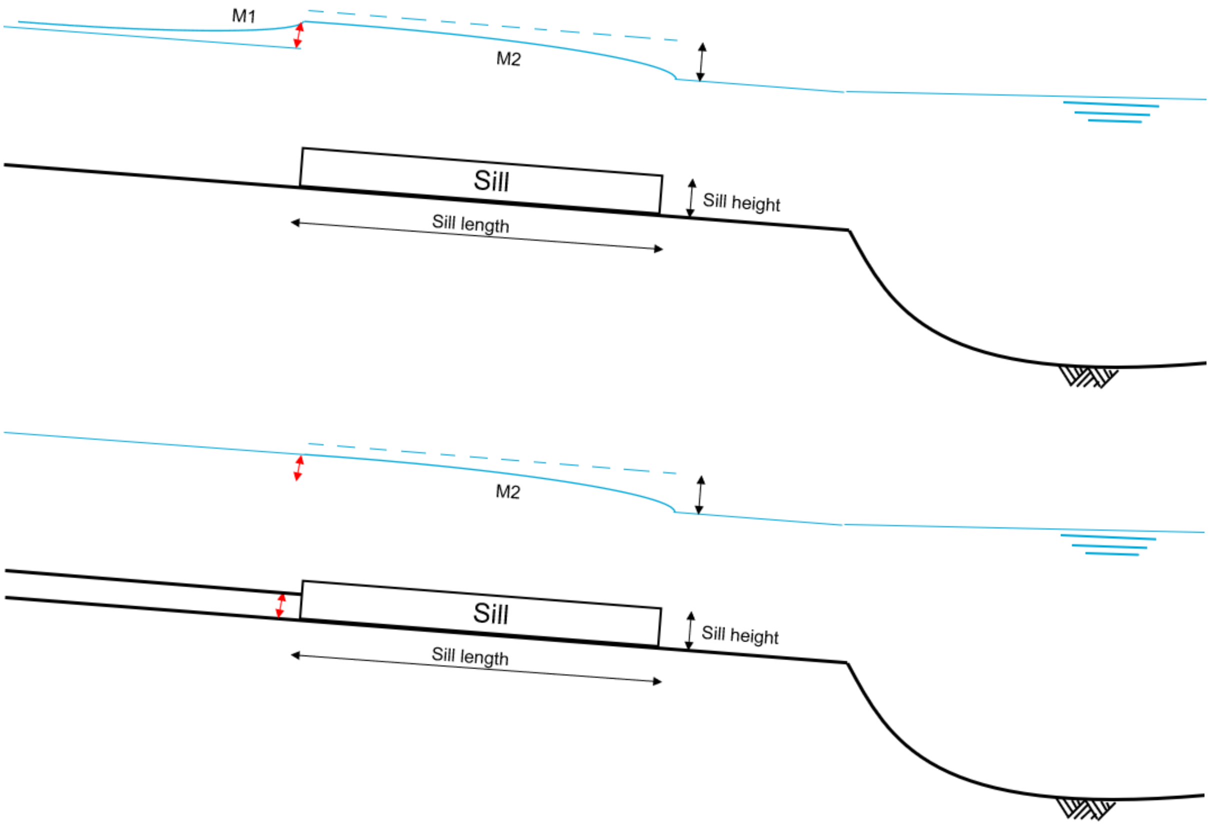

Figure 5.1: Two schematics of a protruding fixed bed including backwater curves, the sill height and the sill length. The upper part shows the initial state of the fixed bed and the lower part shows the equilibrium state of the fixed bed with the upper part filled up with sediment.

The conceptual model for the combination of the fixed bed related effects where the initial, transient and long-term response are drawn, is shown in Figure 5.2. As explained above it is expected that there will be upstream sedimentation. Building on this and the previous findings from the decreased mobility model runs, larger degradation is expected downstream of the fixed bed. It is also expected that there is erosion downstream of the fixed bed, which is the result of large-scale degradation. After this has happened, only the degradation due to the narrowing in the past is left. This degradation will occur all around the fixed bed. In the equilibrium state the M1-backwater curve at the upstream end has disappeared.

The results of the combined numerical model run are shown in Figure 5.3. It shows that on top of the fixed bed there is the formation of an alluvial cover that allows for the sediment supply to be transported downstream. The same was caused at the 3rd effect, where there was the formation of sediment upstream of the immobile layer due to the active layer combined with the hiding and exposure. Downstream the bed level decreases due to degradation. Downstream there is an erosion pit, which decreases in depth, but increases in size and moves downstream.

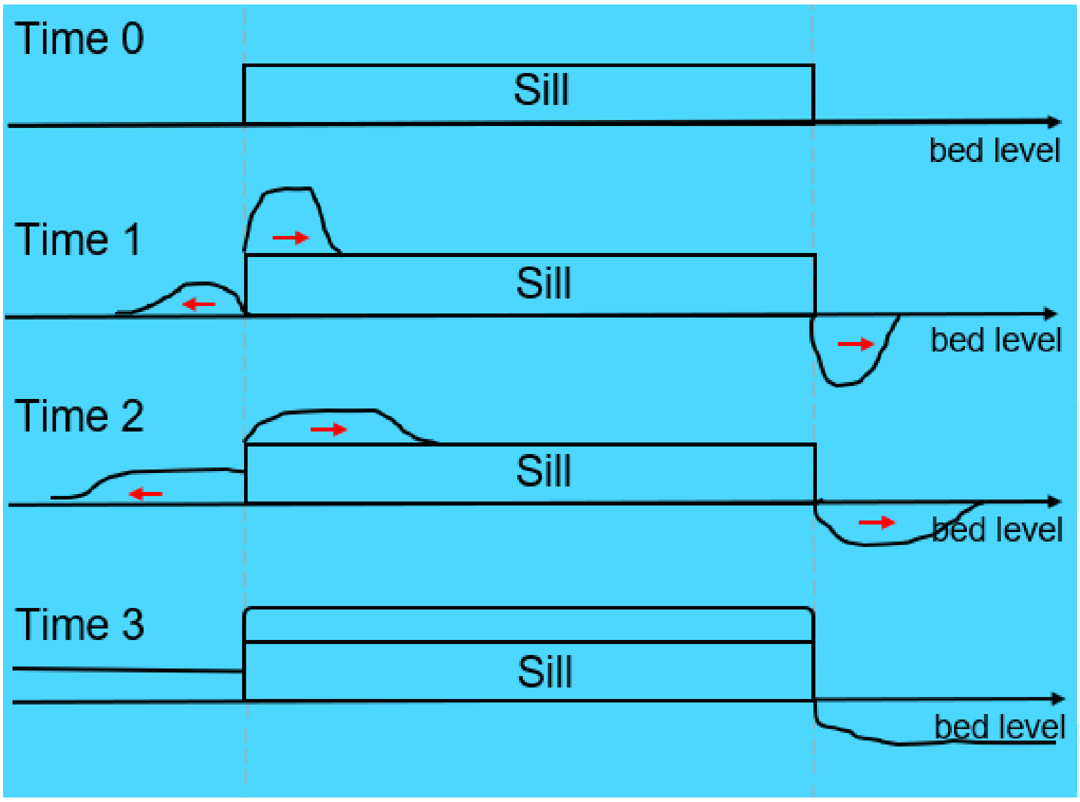

Figure 5.2: Conceptual model of the response to the combined effects.

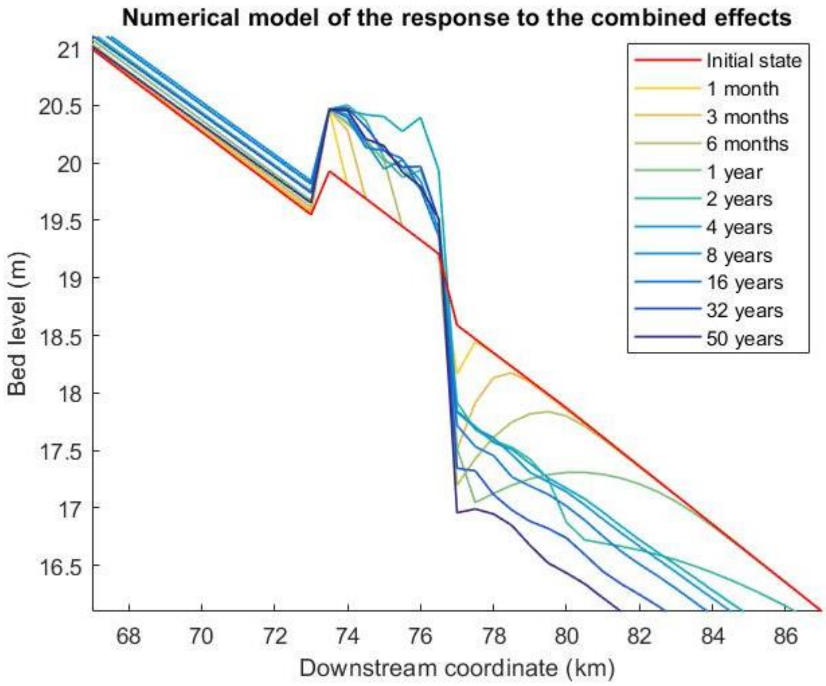

Figure 5.3: Numerical model outcome of the response to the combined effects.

This upstream aggradation is explained by the M1-backwater curve that was just described. This backwater curve decreases the flow velocity, leading to a reduced capacity to transport sediment particles, causing sediment deposition. This is caused by the decreased mobility effect, as the same happened in chapter 4.3 where this specific effect was being looked at. In Figure 5.3, where the long-term is shown, the same effects can be observed.

Wiggles are observed above the fixed bed in this numerical model. These wiggles are caused by the large difference in grainsize in the model, making it hard for the model to execute accurate simulations. For this combined model, the substantial variation in grainsize significantly affects the feasibility of generating reliable model runs. Grainsizes larger than 250 mm would not be able to persist in motion for more than 5 years, leading to errors in the simulation. The expected explanation for this is the large difference with the alluvial riverbed of 10 mm. Also, note that the simulation time of the long-term response is only 50 years. As the sill remains fixed, the M2 backwater curve on top of the fixed bed will be preserved in the equilibrium state. This is also slightly observed in the numerical model runs.

The relatively strong downstream bed level reduction can be attributed to the trapping of sediment upstream of the fixed bed. Due to the formation of alluvial cover and due to the fixed bed itself the flow depth decreases at the fixed bed location, and thus the flow velocities will increase. After surpassing the fixed layer, the water downstream erodes the bed as the velocity increases and its sediment transport capacity is restored. The upstream and downstream bed levels are decreasing because the equilibrium slope decreases, since the river is in a degrading state due to narrowing. The next section addresses the comparison of this slope decrease with reference model 2 and the fixed beds in the Dutch Rhine.

5.2 Comparing the combined effects with the reference model

The bed level slope of the combined numerical run is compared with the bed level slope of reference model 2. This reference model is only affected by narrowing of the main channel, so it is degrading and decreasing its slope. To understand the large-scale morphodynamic effects of a fixed bed, an analysis of large-scale morphodynamics is required.

In Figure 5.4, the numerical model of the response to channel narrowing is shown for reference model 2. It can be observed that the slope decrease, due to only narrowing in the past, is 4% in 50 years. Figure 5.5 shows the same, but now for the numerical run in which the fixed-bed related effects were combined. Here, the downstream part of the river experiences an enhancement of the decrease in slope (7%), and at the upstream part, the decrease in slope is smaller (3%). This difference is significant and can be explained by transport dynamics: less sediment supply downstream of the fixed bed leads to deeper erosion, which means less sediment comes from upstream for a longer time. This explains why the upstream and downstream sections show different rates of slope decrease, as shown in Figure 5.5. Upstream of the fixed bed, the protruding fixed bed traps sediment because of the M1-backwater curve explained before. This causes the degradation of the riverbed upstream of the fixed bed to be smaller than the reference case. As a result, the bed slope decrease upstream is smaller compared to the reference model, and the bed slope decrease downstream is enhanced. Two important parameters are the length of the fixed bed and the height of the protrusion, which determine the amount of aggradation upstream.

This erosion can lead to the loss of land, structures, and vegetation along the banks. Since the downstream decrease in bed slope is enhanced by the fixed bed, the fixed bed itself can also be at risk. The fixed bed can become unstable and fall into an erosion pit. For navigation purposes, the river may become more challenging to navigate if the width of the river is decreased.

In reality, the slope of the Rhine River in the Netherlands, where the fixed beds are located, has also been decreasing over the past century, as seen in Figure 5.6 (Ylla Arbós et al., 2021). The cause for this is human interventions, as described in chapter 1. Since the end of the last century, the riverbed is degrading at a much slower rate in the Dutch Rhine, see Figure 6.3 and Figure 6.5. It is difficult to assess whether there is a distinct and immediate change in channel slope that can be associated directly with the specific fixed beds, as rivers in reality are not made up of a single grainsize. Rivers also consist of bedrock reaches, branches, vary in width, and they do not have a single grainsize. In the Netherlands, the fixed bed effects are not yet fully present, so they cannot manifest to their full extent. Therefore, the large-scale effects are not yet fully present.

Ylla Arbós et al. (2021) found out that in Germany the Rhine is increasing in channel slope, even though there has been channel narrowing going on in the past, which would lead to a lower channel slope. It is expected that this slope increase is caused by the presence of bedrock in this upstream part of the domain. The bedrock parts prevent the riverbed from incising, causing the formation of an M2-backwater curve to form over these reaches. Because of the backwater curve, the flow decelerates, and the sediment mobility decreases. To compensate for this reduction in sediment mobility, the part of the river upstream of this bedrock reach starts to increase its slope. This feature is also happening in this research, as the decreased mobility effect prevents sediment from being transported. As the upstream reach of the fixed bed is slowing down its decrease in channel slope, this may be the same kind of compensation for the lack of sediment mobility downstream.

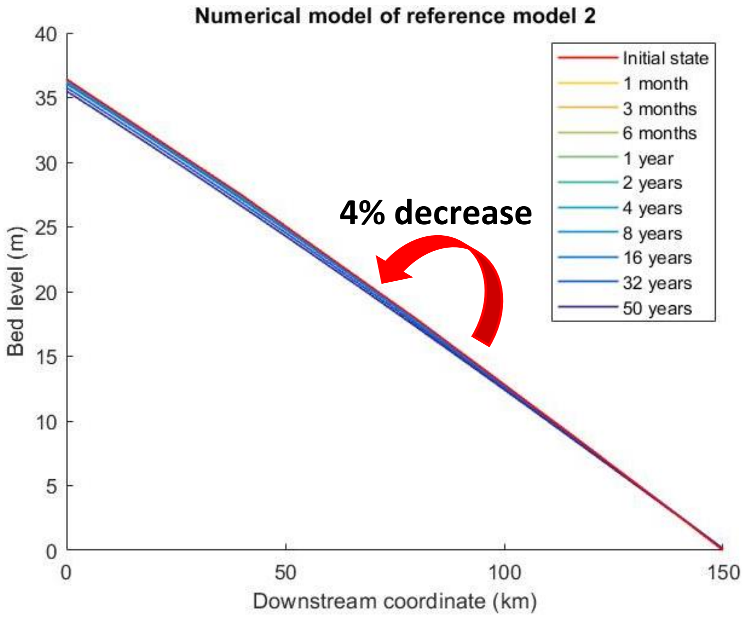

Figure 5.4: Numerical model of the response to only incision on the bed level slope, reference model 2.

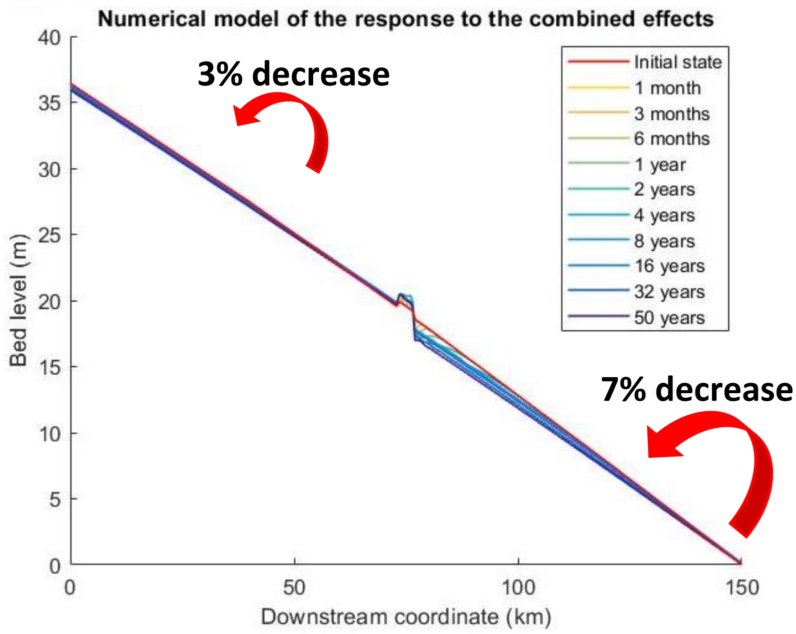

Figure 5.5: Numerical model of the response to the combined effects on the bed level slope.

Finally, the bed levels are analysed. In this analysis, the bed levels of reference model 2 are compared with those of the combined numerical run. Therefore, the bed levels at the upstream part of the domain and the bed levels at the downstream part of the domain are compared with each other. In Figure 5.6 it is seen that the decrease in bed level is 93 cm in 50 years upstream and at the downstream end the bed level increases by 9 cm. This has to do with the transient state due to narrowing where the river is in; the slope is decreasing, and the river is degrading. In Figure 5.7 different results are visible. At the most upstream end there is a 50 cm decrease compared to the reference case and at the most downstream end there is an increase in bed level of only 2 cm. This means that the fixed bed has a positive effect on the degrading riverbed as it slows down the degradation of the riverbed upstream of the fixed bed. The numerical model however starts from the initial state, meaning that there are relatively large changes in the model results compared to the initial state (red line in Figure 5.6 and 5.7). The reduced of the degradation is expected to come from the protruding sill that is trapping sediment upstream of it. It is an important finding that the fixed bed is reducing the degradation of the bed level upstream. The consequence of this could be that after a long time the degradation of the bed level is stopped. Due to the presence of a fixed bed, the slope reduction is smaller, preventing larger slope changes.

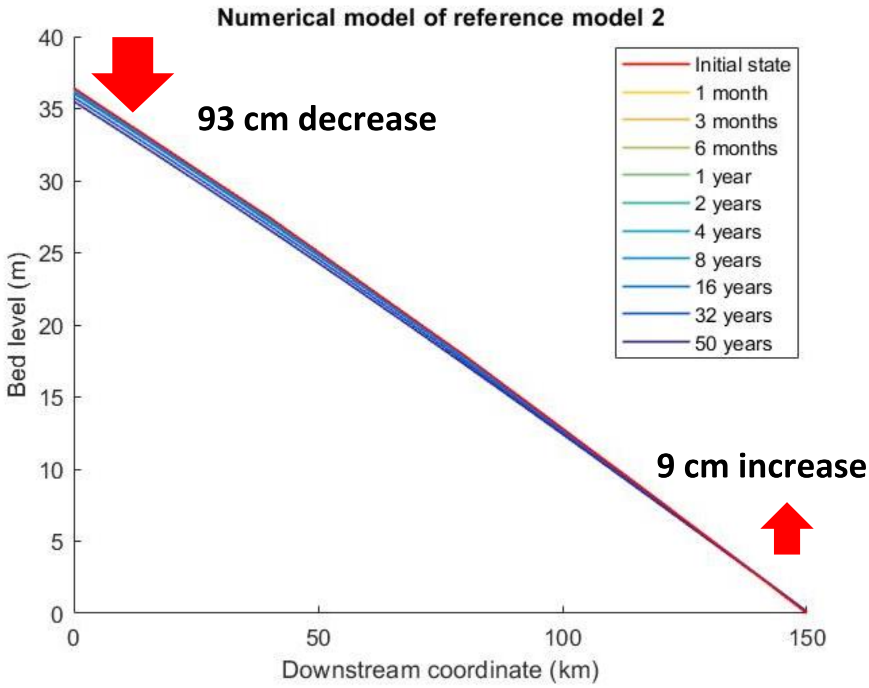

Figure 5.6: Numerical model of the response to only incision on the bed level, reference model 2.

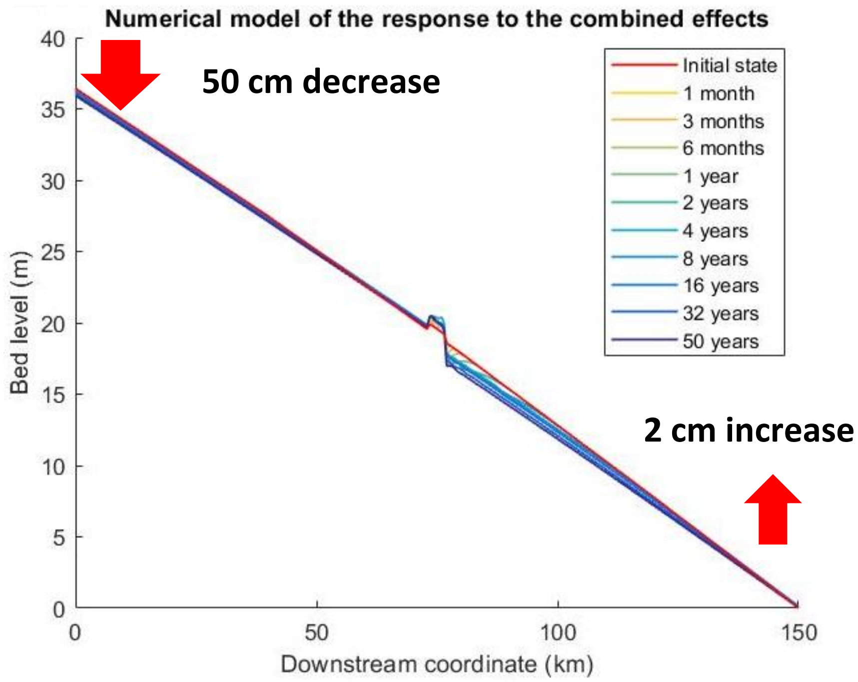

Figure 5.7: Numerical model of the response to the combined effects on the bed level.

6. Numerical comparison with field data and 2D analysis

6.1 Analysis of the spiral flow in a river bend

SOBEK-RE simplifies and simulates complex flow patterns and other water-related processes in a 1D framework. Therefore, the focus is on observing the streamwise waterflow. The variations across the width of the river are neglected. The model assumes a uniform flow depth and width throughout the whole domain. Nevertheless, 3D effects also play a role in the case of Dutch fixed beds.

In the bend of a river, the velocities of the water flow are not uniform. They vary across the width and depth of the river. As a result, centrifugal forces, which push outward from the centre of rotation, are distributed unevenly over the vertical extent of the water column. This variation in centrifugal forces contributes to the complex flow patterns observed in river bends. Due to these centrifugal forces, the water level in the outer bend becomes higher than in the inner bend. This is shown in Figure 6.1. This discrepancy creates a pressure gradient that increases with the curvature of the water's path, directing from the outer to the inner bend. At the edges of the full body of water in the river bend there is a balance of forces, but inside the waterbody there is an imbalance, as shown in Figure 6.2. The direction of this secondary flow at the water level is towards the outer bend and at the bottom it is directed towards the inner bend. This causes the sediment to be transported to the inner bend. This process stops as soon as there is a balance between the gravitational effect counteracting the effect of the helical flow on the bed (Mosselman, 2020).

The imbalance of forces results in a helical motion, known as a secondary flow, which, together with the primary flow, forms a spiral motion, see Figure 6.2.

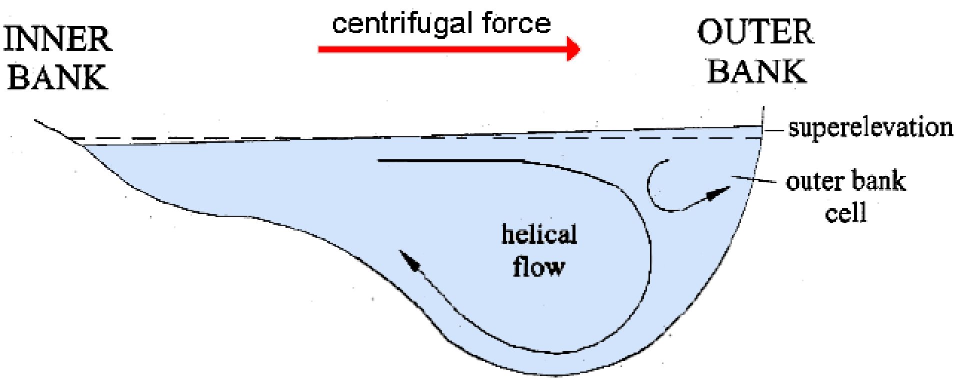

Figure 6.1: Helical flow in the bend of a river. The centrifugal forces are balanced by the pressure gradient (S. Kashyap, 2010).

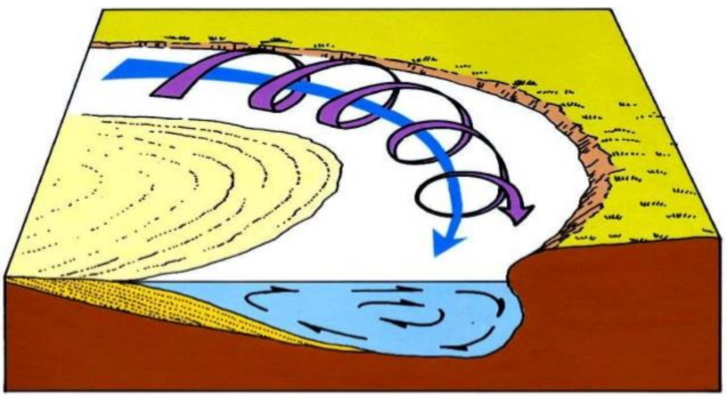

Figure 6.2: Spiral flow of motion river bend (Akolb, 2019).

Since the outer bend is much deeper than the inner bend, the navigable width in the river bend is typically limited. A fixed bed changes the secondary flow pattern, which results in a deepening of the inner bend. Thus, the fixed beds in the Dutch Rhine River utilize the spiral water motion in the river bends.

6.2 Reflection and numerical comparison to measured data

When a fixed bed is protruding, an M1 backwater effect traps sediment, potentially decreasing or even omitting the protrusion at the upstream end of the fixed bed. However, this is depending on whether the water depth can reach the equilibrium water depth. Therefore, it is not guaranteed that a fixed bed will protrude from the riverbed, as this effect relies on reaching equilibrium conditions, which are based on the length and the height of the fixed bed. This holds for the fixed beds in the Dutch Rhine. As a protruding fixed bed also traps sediment upstream, there will be no or small signs of protrusion, as it is being filled up depending on the conditions. In Nijmegen, the protrusion is confined to a relatively short length scale, so only close to the fixed bed it is protruding. At the upstream end there is a small erosion pit of 1 m depth and 500 m in length. At the downstream end there is a pit of about 3.5 m. At St. Andries, no protrusion is observed (White & Blom, 2020).

In Figure 1.6 it can be seen that at Nijmegen upstream of the fixed bed sediment trapping has occurred, likely as a result of a backwater. When a river is not in an equilibrium state yet such as the Rhine River, which has been narrowed in the past, the bed of the river can be degrading. This leads to the degradation of the bed around the fixed bed, causing the fixed bed itself to gradually protrude over time due to its non-erodibility, which can again be eliminated depending on the length and height of the fixed bed. Because the fixed bed at Nijmegen and St. Andries is constructed over a limited width, erosion can occur in the inner bend.

In their field data study, White & Blom (2020) showed that there is a reduction of the alluvial cover on the fixed bed with time at St. Andries. Aggradation is observed both in Nijmegen and at St. Andries at the upstream end of the fixed bed. Both the sill-effect and the increased roughness account for upstream aggradation. The decreased mobility causes a sediment hump on top of the upstream part of the fixed bed. It is expected that the combined effects together contribute to this upstream aggradation. In Nijmegen, there are regions of both erosion and accretion. The edges of the fixed bed are highly eroded, and the ridge is an area of accretion (White & Blom, 2020). However, especially at St. Andries it looks like there is a sediment hump. In Figure 6.3 the bed level change over time for St. Andries is shown. For this a reference level originating from datasets from 1998 and 1999 and measured bed level from 2017 is used (White & Blom, 2020). Since the reference level was already 40 cm higher in the middle third of the fixed bed, the erosion shown in Figure 6.3 is expected to be alluvial sedimentation instead of the fixed bed itself that is eroding. The aggradation shown here is in some regions nearly 60 cm high, but it varies over time. Alluvial dunes are present at the upstream end, with a height of approximately 40 cm. This local sediment accumulation aligns with the expected outcome of the conceptual model.

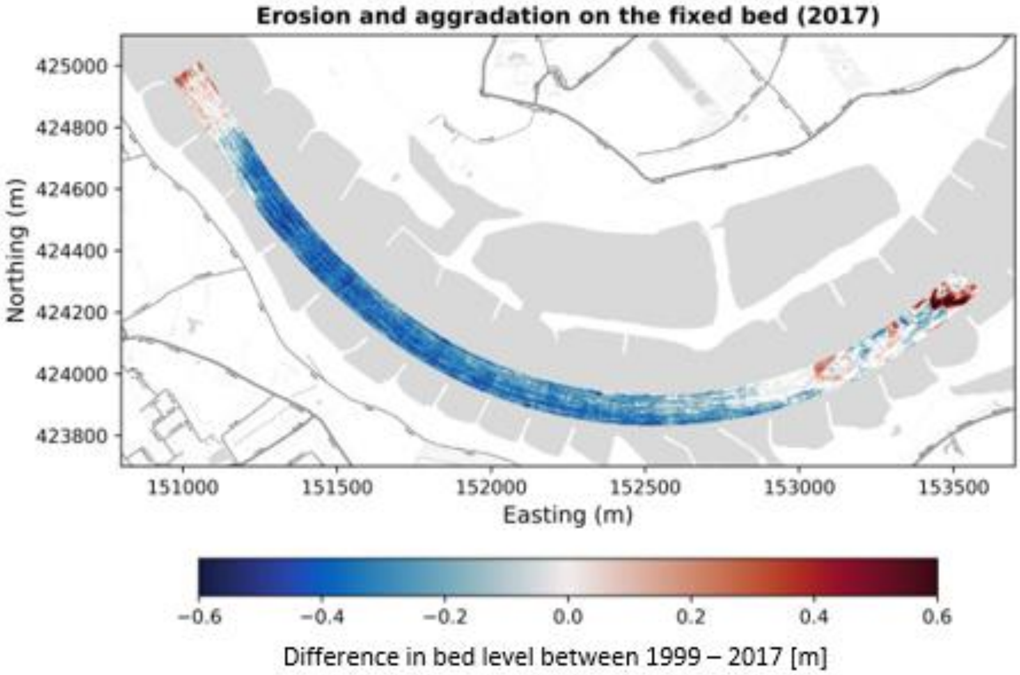

Figure 6.3: Alluvial cover at St. Andries between 1999 and 2017 (White & Blom, 2020). Blue is erosion and red is aggradation. The coloured part (blue and red) is where the fixed bed is located, which is in the outer bend.

In addition to the upstream aggradation, downstream degradation is significantly more prominent in practice. In Nijmegen, a substantial erosion pit is located just downstream of the fixed bed, which is expanding in size and propagating downstream over time, as shown in Figure 6.4. This figure shows the bed level downstream of the fixed bed in Nijmegen of the last 26 years. The pit is roughly 1.2 km in length and reaches a depth of about 3.5 m at its deepest point (White & Blom, 2020). White & Blom (2020) also investigated the rate of incision over time of the downstream erosion pit. Their results are shown in Figure 6.5. It followed that the pit has grown at two incision rates. The first twenty years it was growing at about -8.6 cm/year and from 2003 it was growing at about -2.8 cm/year, meaning that the incision rate slows down over time. Similarly, an erosion pit is observed at St. Andries, measuring approximately 300 m in length and around 7 m in depth. This erosion pit is rapidly growing in size and is also very steep.

This can cause problems with the stability of the fixed bed if it keeps increasing in depth. The erosion pit of St. Andries is shown in Figure 6.6. Also, for this pit, White & Blom calculated the rates of incision over time, which are -63.9 cm/year till 2003 and -13.5 cm/year from 2003-2018. These downstream erosion pits are not solely caused by decreased mobility. Rather, they are influenced by the transition from immobile to mobile sediment, coupled with the effect of the river bend dynamics. In particular, the asymmetry of the 2D sediment transport, where sediment hardly reaches the fixed bed through the outer bend but flows predominantly through the inner bend (resulting in a buildup of sediment), plays a significant role. This asymmetry also leads to accretion adjacent to the erosion pit. Here, the velocity of the water flow decreases rapidly due to the absence of the pit, but a substantial amount of sediment is transported. Such complex interactions highlight the diverse nature of sediment dynamics in river bends. The abrupt transition of the erosion pits around 2003 suggests a potential modification to the river system. It is expected that this modification has to do with a transition in the dredging processes in the Dutch Rhine around 2003. Another option would be the construction of a new hard structure downstream, altering the flow dynamics and subsequently decelerating the growth of the erosion pit.

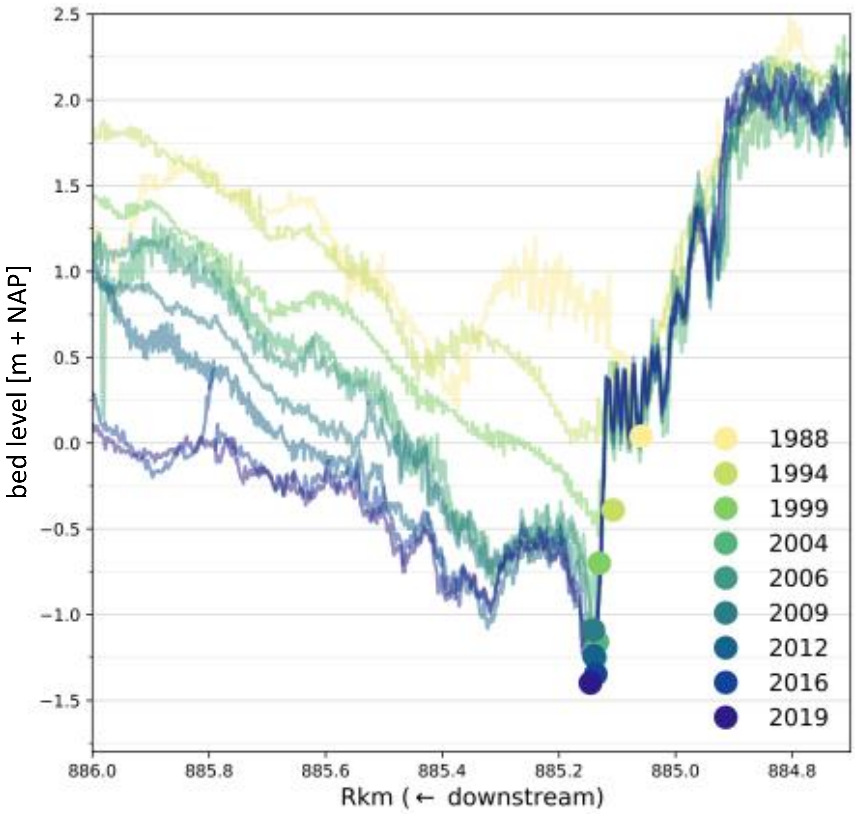

Figure 6.4: Bed level downstream of the Nijmegen fixed bed for different moments in time, showing the erosion pit growing in size. The deepest point is marked with a circle (White & Blom, 2020).

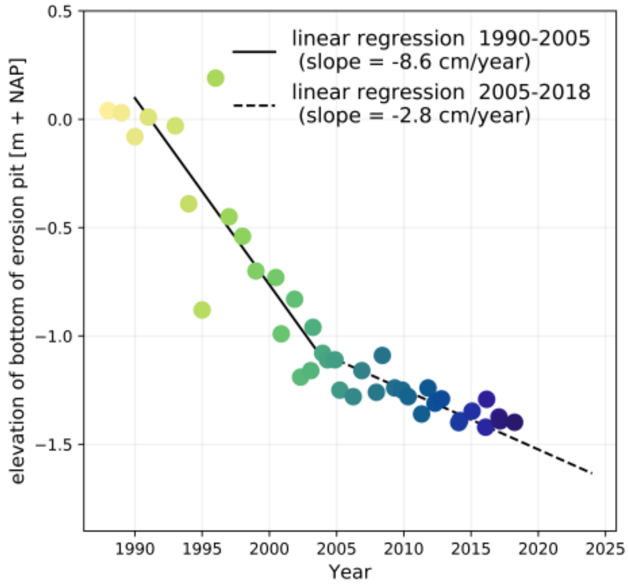

Figure 6.5: Rate of incision over time for the erosion pit downstream of the fixed bed at Nijmegen (White & Blom, 2020).

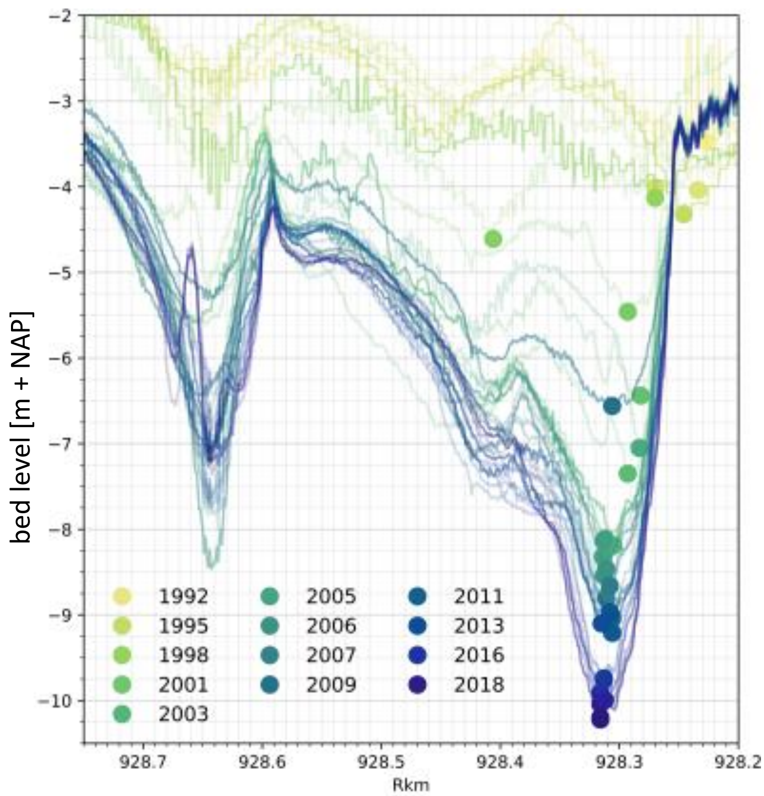

Figure 6.6: Bed level downstream of the St. Andries fixed bed for different moments in time, showing the erosion pit growing in size. The deepest point is marked with a circle (White & Blom, 2020).

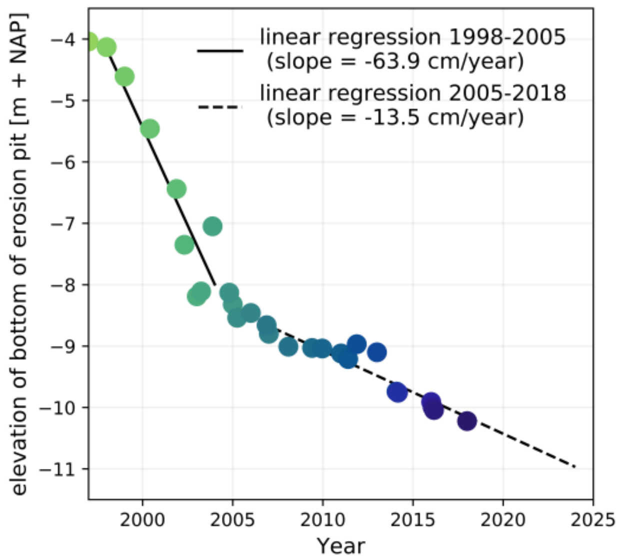

Figure 6.7: Rate of incision over time for the erosion pit downstream of the fixed bed at St. Andries (White & Blom, 2020).

In reality for both fixed beds there is an erosion pit, which is already described in chapter 2. In contrast, the numerical erosion pits measure approximately 2 meters in size, whereas the pit at St. Andries reaches a depth of about 7 meters, and in Nijmegen, it descends to roughly 3.5 meters below the surrounding riverbed. The rate of growth for the erosion pit has diminished over time (White & Blom, 2020). The erosion pits are expected to be 2D effects. If it would be a 1D effect, you would expect the erosion to end. If it's a fixed layer across the entire width, at some point all the sand coming from upstream will flow over the fixed layer, otherwise it would accumulate upstream. When sand is transported over the fixed layer it would fill up. In an equilibrium situation, the sediment transport rate would be uniform everywhere along the riverbed.

7. Discussion

In this chapter, the focus is on the model conditions, limitations, uncertainties, reflections on the findings, and the consequences of the limitations and uncertainties.

The models employed in this study have several limitations. For example, the SOBEK-RE model is one-dimensional (1D), meaning it does not account for the two- and three-dimensional aspects that significantly influence fixed beds. Additionally, SOBEK-RE does not allow for the modelling of fixed beds that occupy only part of the river width. In reality, Dutch fixed beds only cover a portion of the width in the river bend, specifically the outer bend. Since the 1D model assumes uniformity of the river width, this effect is not considered. Although disregarding 2D effects compromises reliability, the model outcomes remain valuable. Long-profiles, essentially examining 1D physics, are analyzed, making the 1D model suitable for this examination. Moreover, many hydraulics and morphodynamics surrounding fixed beds are included and not dismissed. However, the spiral flow is excluded. While erosion pits may result from 2D effects, they are also identified using 1D simplifications. Nevertheless, spiral motion cannot be accurately modeled using a 1D approach. These assumptions affect the accuracy and representativeness of this model. Nonetheless, despite these limitations, this 1D model is expected to yield useful information about the fixed beds.

In the case of decreased mobility, incorporating multisize sediment in the model introduces wiggles in the results. Attempting to eliminate these wiggles poses challenges. The issues are rooted in the large variation in grainsize, making it challenging for the model to manage hiding and exposure dynamics effectively.

The steady flow assumption is also made, meaning that the flow of water is assumed to be steady with a constant discharge over time. The variability of the flow rate (i.e., the flow duration curve) is neglected in this research. In reality natural water systems exhibit significant fluctuations in discharge due to seasonal variations, precipitation patterns, and other factors. Therefore, the simplification of assuming steady flow may overlook important dynamic interactions and temporal changes in sediment transport and channel morphology.

Next to limitations, the choices made in this study also introduce various uncertainties. The decision to decompose the effects of the fixed bed into individual components is sound, enabling a more detailed analysis of the significant effects in specific responses and their relative importance. The initial conditions are partly based on real-world values but have not been precisely replicated. Factors like discharge, slope, and water level include realistic values. However, discharge in the real world shows substantial variability, significantly affecting the morphodynamics. Furthermore, the width of a river in reality is far from constant, leading to varying degrees of narrowing along different sections.

Assuming some degree of reliability in the model outcomes, it is important to recognize that significant fixed beds lead to an increase in downstream slope decrease and a reduction in upstream slope decrease.

In practice, some of the observed effects, which are the sedimentation upstream of the fixed bed and the slope change upstream and downstream of the fixed bed, are visible. The reduction in slope of the lower Rhine River has been quantified in reality. The fixed bed in Nijmegen protrudes quite a lot, but the fact that the M1 backwater causes the degrading upstream riverbed to fill up again, makes it hard to observe the actual sedimentation upstream.

Moreover, actual rivers are not uniform and one-dimensional systems, in contrast to the model. Real-world rivers feature bends, variable bottom materials, fluctuating discharges, and significantly greater lengths. Water management authorities need to understand that fixed structures in the riverbed can be especially important in the future. In the future it is important to know that implementing a fixed bed does not only fulfil its need, which is widening the width of the river, but that it can also cause the upstream and downstream slope to adjust and that there can be upstream sedimentation if the fixed bed is protruding. Especially in highly engineered rivers, putting in a fixed bed can cause substantial changes to the way the bed level and bed slope look and work over a long time. Therefore, it is really important to keep maintaining and measuring the height of the riverbed to manage these changes well and in time.

8. Conclusion and Recommendations

In this chapter the sub- and research questions will be answered. In addition to this to that there will be recommendations.

8.1 Conclusion

Sub-question 1 - *What is the initial morphodynamic response to the construction of a single fixed bed?*

To answer this question, it is important to distinguish between the separate effects that play a role with fixed beds. These are the sill-effect, increased roughness and decreased mobility. All three effects show different behaviours, due to which the total initial response depends on the relative contribution of the effects. For the sill-effect and the increased roughness upstream aggradation is expected due to an M1-backwater curve. The expected degradation on the location of the fixed bed cannot occur, due to the immobility of the layer. The sill results in a downstream sediment hump, while the decreased mobility effect produces the exact reversed effect. The total morphodynamic response of a single fixed bed does not result from a simple summation of the individual effects, as they also interact with each other. As in reality there is a lot of erosion going on downstream of the fixed bed, the decreased mobility is assumed to be the strongest of the three effects.

Sub-question 2 - *What is the large-scale transient and long-term morphodynamic response to the construction of a single fixed bed in terms of bed level change and bed slope?*

Also, for this sub-question the fixed bed-related effects are treated separately. For the sill-effect the sill is eroding and propagating downstream. This means that erosion takes place on top of the sill. On the long-term this sill has disappeared completely. For the increased roughness effect there is degradation going on at the location of the fixed bed. In the long-term there is just the trench. The alluvial surrounding riverbed is not influenced by this effect and by the sill-effect. The third effect, related to decreased mobility, results in aggradation on top of the fixed bed location due to non-erodibility. Downstream of the fixed bed location, erosion takes place, caused by the increase in sediment transport capacity. When combining the three effects and looking at the transient and long-term response, some things stand out. The three effects all have a meaningful contribution to the combined morphodynamic effect. The decrease in bed level, due to narrowing in the past, is slowed down by the fixed bed. Another important finding is that the decrease in bed slope, also due to narrowing in the past, is enhanced downstream of the fixed bed and is decreased at the upstream end. The fixed bed serves as an intermediate barrier in the change of the rivers' bed slope.

Research question - What are the large-scale morphodynamic effects of fixed beds?

The effect of a fixed bed can be separated between the sill-effect, increased roughness and decreased mobility. They all have a significant contribution to the morphodynamics of a fixed bed. When these effects are combined and their transient and long-term responses are examined, it becomes clear that the fixed bed plays a crucial role in altering the riverbed slope by acting as an intermediate barrier. The downstream slope reduction is enhanced by the fixed bed and the upstream slope reduction is reduced by the fixed bed. This barrier also causes the upstream degradation of the bed level to decrease. The fixed bed also traps sediment at the upstream end, caused by an M1-backwater curve at this location. The height and length of the sill are two important parameters. They determine whether the M2 backwater curve reaches its equilibrium depth upstream of the fixed bed. This, in turn, dictates whether the bed level upstream of the fixed bed will completely fill up with sediment due to its M1 backwater curve or not.

8.2 Recommendations

The following recommendations are offered as a guidance for future research on fixed beds.

- Expansion of the model: Consider the expansion of the model to explore a theoretical river with multisize sediment grains rather than unisize sediment. Also, variations in discharge from constant flow to bimodal discharge can be used to expand this model. Having multisize sediment and a bimodal flow will give a more realistic result.

- Multiple fixed beds within a single river: Examining a sequence of multiple fixed beds within a river provides insights into the interconnected response among these fixed beds. Since a fixed bed can significantly influence the upstream and downstream slopes, these effects may either synergize or counteract each other.

- Extended sensitivity analysis: An analysis of the impact of the sill height and the sill length. These two parameters determine to which height there will be upstream aggradation when having a fixed bed. Other parameters that can be involved are adjustments in surface roughness for the fixed bed, the use of different sediment grainsizes for the fixed bed, and the research to the effects of multiple fixed beds within a river system instead of only one.

- Utilizing more complex numerical models: While this research focuses on modelling fixed beds using a 1D model, SOBEK-RE, fixed beds typically exist in river bends where 2D or 3D effects play a role. Therefore, using a 2D or even a 3D model may provide a more accurate simulation. This allows for a more in-depth exploration of numerous factors, including specific local effects observed in the Rhine, as 2D or 3D models generally better approximate the real world.

- Laboratory-scale physical modelling: Conducting laboratory-scale physical modelling to gain insights into the large-scale morphodynamic effects of fixed beds. A physical model in a laboratory could provide valuable data for validating and enhancing the results obtained from a numerical model.

- Smaller active layer and representative grainsizes: Considering reducing the active layer to better match real-world conditions, and using smaller grainsizes that are more representative of those found in natural river systems can enhance model accuracy and realism.

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Appendix A: Overview of numerical parameters

	Numerical parameter	Value
Water flow	G (m/s^2)	9.81
	Theta (-)	0.75
	Psi (-)	0.5
	ρ fresh water (kg/m^3)	1,000
	Calculation	Steady
	Max. iterations	300
Sediment	Kinematic viscosity (m^2/s)	$1 * 10^{-6}$
	Relative density	1,65
	Packing factor (-)	0.3
Morphology	Maximum number of time step reductions	10
	Stability factor	1.01