MASTER THESIS

TWO-DIMENSIONAL MORPHOLOGICAL MODELLING OF THE EFFECTS OF THE ROOM FOR LIVING RIVERS VISION IN THE MIDDLE-WAAL

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Abstract

Ongoing bed degradation in the River Waal, partly induced by a long period of human intervening in the river Rhine, is leading negative impacts on different river functions. To mitigate these impacts, nature organisations in the Netherlands have come up with Room for Living Rivers (RfLR): a vision which balances ecology, flood protection and shipping interests. In this research, the ability of RfLR on mitigating the ongoing erosion in the Middle-Waal is investigated in 2D using the DVR model. This model, based on the Delft3D computational core, is capable of long-term, large scale morphological modelling using a series of steady-state flow conditions based on a representative hydrograph. By analyzing the difference in bed development in two scenarios, morphological changes induced by a combination of side side channels, large scale lowering of floodplains and removal of obstructions can be isolated. It is found that without intervening in the river, the river Waal does not reach a (dynamic) equilibrium within fifty years. The interventions are thus not able to stop this ongoing erosion; however, they show abilities to reduce the erosion rate locally and close to their location. The 2D model also shows large variability in the bed response in transverse direction. Depending on the connection of the side channel to main channel, two-dimensional processes, such as secondary flow may be enhanced, leading to decreased reduction of the ongoing erosion.

Contents

1 Introduction

The bed level in the upper reaches of the river Waal is subject to erosion with a rate of 2 cm/year (Kleinhans et al., 2013; Blom, 2016). Past studies have shown that this erosive trend will continue in the future, leading to a bed level decrease of up to 2 meters at the end of this century (Spruyt et al., 2020; Barneveld et al., 2019). This erosion has multiple origins, which almost all can be attributed to a higher sediment transport capacity than the current sediment supply. Part of this sediment deficit is due to the river Rhine not having reached its equilibrium configuration (Frings et al., 2019). One of the causes for this, is that the river Rhine has been heavily trained over the last 200 years, hindering reaching its equilibrium state (Sieben, 2009). These training works have been carried out to enhance water discharge and navigability. Although the degradation is beneficial for the first (as water levels reduce almost equally to the bed elevation decrease (Blom, 2016)), the training works now tend to have the opposite effect for the latter: parts of the river bed might not be able to lower due to the bedrock, leading to local shallows in the main channel. This is problematic to shipping of goods, as the shallows lead to a lower possible draught for ships (Gölz, 1994; Spreafico and Lehman, 2009; Blom, 2016; Berkhof et al., 2018; Streng et al., 2020). A the same time, the degradation of the bed leads to instability of groynes and lowering of the groundwater level in the vicinity of the river (Spreafico and Lehman, 2009).

Mitigating erosion

To mitigate this erosion, Rijkwaterstaat has stopped extracting sediment from the main channel in the upstream reaches of the river Waal in the late 1970's. In the following years, amongst others, groynes have been lowered and the river has been widened at certain places (Ten Brinke and Gölz, 2001). However, the erosive trend is still present, although most of the morphological response to the training works has probably taken place (Visser et al., 1999). Therefore, a combination of dredging and nourishments is carried out annually. However, this is both costly and has large impacts on the environment (Berkhof et al., 2018).

In recent years, Dutch engineers and policy makers have shifted their views on river management towards a pro-active approach called 'building with nature' (De Vriend et al., 2014). In this new approach, the idea is to make use of the dynamics of the natural environment rather than simply minimising the environmental impacts. This mindset has been put to practice on a large scale within the Room for the River project, which was carried out to increase the high water safety (De Vriend et al., 2014). Although the effects of the most recent large scale river training works, Room for the River, have not been fully developed, it is not expected that they will fully stop the ongoing erosion (Giri and Spruyt, 2016).

After completion of the Room for the River program, policy makers in the Netherlands already started looking forward to new river related challenges which are incorporated in a new program: Program Integrated River Management (NL: Programma Integraal Riviermanagement), or 'IRM'. The program focusses on national and regional challenges in the Rhine-Meuse area (Ministry of Infrastructure and Water Management, 2019). Within the IRM, the focus lies on an integral approach, regarding the river as one system, rather then a set of individual functions (Schielen et al., 2018). The focus lies on the period up to 2050, with an outlook to 2100 (Rijksoverheid, 2021). This integral approach is necessary, since river interventions aimed at reducing one problem, have had negative impacts on other river functions (i.e. bed level degradation, shipping hindrance, reduction of flood safety and nature).

Room for Living Rivers

In anticipation of the IRM, the World Wide Fund for Nature (WWF) has come up with a vision on such integrated river approach, called 'Room for Living Rivers' (RfLR) (Beekers et al., 2018). In this vision, a combination of river interventions along all Dutch Rhine branches (Waal, Nederrijn and IJssel) is proposed. Together they would form a balance between ecology, flood protection and shipping. These interventions comprise lowering of the floodplains and existing groynes, removal of summer dikes, and the creation of side channels and longitudinal dams. A conceptual drawing of the resulting intervened river is shown in Figure 1. Whereas Room for the River was aimed at increasing flood safety, Room for Living Rivers considers the river as one system, where all river functions should be regarded as one. The main principle is that during discharges for which the minimum shipping depth is exceeded, the excess of water will start flowing outside the main channel, increasing the area of flow and thereby reducing the flow velocities in the main channel (Van Loenen Martinet et al., 2018; Barneveld et al., 2019). The reduced flow will in turn lead to a reduced transport capacity in the main channel, which should reduce the erosion.

A first assessment by Barneveld et al. in 2019 using a 1D model shows that the measures in the vision may reduce the necessary nourishment volume to keep the river bed at its current level by 14-33% in the coming 75-100 years, based on the current bed degradation.

Aim of this study

What is currently missing, is insight in whether or not the effect of the Room for Living Rivers vision on mitigating erosion shows different results if an assessment is done using 2D modelling. At the same time, 2D modelling often increases the necessary resources, which may not be needed if a 1D model shows comparable outcomes. In a 1D model, certain multidimensional processes are parameterized to certain extent, introducing significant uncertainty in the model outcome (Van Denderen et al., 2018; Williams et al., 2016). Besides, the implementation of river interventions has been highly idealized in the study by Barneveld et al. (2019), leading to certain processes being neglected. An important 2D process which is idealized in the study by Barneveld et al. (2019) is the distribution of sediment over the main channel and the floodplains influencing the main channel morphodynamics.

Now that a conceptual design of RfLR on the Middle-Waal has been drafted, the effects of this combination of interventions can be assessed more easily in 2D, incorporating 2D river processes and reducing the level of idealization. This paper aims to provide insight in the possible reduction of bed erosion through the implementation of river interventions over a period of 50 years using the Room for Living Rivers vision as guiding principle. Moreover, it aims to give an insight in the necessity of using a 2D model over a 1D model. This is done using a calibrated 2DH morphodynamic model of the Dutch River Rhine and its branches: the Waal, Nederrijn and Ijssel. The area where the river interventions are incorporated is limited to the Middle-Waal (riverkilometer 892 - 924). The focus of this study will therefore be on the River Waal.

This paper starts with an introduction on the modelling method used in Section 2, after which the simulated scenarios are elucidated. The bed development of the River Waal, the extent to which the interventions have been incorporated in the model and the bed development after the implementation of the interventions are presented in the results in Section 3. The main findings of this paper are discussed in Section 4, leading to general conclusions in Section 5.

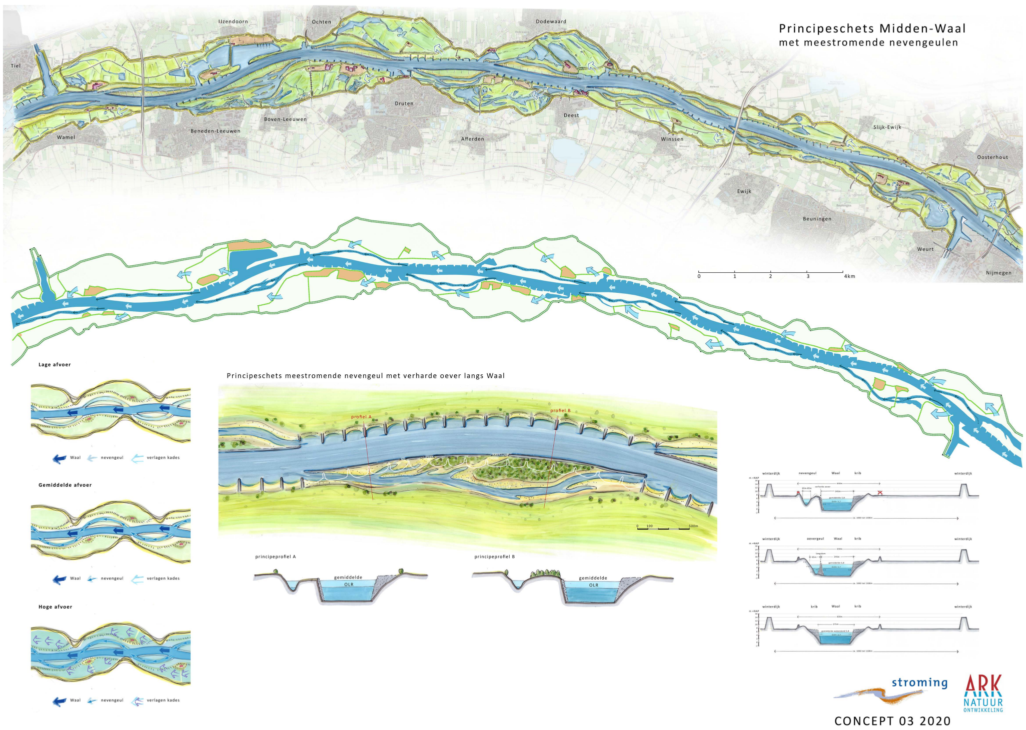

Figure 1: Conceptual drawings of the river within the Room for Living Rivers vision (ARK Natuurontwikkeling and Bureau Stroming, 2020). Top: an artist impression of the RfLR vision. The three drawings bottom left: the flow profile for different types of discharge. Bottom center: a more detailed view of a side channel. Bottom right: cross sections of three different river sections.

2 Method

To assess the effects of the interventions proposed in the Room for Living Rivers vision, the morphological development of the bed level is modelled for a period of fifty years. First, a reference scenario will be created, which will give insight in the bed development when the river is let to evolve freely in the next fifty years. Second, the Room for Living Rivers measures will be incorporated in this reference scenario, such that a second scenario is created which represents the bed level developments in the proposed vision. By comparison of these two scenarios, insights will be generated into the effects of the proposed interventions.

Morphological modelling

To assess the influence of the proposed interventions on the bed development, this study makes use of the DVR model which is developed by Rijkswaterstaat and Deltares (Sloff et al., 2013). This is a 2D morphological model of the Dutch Rhine system, which was developed as a prediction tool to assess constructive and sediment management measures in the Rhine Delta (Van Vuren et al., 2015). The DVR model can be used to assess the long-term, large scale evolution of the Rhine system (i.e. at the scale of longitudinal profile evolution of river reaches in response to training works) (Yossef et al., 2008), which is the aim of this study. The model covers the River Rhine from Xanten (Germany) to the Merwede, Nederrijn and the Ketelmeer for the Waal, Nederrijn and IJssel branches respectively. It is based on the Delft3D-FLOW computational core, which numerically solves the unsteady shallow water equations in two dimensions (averaged over depth).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z_w}{\partial x} = -g\frac{u\sqrt{u^2+v^2}}{hC^2} \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial z_w}{\partial x} = -g\frac{v\sqrt{u^2+v^2}}{hC^2} \tag{2}$$

Where u [m/s] and v [m/s] are the velocities in longitudinal and transverse direction respectively, g [m/s^2] is the gravitational acceleration, z_w [m] is the water level, h [m] the water depth and C [$\sqrt{\text{m}}$/s] the Chézy roughness coefficient. These hydrodynamics are furthermore coupled to a morphological module, which computes the sediment transport and in turn the bed development using the Exner equation (Deltares, 2020).

$$(1-\epsilon)\frac{\partial z_b}{\partial t} + \nabla \cdot q_s = 0 \tag{3}$$

Where ϵ [-] equals the bed porosity, z_b [m] the bed level and q_s [m^2/s] the bed-material load sediment flux per unit width. The sediment transport is determined by using either a general equation which has the structure of Meyer-Peter and Muller (1948) or using the equations of Van Rijn (1984a,b,c). The model is capable of predicting large-scale 2D morphological response to a multitude of interventions (Sloff, 2011), as it has been morphologically calibrated for both low and high discharges (Yossef et al., 2008). This model has therefore been widely used within the engineering community for the assessment of morphological developments since 2010. Besides, it has been used as the official tool for designing and testing the large scale Room for the River measures in the Netherlands (Sloff, 2011).

To determine the sediment transport, the model makes use of two different sediment transport equations. Which equation is used depends on the representation of the bed composition, as the model distinguishes between non-uniform and uniform sediment particles (see next paragraph). In the former, the transport is described by a general equation, which has the structure of Meyer-Peter and Muller (Eq. (4)). In this equation, α, b and c [-] are user specified calibration factors, Δ [-] is the relative density of the sediment, g [m/s^2] the gravitational acceleration, D_{50} [m] the median grain size diameter, θ and θ_{cr} [-] the Shields stress and critial Shields stress respectively, μ [-] the ripple factor and ξ [-] a hiding and exposure factor for the sediment fraction. The ripple factor (μ) and the critical Shields stress (θ_{cr}) have a constant value of 0.7 and 0.025 respectively (Sloff et al., 2014; Yossef et al., 2008). In the uniform sediment domains, the sediment transport is determined using the equation of Van Rijn (1984) (Eq. (5)), which has been adapted to calibrate the bed load and suspended load transport independently by Yossef et al. (2008). Here, α_{SUS} and α_{BED} [-] are user defined calibration factors for the suspended and bed load transport respectively, f_{cs} [-] is a shape factor, ξ_c [m] the reference height and D_* [-] a dimensionless particle diameter. T [-] is a dimensionless transport parameter, which is normalized by the critical bed shear stress according to Shields (τ_{bcr}) (see Eq. (5)). Again, the critical Shields parameter is set constant, this time at 0.016, while the ripple factors consist of adapted calibration factors for both the suspended and bed load transport (Sloff et al., 2014). The choice of transport formulae and calibration values is carried out by Yossef et al. (2008). An overview of the user defined parameters for both equations is given in Tables 1 and 2.

$$S = \alpha D_{50}\sqrt{\Delta g D_{50}}\theta^{b}\left(\mu\theta - \xi\theta_{cr}\right)^{c} \quad \text{with} \quad \theta = \left(\frac{u}{C}\right)^{2}\frac{1}{\Delta D_{50}} \tag{4}$$

$$S = \underbrace{\alpha_{SUS}\cdot f_{cs}uh\cdot 0.015\frac{D_{50}}{\xi_c}\frac{T^{1.5}}{D_*^{0.3}}}_{S_s} + \underbrace{\alpha_{BED}\cdot 0.1\sqrt{\Delta g D_{50}^{3}}\frac{T^{1.5}}{D_*^{0.3}}}_{S_b} \quad \text{with} \quad T = \frac{\mu_c\tau_{bc} - \tau_{bcr}}{\tau_{bcr}} \tag{5}$$

Table 1: User defined parameters used in Eq. (4) (Yossef et al., 2008).

Parameter	Description	Value
α	Calibration coefficient	5
b	Power	0.0
c	Power	1.5
μ	Ripple factor	0.7
θ_{cr}	Critical bed shear stress	0.025

Table 2: User defined parameters used in Eq. (5) (Yossef et al., 2008).

Parameter	Description	Value
α_{SUS}	Calibration coefficient for suspended transport	0.2
α_{BED}	Calibration coefficient for bed load transport	0.3
τ_{bcr}	Critical bed shear stress	0.016
ξ_c	Bottom roughness height	0.3

As stated, the model destinguishes between graded and uniform sediment along the river trajectory. This is made possible by a unique feature of the DVR model, the so-called domain decomposition. As the River Rhine is characterised by non-uniform sediment, significant downstream fining and vertical segregation of coarse and fine sediments are observed (Van Vuren et al., 2015). However, in the Waal and Ijssel, the vertical sorting process is less important (Van Vuren et al., 2015). Therefore, not all domains make use of the graded sediment approach. In the domains which use the graded sediment approach, the sediment is divided into ten sediment fractions, ranging from $d = 63$ μm (fine sand) to $d = 16$ mm (medium-coarse gravel) (Sloff et al., 2014). Within these domains, the median sediment diameter, D_{50}, is able to change in space and time. In the uniform sediment domains only one sediment fraction is taken into account, by specifying a D_{50} at each location which is constant in time, to include the longitudinal sorting. In Figure 2, an overview is given of the extent of the DVR model, including the distinction between where the bed composition is represented by non-uniform or uniform sediment particles. At the interface between graded and uniform sediment domains, continuity of mass is used to allow for a smooth transition of sediments.

Another special feature of the DVR model, is the inclusion of a dredging and dumping module. This module makes it possible to include the current fairway management set by the Dutch government (Deltares, 2020). Using this module, nourishments can also be introduced to the model. However, since the dredging module is based on a dynamic dredging strategy (i.e. it does not consist of static dredging volumes and locations), it is not included in this study. This makes it easier to assess the natural bed development, without introducing human-induced disturbances. Due to the exclusion of this module however, the recent nourishments in 2016 and 2019 are also excluded from the study.

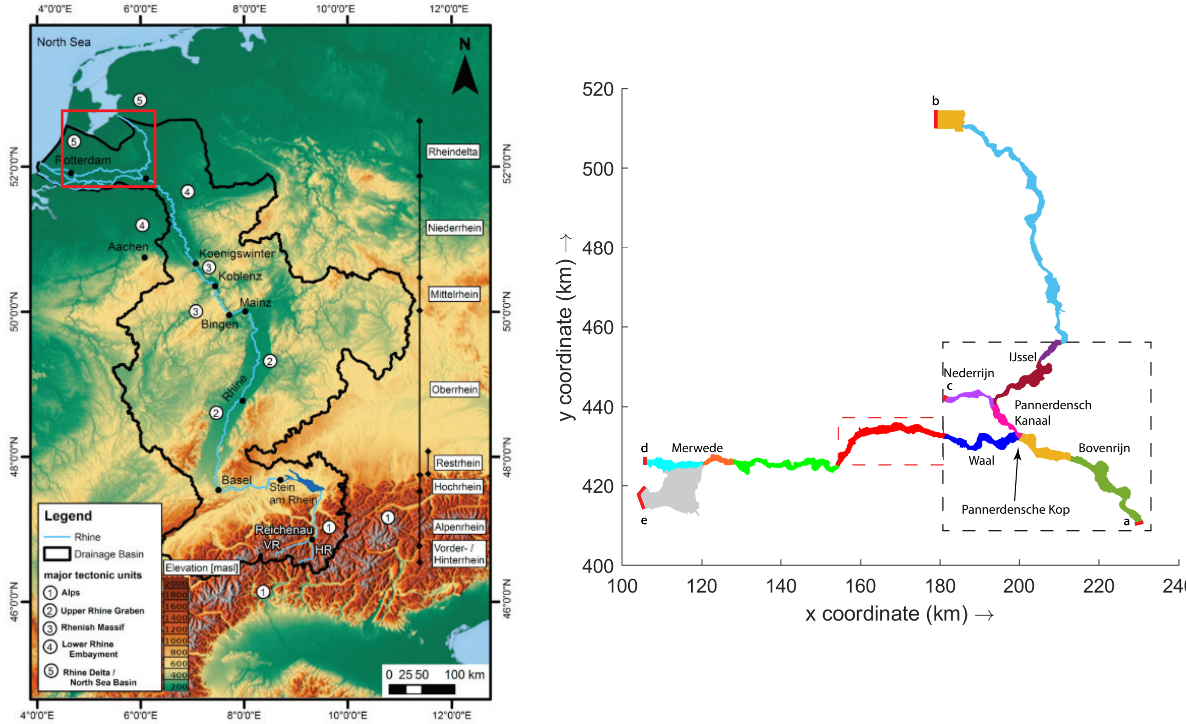

Figure 2: Left: Overview of the River Rhine basin with the red square marking the study area. Adapted from (Frings et al., 2019). Right: The extent of the DVR model. Each color represents a separate computational domain. Domains within the black dashed box make use of a graded sediment approach. The RfLR interventions are located in the red dashed box. The open boundaries are marked by the red lines in combination with a letter: location a is the upstream end at Xanten, b, c, d and e are downstream ends at the Ketelmeer, Nederrijn, the Beneden-Merwede and Nieuwe-Merwede respectively.

The reference scenario

The spatial model input is generated from a GIS database, which contains a spatial representation of the river between the winterdikes. In this study, the reference scenario consists of the river's configuration by 2015, as it was foreseen in 2012. To obtain this representation, the schematization is actualized up until 2011, which is supplemented with the interventions as part of the Room of the River program and the Water Framework Directive (Rijkswaterstaat-WVL and Deltares, 2019). Using Baseline, the topographic data in the database, such as bed levels, weirs and groynes, are projected on the computational grid (Sloff, 2011). In Appendix A an overview of used Baseline schematizations and included interventions is given.

The computational grid used in the model is a curvilinear grid, which is aligned such that the cells in the main channel are always oriented parallel to the direction of flow. The resolution of the grid is highest in the main channel and reduces in resolution as the distance from the main channel increases. As the model uses domain decomposition, the resolution of the curvilinear grid may be different in each domain. Since the focus in this study is on the River Waal branch, this part of the grid is shown in Figure 3. The dimensions of the this part of the grid will be elaborated on shortly. The main channel of the River Waal is represented by twelve cells in transverse direction, which have a length of roughly 80 m and a width between 21 - 26 m in the three different domains covering the River Waal. Due to the nature of the curvilinear grid, the cells in the floodplains become more coarse in transverse direction. In the domains representing the River Waal, they range between 16 and 325 m in width and 9 and 140 m in length. To numerically solve both the hydraulics and the morphodynamics, the model duplicates this grid to create a staggered grid, which results in the water and bed level being computed at the middle of the cell, while all fluxes are solved at the interfaces of the cells.

During the projection of the schematization on the grid, spatially varying data is generated from land-use and vegetation classifications and converted to so-called roughness codes for the floodplains. These so-called trachytopes determine the bottom roughness used in the hydraulic computations. For certain vegetation types, the roughness is not fixed, but rather depending on the inundation depth. The

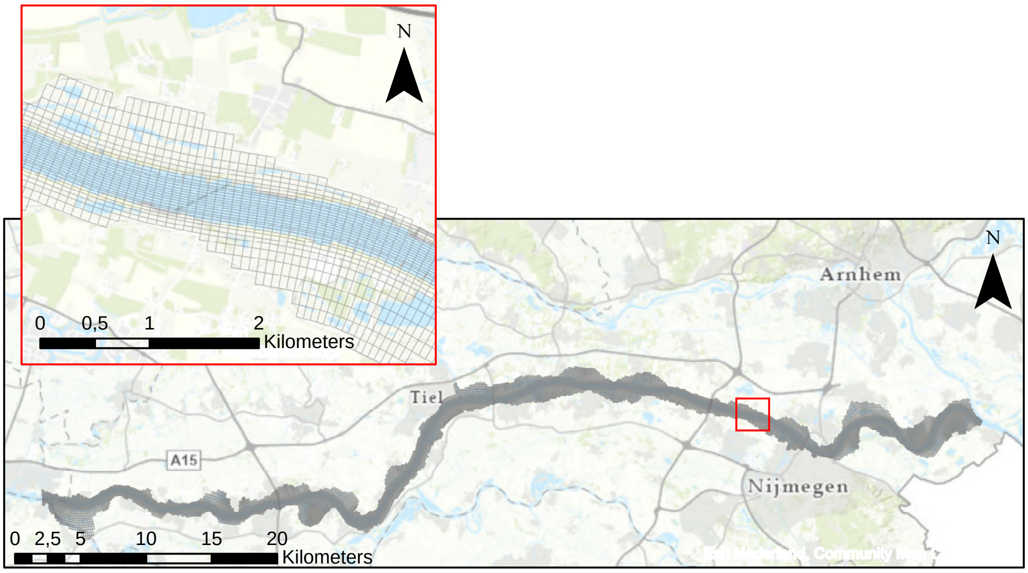

Figure 3: Numerical grid covering the river Waal. Background image adapted from Esri Nederland.

alluvial roughness in the main channel is used as a parameter during the calibration of the model and is therefore composed of a combination of the fixed value as well as a function of the local water depth and bedforms which are predicted with a bedform prediction module, based on the Van Rijn equation (Van Vuren et al., 2015; Yossef et al., 2008; Flierman, 2017). Structures with sub-grid dimensions, such as groynes, are schematized as sub-grid elements which cause a hydraulic loss based on their height and downstream bed level (Van Vuren et al., 2015; Deltares, 2020).

The bed composition is based on different measurement campaigns (Yossef et al., 2008). For the domains using uniform sediment, an initial bed composition is imposed represented by one layer, uniformly mixed in depth, where the D_{50} only varies in space as introduced by Sloff et al. (2013). In the graded sediment domains, the bed is composed of four layers of different thickness and composition, to allow for a changing bed composition in space and time (Sloff et al., 2014). In Figure 4 the width averaged D_{50} is shown for the river bed (top layer in the graded sediment domains). Additionally, the D_{84}/D_{16} is shown as a measure of uniformity of the sediments. It can be seen that in the upstream (graded) reaches, the D_{50} varies greatly, in combination with a large non-uniformity within the bed composition. In the downstream (uniform) reaches, the D_{50} only changes gradually with little downstream refinement. Although the bed composition shows some nonuniformity, only the D_{50} is used in computations. Fixed layers in the study area, at Erlecom (rkm 873-876), Nijmegen (rkm 883-885) and Sint-Andries (925-928), are also included in the model (Sloff, 2011; Van Vuren et al., 2015). At Erlecom and Sint-Andries, these fixed layers cover the outer bend, while at Nijmegen, the fixed layer covers the whole main channel. These layers are schematized by setting the sediment layer thickness to zero at these locations. The sediment layer is also set to zero for the groyne fields and floodplains. This way, sedimentation may occur anywhere, while only previously deposited sediment during the model run may be eroded outside the main channel.

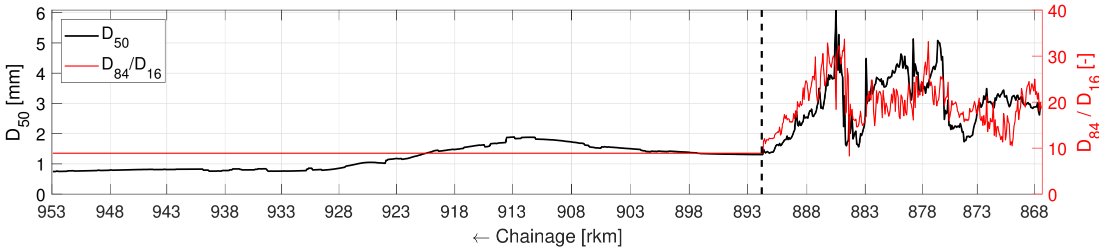

Figure 4: Width averaged characteristics of the initial bed composition in the River Waal: D_{50} (left axis) and the non-uniformity of the sediment given by $\mathrm{D}_{84}/\mathrm{D}_{16}$ (right axis). The dashed line indicates the border between the domain using graded sediment (right side) and the uniform sediment (left side).

The Room for Living Rivers scenario

The scenario containing the proposed interventions is based on the input used for the reference scenario. The conventional method for including river interventions in this model is by altering the GIS source (so called 'Baseline tree') and again use Baseline, which is a GIS extension created to convert GIS schematizations to (among others) Delft3D input files, to create the input files. However, the baseline tree used to create the reference scenario was not available for this study. To overcome this problem, the input files have been adjusted directly using FME software. This method however introduces some inaccuracies, as the adaptations are bound to the existing grid.

As described in Section 1, the RfLR measures considered in this study consist of the construction of side channels, lowering of floodplains and the removal of summer dikes in the Midden-Waal. The measures will thus have an influence on the bathymetry, roughness and constructions around the main channel and groyne fields. Hence, only input files containing this data in the corresponding domain (red domain in Figure 2) have been adapted. The earlier mentioned lowering of groynes is not applied, since this has already been incorporated in the reference model in the considered model domain (See Appendix A).

The side channels have been incorporated in line with the conceptual sketches by ARK Natuurontwikkeling and Bureau Stroming (2020) (Figure 1). The bed level of these channels is located at the agreed low water level (NL: 'Overeengekomen Laagste Rivierstand'; OLR), such that the side channels do not lower the water level during droughts. Depending on the local grid resolution, the channel width is between 65 and 85 m. Next to the change in bathymetry, the bed roughness in the side channels is adapted to match the roughness codes for sandy side-channels as defined in the Vegetatielegger (Rijkswaterstaat Waterdienst and Deltares, 2013). Furthermore, to allow for unobstructed flow, obstacles such as weirs and thin dams in the new channels have been removed.

For the lowering of the floodplains, a more generic approach has been taken. Since this research has an exploratory character, the floodplains have been lowered uniformly with 2 m. This approach is analogous to an earlier 1D study by Barneveld et al. (2019). To prevent the floodplains from extracting discharge from the main channel at too low discharges, a constraint has been applied that the new floodplain level may not become lower than OLR +1.20 m. Also, the floodplain level within 100 m of the toe of the winter dikes has been left unaltered.

The last part of the interventions, removal of the summer dikes, has been applied by removing all sub-grid structures (weirs and thin dams), which are located within 50m on the floodplain side.

An overview of the interventions and used constraints is given in Table 3. In total eight side channels are implemented between Ewijk and the already present longitudinal training dams at Tiel (rkm 892 - 912) which alternate between both sides of the main channel, covering 1.7 km^2 (3.7% of the total area). A total of 26.4 km^2 floodplains will be lowered, which is 56.4% of the area between dikes, where the main channel takes up 21.1% between the dikes. The rest of the area, 18.7 km^2 (18.7%) remains unaltered. In order for all interventions to be carried out, roughly 38.1 million m^3 of soil need to be excavated.

Detailed elaboration on the incorporation of the measures can be found in Appendix B.

Table 3: Overview of interventions and applied constraints during modelling.

Intervention	Constraints	Concerned input
Construction of side channels	Width between 60 and 85 m	Bathymetry
	Depth at agreed low water (OLR)	
	Removal of objects in new channels	Groynes and weirs
	Roughness changes to side channel classification	Roughness areas
Floodplain lowering	Uniform lowering by 2 m	Bathymetry
	New floodplain level not below OLR +1.2 m	
	No lowering within 100m of the toe of the winter dike	
	No additional lowering at locations of new side channels	
Removal of summer dikes	All dikes and levees within 50m of the groyne fields are removed	Groynes and weirs

Boundary conditions

In the model, boundary conditions have to be applied at all open boundaries. These boundaries are located at the up- and downstream ends of the model (Figure 2). At the upstream boundary (location a) a discharge hydrograph is imposed. In order to reduce the computational time, the hydrograph is discretized, so that a sequence of steady-state steps remains (Sloff, 2011). Specificially, a representative yearly hydrograph consists of fourteen steps based on measurements between 1999 and 2006 (Yossef et al., 2010). This hydrograph is repeated annually during all fifty years and is shown in Figure 5. At the downstream boundaries of the Ketelmeer and both Merwedes (locations b, d and e in Figure 2), the water level as a function of the upstream discharge is imposed. At the downstream end of the Nederrijn (location c in Figure 2) a discharge condition has been applied due to the presence of a weir at this location. The used relationships at the downstream boundaries are shown in Figure 6.

Next to the hydraulic boundary conditions, morphological boundary conditions should be imposed at least at the upstream boundary. In line with past measurements in the Niederrhein, an annual bed degradation of 1.5 cm is therefore imposed at the upstream end. Since this boundary is located sufficiently far upstream from the area of interest, the influence of this boundary will not affect the model results (Sloff et al., 2014).

A last user-defined parameter is the spin-up time. As mentioned earlier, using steps of steady state discharges makes it possible to reduce the computational time. However, each time the model changes to a different discharge level, the flow fields should adjust to the new steady state conditions. The duration of this adjustment period can be reduced by storing and retrieving the flow fields corresponding to a discharge level in a separate database at the end and start of a simulation, respectively (Sloff, 2011). Using this approach, the flow fields only need to adapt to the relative small changes due to morphological developments between two equal discharge steps, since the most recent flow fields are retrieved from the database. Only at the first year, when the database is still empty, the spin-up time should be long. For the reference scenario, no spin-up time in the first year is set, since the used database already contains the steady-state flow conditions, while after the first year, the spin-up time is set to ten minutes. The introduced changes in the RfLR scenario are expected to affect the flow patterns compared to the reference situation, therefore, the spin-up time in the first year is increased such that steady-state flow conditions are reached at the start of morphodynamic modelling in this scenario. The spin-up time after the first year is kept equal. Final spin-up times used in the RfLR scenario are 3000 minutes per discharge step within the first year and 10 minutes before each discharge step in consecutive years. Verification of this chosen spin-up time is given in Appendix C.

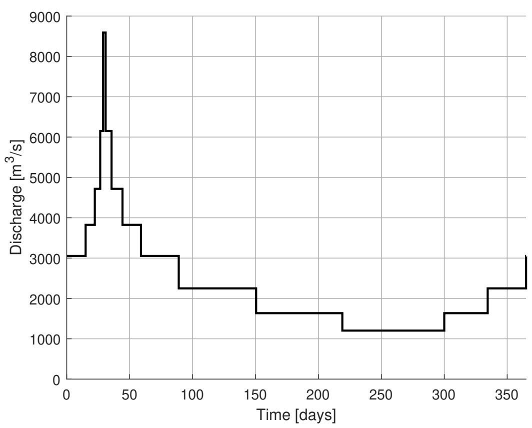

Figure 5: The annual discharge hydrograph as applied at the model upstream boundary. This hydrograph is repeated for fifty years. Adapted from Yossef et al. (2008).

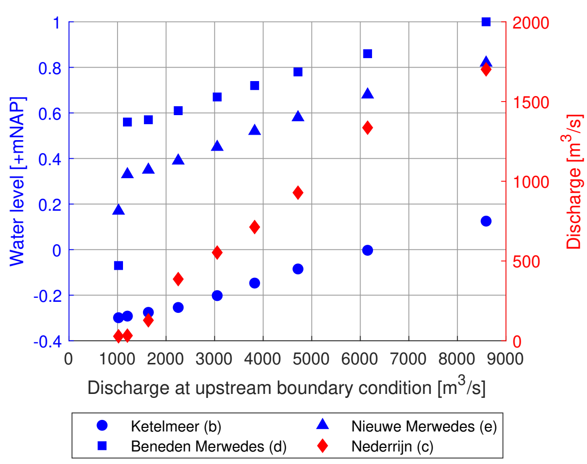

Figure 6: The applied downstream boundary conditions. The letter between parenthesis corresponds to the locations marked in Figure 2. Adapted from Yossef et al. (2008).

3 Results

Reference scenario

Simulation of the reference scenario sets a benchmark for the bed degradation in the river Waal over 50 years. The results are shown in Figure 7. The figure shows that the river bed in the main channel in the Waal will erode up to 2 m locally over a period of 50 years. In the Upper-Waal (rkm 686 - 892) the erosion shows great variance in longitudinal direction, while in the Middle-Waal (892 - 924), the river erodes more gradually. In the Lower-Waal, the extent of the erosion decreases and is limited to 1 m at most.

Due to the model settings, it is indeed found that the floodplains show no net erosion. However, especially in the Upper-Waal, deposition of sediment does take place in the floodplain. The larger deposition in this area can be explained by the fact that this model domain differentiates in sediment fractions. Due to this differentiation, larger grain sizes may be present, which are likely to settle faster than the grain sizes in downstream domains.

To explain the variability in bed erosion in the Upper-Waal, Figure 7(b) shows a closer look. Here, four interesting developments can be destinguished. The first is around rkm 874, where erosion occurs in the inner bend, while the bed in the outer bend remains almost in place. This is due to the fixed layer in the outer bend as described in Section 2. Just downstream of the river bend, the erosion is at a maximum. This might be a result of decreasing secondary flow, leading to increasing flow velocities in the inner bend which become capable of moving bed material. The second interesting development is the high erosion between rkm 879 and 880. This development can be justified by a rapid change in grain size. Possibly, the bed composition at this location contains a large fraction of smaller sediment particles, which results in a flush of the finer sediments. The third interesting outcome is the strong deposition at rkm 882.5. This is likely due to the recently constructed bypass in the inner bend of the river within the Room for the River program. In order to activate this channel only during high discharges, a sill is constructed at the entrance of the channel, which is located at the location of the sedimentation. Since the bed level in the model originates from before the construction of this sill, the results may be a morphologic response to this construction of the sill. The fourth interesting development is at rkm 885. Here, an erosion pit evolves. This is in line with the current development, since again a fixed layer is present just upstream. At this location, the fixed layer covers the full width of the main channel, which should prevent erosion from occurring between rkm 883 and 885. However, the results do show erosion although it is significantly lower compared to the surrounding bed. This suggests that the fixed layer is not incorporated perfectly.

Taking a closer look at the area in which the interventions have been incorporated (Figure 7(c)), it is found that the erosion at the upstream is in the order of 2 m over fifty years. This magnitude changes in downstream direction. This suggests that the river tilts around a point downstream of the study area, adjusting its bed slope towards a new possible equilibrium. To find a possible explanation for this behaviour, the development of the river in time is analysed.

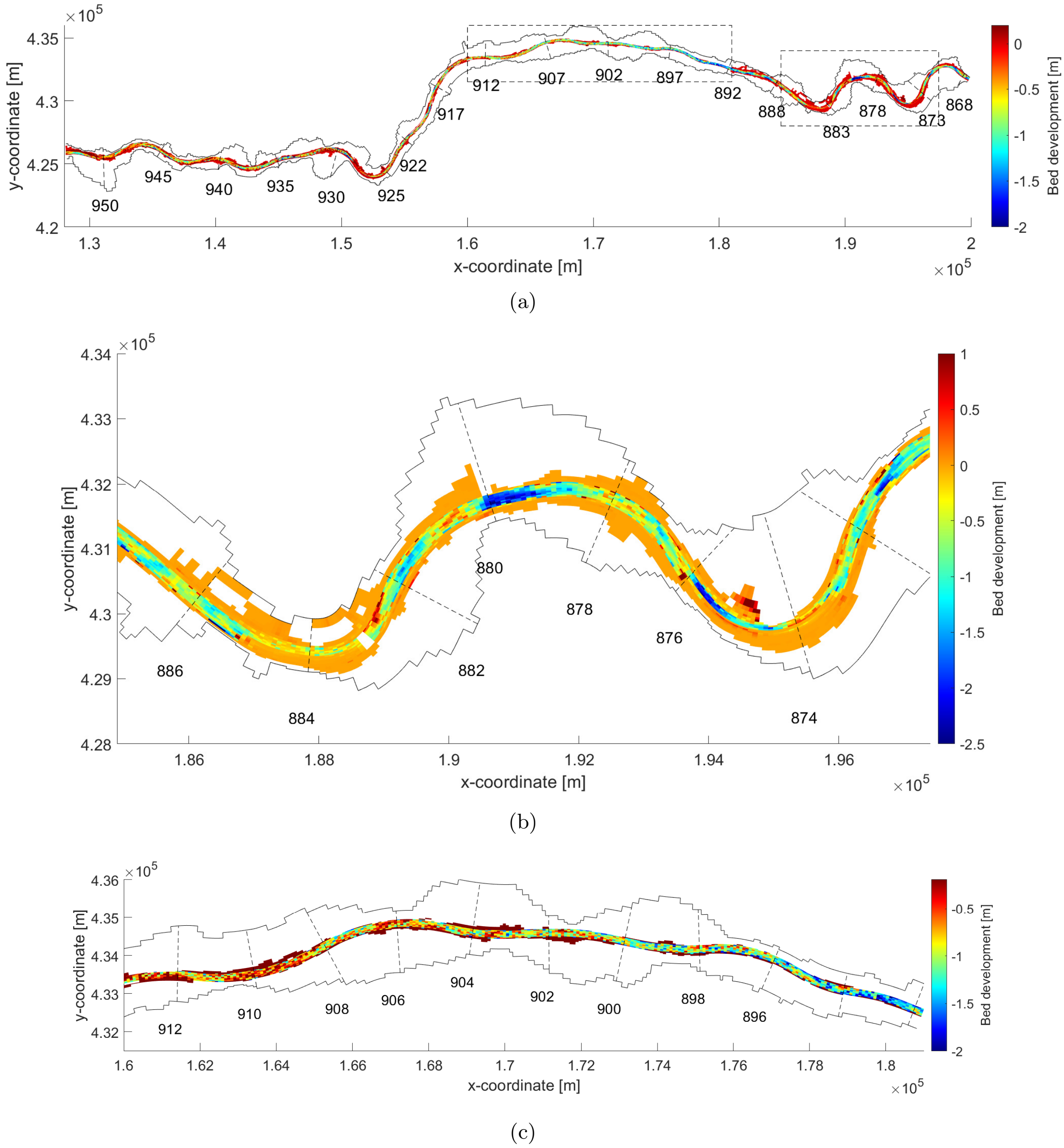

Figure 7: Bed level development of the river Waal in the reference scenario over fifty years. The dashed lines indicate the riverkilometers. The direction of flow is from right to left. (a) River waal from the Pannerdensche Kop until Gorinchem. The boxes indicate the areas zoomed in below. (b) Zoom of the river section between rkm 870 and 888 (right box). (c) Zoom of the river section between rkm 892 and 913 (left box).

To assess the bed development over time, we turn to a one-dimensional representation of the river bed. To make this conversion, the bed level is width averaged only over the main channel. Bed level changes in the floodplains will not be taken into account for two reasons. First, the scope of the Room for living Rivers vision is to reduce the erosion in the main channel. Second, in the model, the floodplains are little morphologically active: the floodplains can only erode sediments which are deposited earlier in the simulation. Excluding the floodplains in the width averaging will thus not lead to neglecting large morphodynamic developments.

The width averaged bed level after fifty years is shown in Figure 8. This shows an erosive trend along almost the full extent of the Waal, locally up to 1.68m over 50 years at rkm 879.6. At rkm 883, the model predicts the bed level to be at -6.7 +mNAP. As the result is extremely local (one row of grid cells) and differs in value to such great extent, it is considered to be an numerical artefact. Therefore, this row of cells is excluded from the figures and analysis.

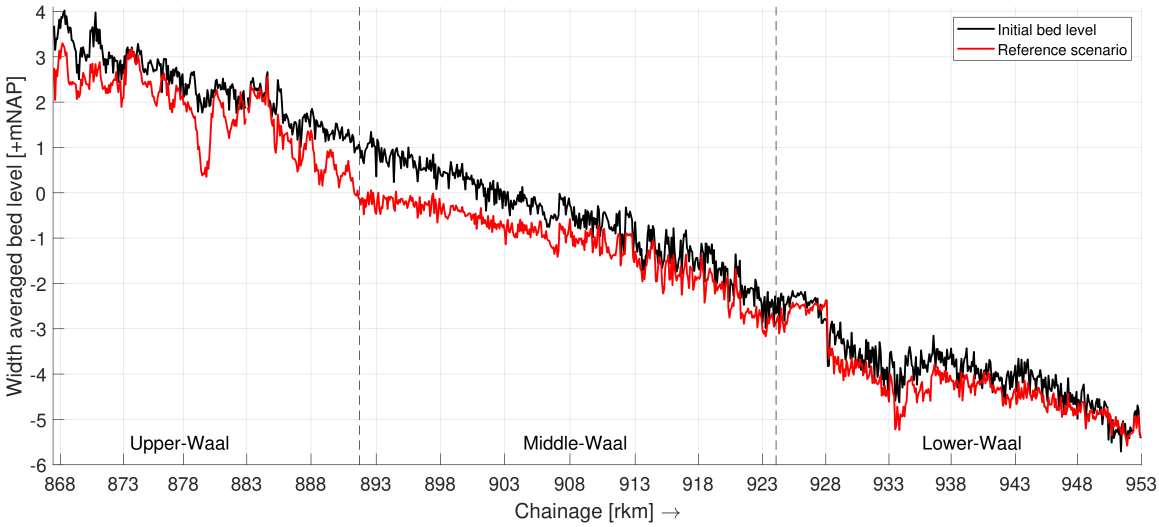

Figure 8: Bed level in the reference simulation initially and after fifty years. The dotted lines indicate the domain boundaries.

In contrast to the areas with high erosion, the 2D width-averaged representation of the reference case also shows locations where almost no erosion is present. The locations are just downstream of rkm 873, 883 and 926. This corresponds to the fixed layers at Erlecom, Nijmegen and Sint-Andries near rkm 873, 883 and 926 respectively. Another interesting finding is the relative limited erosion between rkm 913 and 923, while just upstream, the erosion is substantial. This can be contributed to different causes. In this trajectory with relative limited erosion, longitudinal training dams have been constructed in 2015, which aim to reduce erosion in this river section (De Ruijsscher et al., 2018; Van Weerdenburg, 2018). To explain the higher erosion in between rkm 888 and 913, Figure 9 provides insight in the bed level development over time.

The top figure shows that most of the erosion between rkm 883 and 923 takes place in the first ten years of the simulation. Looking at this erosion in even more detail, it is found that after the first five years the erosive trend decreases. A possible explanation for this is the rapid change in D_{50} in the Upper-Waal domain, an increase by 55% in the first ten years (Figure 10). The rapid change indicates that the initial bed composition in the model contains fine sediments which are entrained during the first simulated years. In turn, the slope increases, which leads to higher flow velocities. This increased flow velocity potentially causes the bed level to erode to a large extent in the first years in the Upper-Waal. After two years, most of the bed degradation has taken place, presumably since the bed level has reached a new bed slope which fits the hydraulic conditions better. The large initial erosion in the first two years is thus considered a numerical artefact.

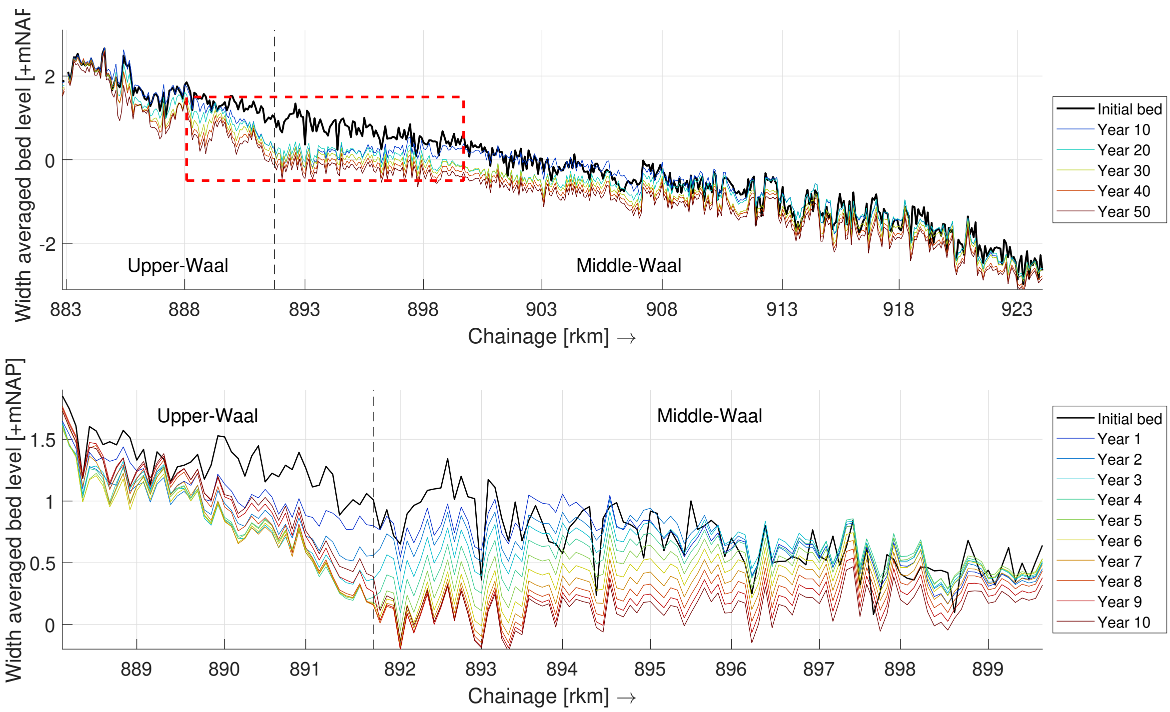

Figure 9: Bed level development in the reference scenario in time. The dashed line indicates the domain boundary where the bed sediment composition and sediment transport equation changes. Top: Every ten years, bottom: zoom to area marked by red rectangle.

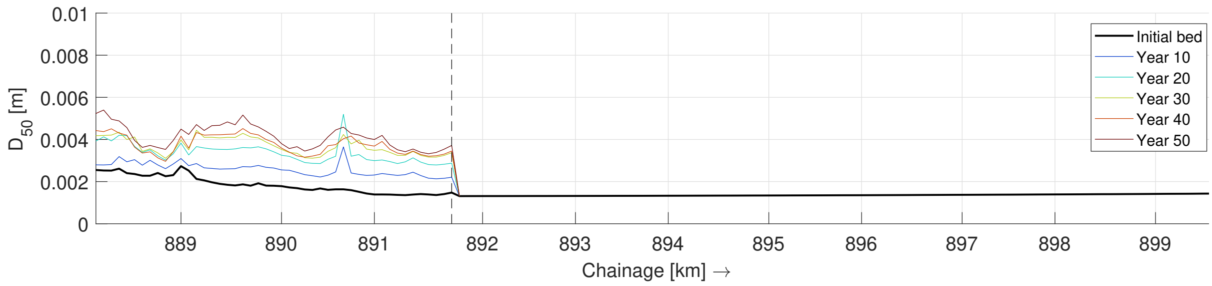

Figure 10: Development of the width averaged D_{50} in the reference scenario in time. The dashed line indicates the domain boundary where the bed sediment composition and sediment transport equation changes.

Room for Living River Scenario

The main principle of the RfLR measures is to increase the area of flow, such that the water level and flow velocity in the main channel are reduced. In Figure 11, a cross-section of the river is shown before and after the implementation of the RfLR interventions. Here, it can be seen how the interventions have been incorporated in the model. The floodplains have been uniformly lowered by 2 m, with OLR as a minimum floodplain height, everywhere except for the first 100 m from the dike toe and between the main and side channel.

In the following section, the influence of this change in bathymetry (together with other changes stated in Section 2) on the water levels and flow velocities is elaborated on. This is done by comparing each parameter in the reference scenario with the RfLR scenario, both width averaged over the main channel. The comparison is based on steady-state conditions complying to the respective discharges using the same bathymetry. After analysis of the hydraulic changes, the morphological changes will be assessed.

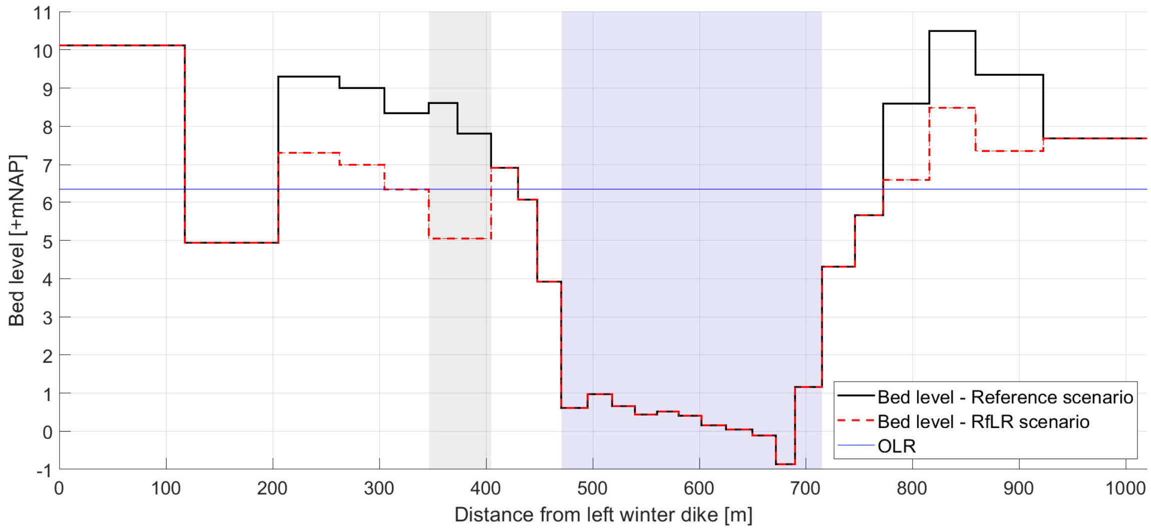

Figure 11: Cross-section of the river bed level at rkm 893 for both scenarios. The shaded areas indicate the two channels: main channel (blue) and the new side channel (grey). The floodplains within 100 m of the dike remain unaltered, while the rest of the floodplains have been lowered by 2 m, with OLR (blue line) as minimum floodplain level. The bed of the side channel lies 1.2 m below OLR and the area between the side and main channel is left as currently present.

Hydraulic changes

Water levels

Figure 12 shows that the interventions lead to a reduction in water levels for an Upper-Rhine discharge from 3053 m^3/s onwards. For the lower discharges, the water level in the main channel remains almost unaffected compared to the reference scenario. Partially this is desired, as the interventions thus do not enhance the limited draft during low waters. On the other hand, as discussed in Section 2, the side channels were designed such that they would become active for all discharges above the agreed low water discharge ($Q = 1020$ m^3/s), which does not become apparent from this figure. The general effect of the side channels on the water level is difficult to isolate from the effects by the floodplain lowering, since no extended reduction of water level is seen around the locations of the side channels. This is expected as sudden water level changes are likely to smooth out in space.

The figure also shows that the water level upstream of the interventions gets reduced for discharges above 3053 m^3/s. Since these findings are based on steady-state conditions, it can be concluded that the lowering is the result of the backwater effect induced by the interventions. This backwater effect reaches almost 25 km upstream, until the bifurcation at the Pannerdensche Kop (Figure 2). Although the difference at the bifurcation is 4 mm at 3053 m^3/s, it increases to 8 cm at 8592 m^3/s, which is significant. This might also affect the discharge distribution at the bifurcation upstream of the River Waal. Figure 13 shows however that the influence of the interventions on the discharge distribution is limited: at the highest discharge the increase of the Waal's discharge is 1%. Downstream of the interventions the water level remains unaffected.

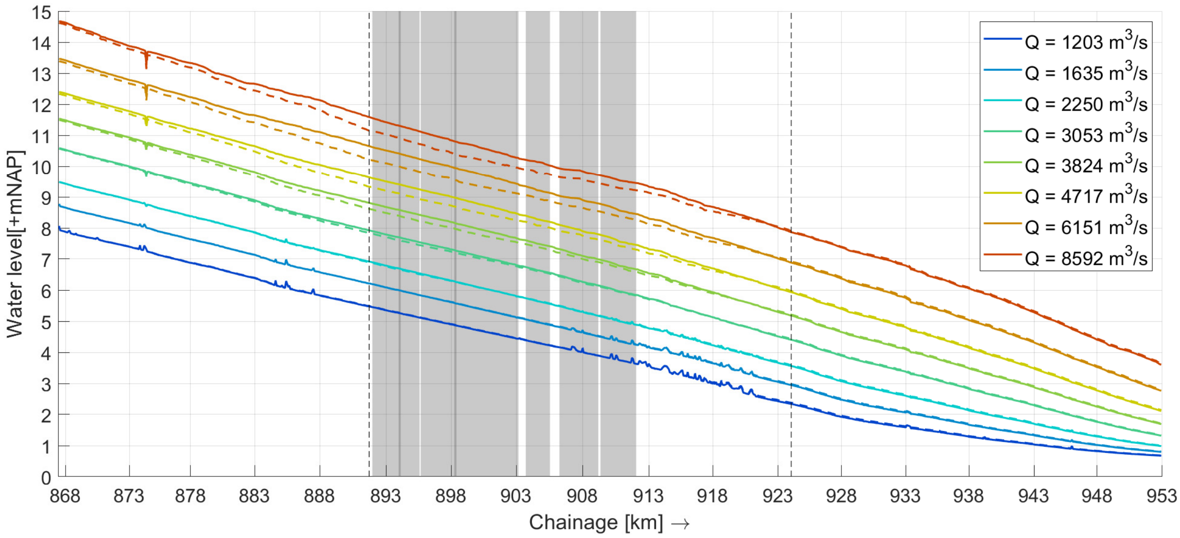

Figure 12: Width averaged water level in the main channel for the reference case and the RfLR scenario. The solid lines indicate the reference, dashed lines correspond to the RfLR scenario. Grey areas show the locations of the implemented side channels. The black dashed lines indicate the boundary of the floodplain lowering. The discharges stated in the legend correspond to the discharge at the model upstream boundary in the Niederrhein at Xanten. The small ripples for the lowest discharges downstream of rkm 910 are considered to be numerical artefacts of the width averaging process.

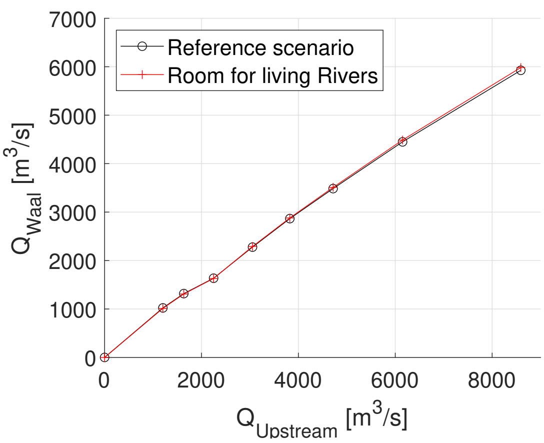

Figure 13: Discharge distribution at the bifurcation Pannerdensche Kop from which the River Waal originates for both the reference and Room for Living Rivers scenario.

Flow velocities

Figure 14 shows the difference in 2D width averaged flow velocity in longitudinal direction between the reference and RfLR scenario. The flow velocities for each scenario can be found in Appendix D. It becomes clear that the flow velocity in the main channel along the trajectory of the interventions gets reduced for almost all discharges. Only for an Upper-Rhine discharge of 1203 m^3/s, the flow velocity increases compared to the reference scenario in the Middle-Waal until rkm 914. From this location onward until rkm 918, the flow velocity decreases as well. It remains unknown what is the cause of this difference.

For the four highest discharges simulated, the effects on the flow velocity are much larger. Partly this is due to the floodplains becoming inundated at Upper-Rhine discharges above 3053 m^3/s. Also, the changes in flow velocity show less correlation with the locations of the side channels. This is in line with expectations, as the relative conveyance of discharge through the side channels becomes smaller when the floodplains get inundated. The correlation stands out better for discharges up to 3053 m^3/s. For these discharges, the flow velocity remains almost unaffected outside of the river stretches where no side channels are implemented.

As no interventions have been carried out in the Upper-Waal, the backwater effect causes the flow velocities in the main channel to increase for all discharges above 1203 m^3/s. As the discharge and bed level remain equal while the water levels reduce, the flow velocity must thus increase. The small changes in water levels thus show to have a noticeable effect on the flow velocities, even for the discharges below 3053 m^3/s.

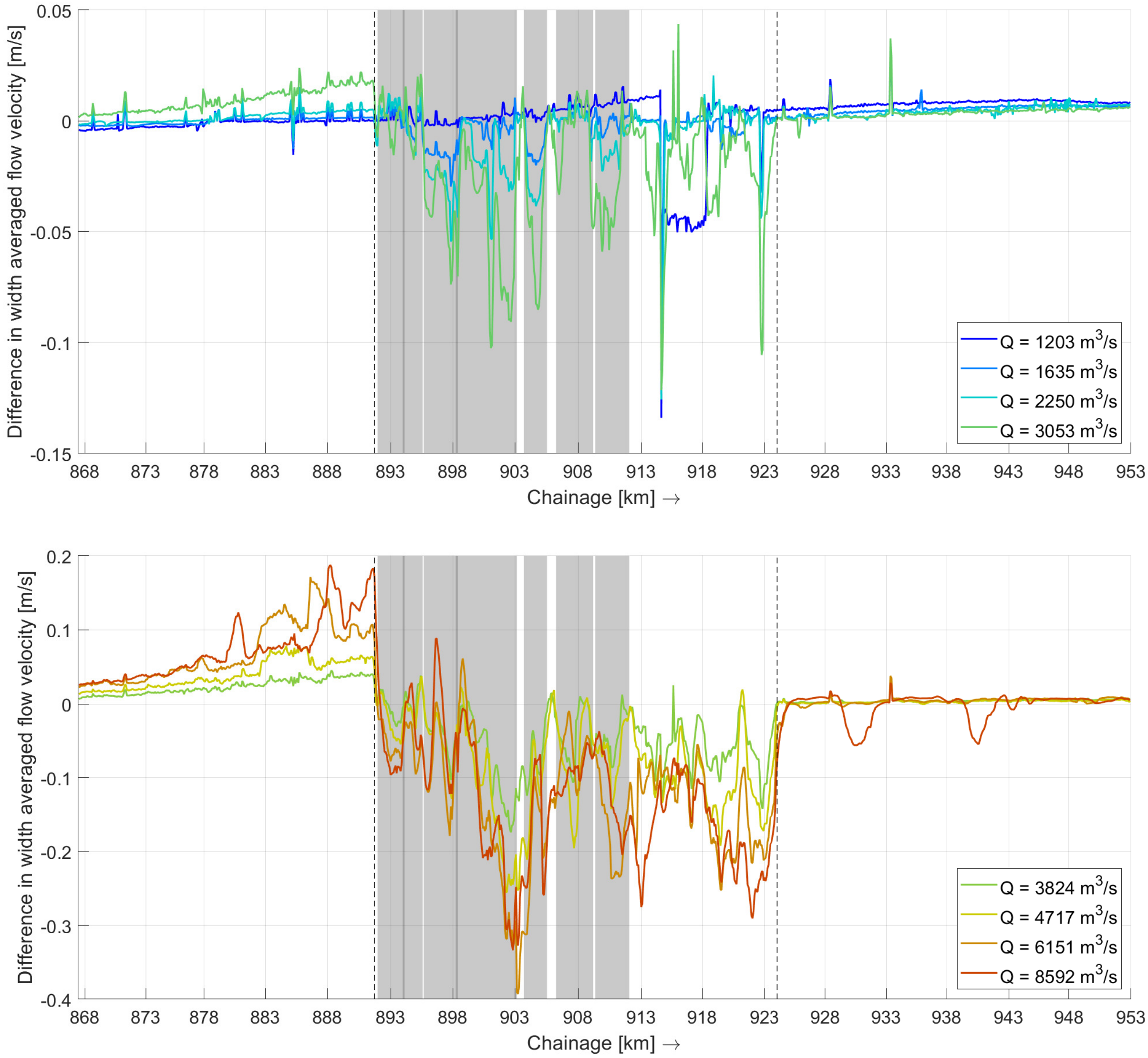

Figure 14: Difference in width averaged flow velocity in the main channel between the reference and RfLR scenario based on steady-state conditions for the lowest four (top) and highest four (bottom) discharges in the used discharge hydrograph. Each steady-state condition is based on the initial bed level at $t = 0$ in each scenario, excluding morphological development. A negative value indicates a reduction in the RfLR scenario. Grey areas show the locations of the implemented side channels, while the black dashed lines indicate the boundary of the floodplain lowering. The discharges shown in the legend correspond to the discharge at the model upstream boundary in the Niederrhein at Xanten.

Morphological changes

Even though the interventions have shown to reduce the water level and flow velocity, they are not capable of bringing the erosion to a halt in the Middle-Waal (Figure 15). The same pattern as in the reference case is found: upstream the erosion is highest (up to 1.5 m after fifty years) and decreases in downstream direction. The erosion also appears to be equally distributed in transverse direction. To isolate the erosion effects of the RfLR interventions, the autonomous bed degradation in the reference scenario is subtracted from the simulated bed level for the RfLR scenario after fifty years. These findings are presented in Figure 16.

Isolating the effects of the combination of interventions from the autonomous bed degradation, it becomes evident that the interventions do reduce the extent of the bed degradation. Along the complete Middle-Waal, the erosion is on average reduced by 21 cm after fifty years taken over the main channel. If assessed on individual cell level however, after fifty years, the interventions do induce additional erosion compared to the reference case at one river section. This is between rkm 917.5 and 919 where two already present side channels due to the longitudinal training dams have their respective downstream and upstream connection with the main channel. Here, the additional erosion amounts up to 48 cm over fifty years. As this erosion is only simulated at two consecutive computational cells, while surrounding cells show bed level changes below 1 mm, these findings are considered to be numerical artefacts. Downstream in the side channel bifurcating at this location (red circle in Figure 16), additional erosion of 5 mm over fifty years is found. This may pose a problem for the stability of this side channel in time. However, the rate of this additional erosion is small (0.1 mm/year) and compared to the simulated erosion in the reference case, the absolute additional erosion is negligible.

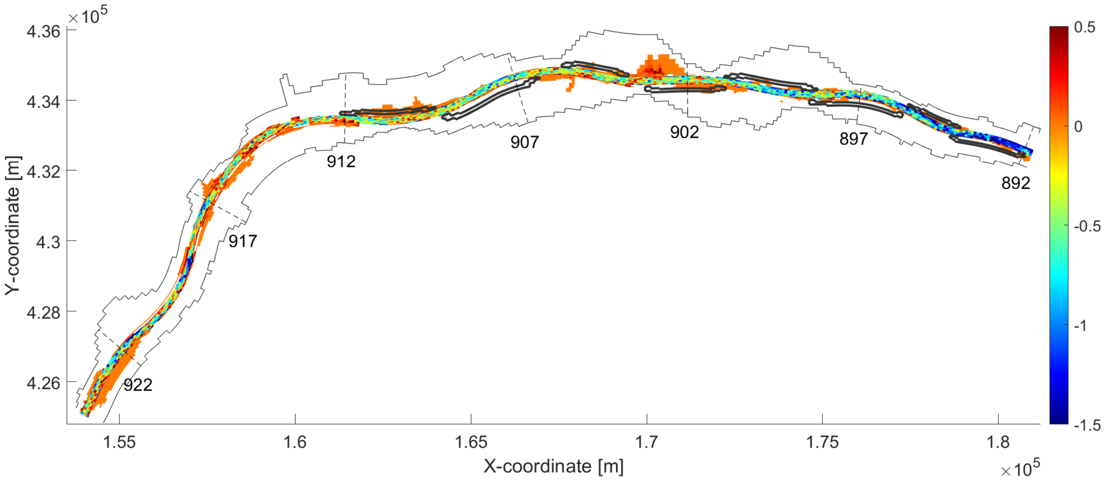

Figure 15: Bed level change in the Middle-Waal after fifty years including the RfLR measures. In black the location of the side channels are shown. The dashed lines indicate the riverkilometer.

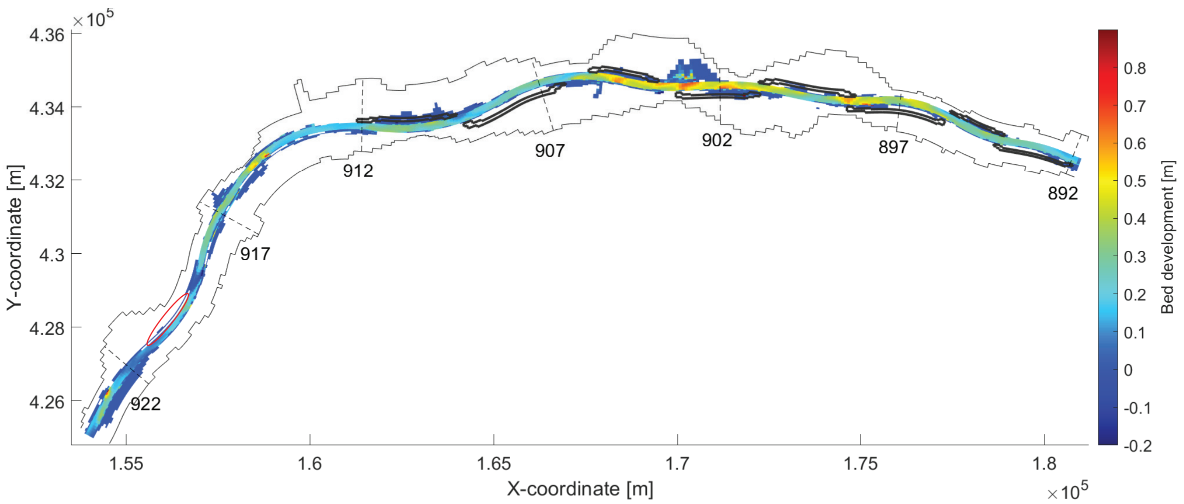

Figure 16: Difference in bed development after fifty years. The bed level in the reference scenario is subtracted from the RfLR scenario; hence a positive value implies less erosion in the RfLR scenario. The dashed lines indicate the riverkilometer, the red circle encircles the only area where the RfLR measures induce additional erosion compared to the reference scenario.

The scale of the relative sedimentation differs both along and across the main channel. In the longitudinal direction, the positive difference in bed development is greatest in the river between rkm 900 and 905. (see Figure 16). At the same river section, the response also shows large variability. Especially around the locations where the side channels connect to the main channel, the bed response shows a dominant respons: either large or little difference in bed level. Contrary, in the area between the connections, where the side channel runs parallel to the main channel, the bed response shows large variation in the bed level difference. A closer look on both is given in Figure 17.

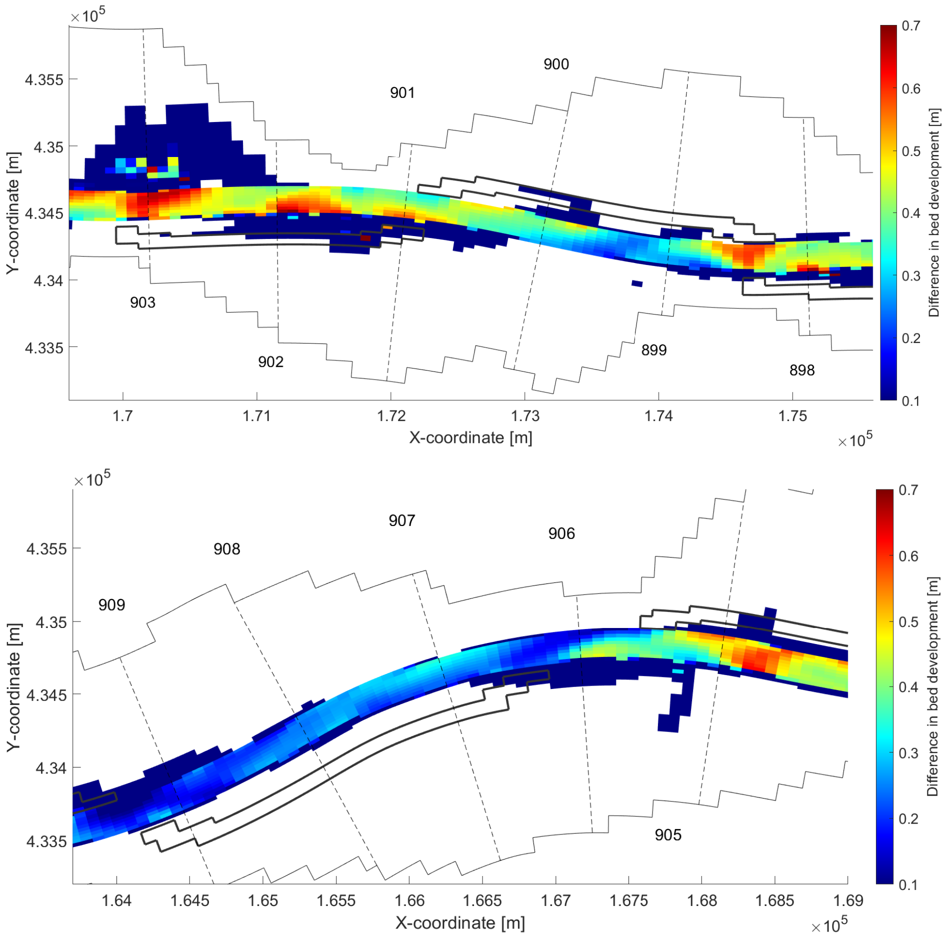

Figure 17: Close-up view of the difference in bed development after fifty years between both scenarios between rkm 897 and 903 (top) and between rkm 904 and 910 (bottom).

In most cases, the initial and the long-term morphodynamic response to river interventions are opposite to each other. This is also seen when the bed development induced by the interventions is assessed at different moments in time. In Figure 18, the initial response (after one year) induced by the interventions is shown for the Middle-Waal. It becomes clear that the positive effects seen after fifty years, are not induced directly after the construction of the interventions. Contrary, shortly after construction, large scour holes and sedimentation zones are formed around the connections of the interventions. Depending on the connections of the side channels, two different patterns are found.

The first type of side channel connection is when the side channels starts where the previous ends. In this case, the side channels form a connected chain, such that the extraction of discharge and bed-material load from the main channel (i.e. the discharge in the main channel) remains relatively constant and the side channels reduce the ongoing erosion from the start on. A distinct exception to this is along the fourth side channel starting at rkm 898. Here, strong additional sedimentation occurs in the main channel. This is partly due to the implementation into the model: this side channel becomes active at higher discharges than the others, due to a higher bed level at its entrance. Therefore, less discharge is extracted and since less sediment was entrained by the flow upstream of this location, additional erosion is caused in this section.

The second type of side channel connection is that the side channel's end and start do not connect, nor overlap. This creates areas where the discharge in the main channel increases before it decreases again. It is found that at the upstream end of the side channel, directly after the discharge is extracted from the main channel the erosion rate reduces, since the extracted discharge decreases the transport capacity in the main channel. Downstream of the intervention, where both channels confluence again, erosion rates increase, since the transport capacity increases again. This leads to a pattern of relative erosion alternated by relative sedimentation compared to the bed degradation in the reference scenario. These findings are in line with an earlier study by Oldenhof (2021), who found that sequential side channels may induce a scour hole, due to the way the discharge is extracted. However, this scour hole is found to be less than the additional erosion created by the side channel, which agrees with the erosion and sedimentation pattern shown in Figure 17, where downstream of the side channel less sedimentation (but no additional erosion) is found than along the trajectory of the side channel.

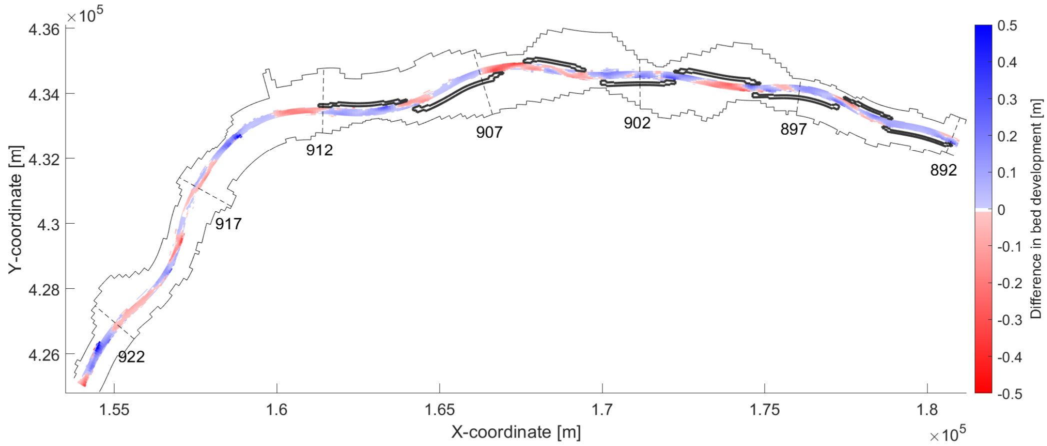

Figure 18: Difference in initial bed level response due to the river interventions between the Reference and RfLR scenario after one year. Negative values indicate more erosion in the RfLR scenario. Flow direction is from right to left.

Over time this initial response smooths out and turns into relative sedimentation compared to the reference scenario along the whole Middle-Waal (Figure 19). The sedimentation which occurs at the upstream end of the interventions starts propagating in downstream direction, such that the initial relative erosion is filled up. Eventually, after 24 years, the undesired initial response (i.e. the additional erosion) has turned into relative sedimentation, such that the interventions induce no additional erosion compared to the reference scenario. This is visible in Figure 19, as no negative difference in bed level is left along the trajectory of the interventions after 25 years. Eventually, the rate of the relative sedimentation decreases, suggesting that the maximum effects of the interventions have been reached.

However, restricting the analysis to the Middle-Waal only shows part of the effects induced by the interventions. Morphodynamic effects are not always only bound to the location of interventions. Figure 19 shows that this is also the case for the RflR measures. Both up- and downstream of the interventions, the bed level after 50 years is affected. Whereas the relative changes upstream of the interventions show an erratic response, they show an almost uniform response downstream.

Downstream of the interventions, it stands out that the interventions only cause additional erosion. After the first five years extensive bed degradation has taken place over a distance of 7 kilometers. In the following years, this scour then propagates in downstream direction in line with a bed celerity of 1 km/y. However, the sedimentation front propagating through the Middle-Waal does not seem to propagate into the Lower-Waal after the scour has passed. This additional erosion is presumably caused by the relative sedimentation in the region of the interventions, which lies upstream of this trajectory. Since relatively less sediment is supplied by the flow from upstream, additional sediment needs to be eroded in this area to match the sediment transport capacity.
Figure 20 shows the width averaged bed levels of both simulations after fifty years. It shows clearly that the interventions reduce the bed slope in the Middle-Waal. However, the effects are mainly limited to the area of the interventions between rkm 892 and 924.

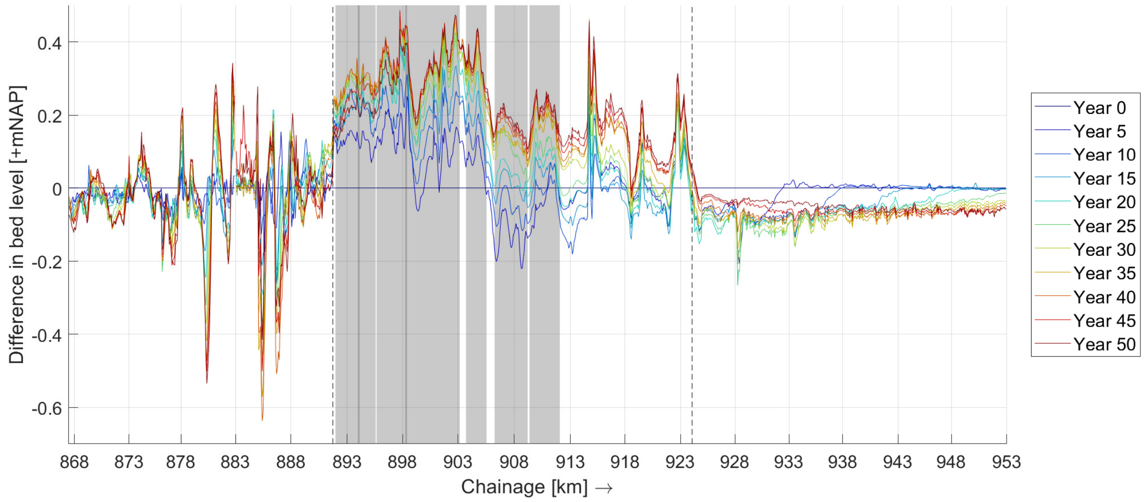

Figure 19: Width averaged bed level difference for every five years. The locations of the side channels are marked in grey, while the black dashed lines indicate the boundary of the floodplain lowering.

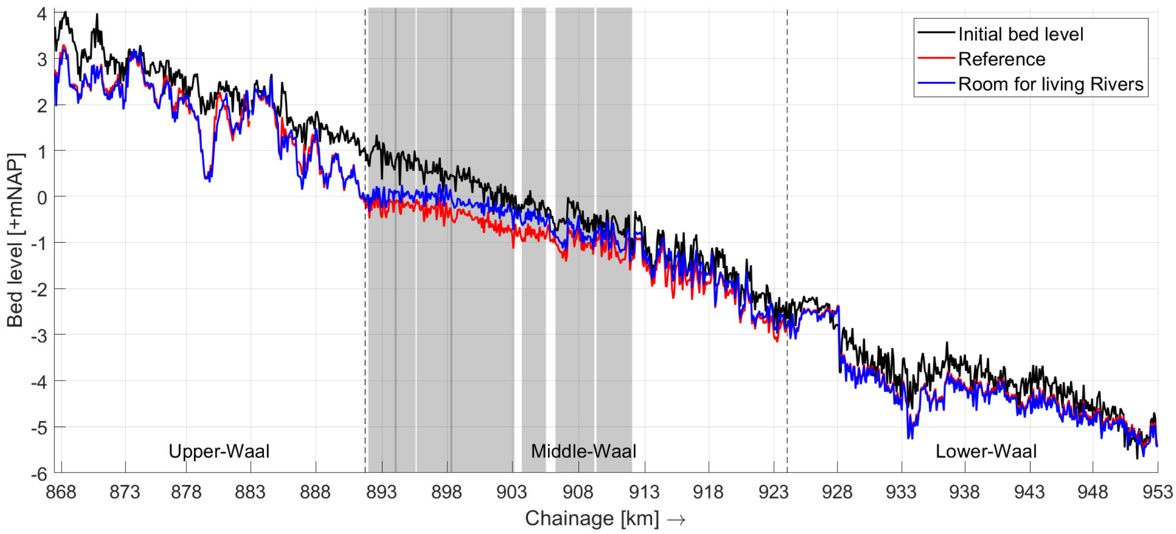

Figure 20: Width averaged bed level of the main channel initially and after fifty years for both scenarios. The locations of the side channels are marked in grey. The black dashed lines indicate the boundary of the floodplain lowering.

4 Discussion

In the previous section, effects of the Room for Living River have been shown. However, these findings do not necessarily imply the same effects will be obtained in practice. Some remarks should be placed to interpret the results.

One of the most striking findings is the large bed degradation occurring in the first years in both the reference and the RfLR scenario. In reality it is highly unlikely that such large developments take place without a certain trigger. It is therefore expected that this response is most likely attributed to the model configuration. As stated, during the large bed degradation it was found that also the bed composition in the Upper-Waal changes rapidly. Since the bed composition and bathymetry originate from measurement campaigns up to 2012, while the river's other spatial characteristics are based on its configuration in 2015, the initial configuration may not match a realistic distribution of sediment fractions. Similar behaviour of the DVR model was found by Flierman (2017). Although she made use of the dredging module, she found that in the first five years of simulation, bed level changes show unstable behaviour with much variation over small distances. Especially around the border of the graded and uniform sediment domain (at rkm 891), erosion in the same order of magnitude was found. To overcome this behaviour, Sloff et al. (2014) introduced an additional spin-up procedure to redistribute the initial bed composition more realistically since 'otherwise large morphological changes may occur which are just the effect of the initialisation of the model'.

The simulated bed degradation can be compared to measurements by Sieben et al. (2008) (Table 4). Although the measurements in more recent years (1999 - 2006) are too short to draw solid conclusions, it seems that the model overestimates the amount of erosion in the Middle-Waal largely. This is most likely a result of the large erosion downstream of rkm 890 in the first years as discussed above.

Another factor of influence, is the transition from graded to uniform sediment within the model. Besides the change in sediment size, which is accounted for by the continuity of mass, the sediment transport equations also change. The chosen sediment transport equations and their calibration factors have great influence on the size of the computed sediment transport. As shown by Kitsikoudis et al. (2014, 2015), the choice of sediment transport equation greatly influences the computed sediment transport. In case of such boundary where the sediment transport equations change, a bias due to the change in sediment transport equation may thus occur. Even though the choice of equations and calibration is justified by Yossef et al. (2008), uncertainty remains present in the computed sediment transport (Flierman, 2017).

Another large model-based uncertainty is due to the method of implementation of the interventions. Whereas this would normally be done through a standardised method including Baseline, a different non-standardised procedure has been carried out in this study because only the Delft3D model specific input files of the reference scenario were available. The derivation of files for Delft3D is a one way process, making it impossible to reconstruct the original GIS representation in which adaptations could be made. Within the Delft3D input it is for example impossible to distinguish between types of dikes, while the aim is to only remove the summer dikes. Projecting the input files on available recent Baseline schematizations, it was tried to stay as close as possible to the Baseline protocol when implementing interventions. Therefore, it cannot be stated with certainty that the interventions have been implemented exactly as imposed in the RfLR vision. However, the proposed interventions are still in a conceptual design stage rather than a definite design, which makes it sufficient to approach the design as much as possible. Although it remains thus uncertain to which extent the interventions have been implemented exactly according to the vision and constraints (Table 3), the effects of the implementation have been assessed in Section 3. It was envisioned that the interventions would reduce the flow velocity in the main channel for discharges above OLR. However, results show that only for discharges above 3053 m^3/s the interventions affect the hydraulics in the main channel. Whilst it was intended that the side channels become active at discharges lower than what is currently found, a previous 1D study by Barneveld et al. (2019) show similar behaviour for the same set of interventions. A possible explanation may be due to the method of implementing the interventions: the side channel's minimal bed level is based on the OLR in the reference case, while the interventions will affect the hydraulic conditions of the river. Due to sub-critical flow conditions, the downstream interventions affect flow at the upstream interventions throughout the induced backwater effects. Therefore, the individual side channels become active at different discharges. This suggests that the current contribution of the interventions in reducing the bed degradation can potentially be increased. In case the interventions are implemented such that they influence the main channel hydraulics also for lower discharges, it is expected that the long-term resulting bed level reduction will be larger.

Regarding the boundary conditions, another point of discussion should be noted. In this study, the boundary conditions both up- and downstream have been kept constant both in time and for each scenario. The first implies that the used hydrograph remains equal over fifty years and downstream the water levels remain constant for given discharges. The recent IPCC report however, foresees strong climate change leading to longer droughts and more frequent high precipitation (IPCC, 2021). A constant hydrograph thus introduces a bias. In addition, sea level rise will influence the downstream water levels at all discharges: over time the water level will increase. Where the change in upstream discharges

Table 4: Annual average bed degradation [m/year] for three river trajectories based on measurements and simulations. Measured bed level changes are given by (Sieben et al., 2008).

Trajectory	rkm	1950 - 1973	1970 - 1999	1999 - 2006	Average	Simulations
Upper-Waal	868 - 886	-0.01	-0.03	-0.017	-0.021	-0.012
Middle-Waal	887 - 915	-0.01	-0.01	-0.005	-0.009	-0.012
Lower-Waal	916 - 951	0.01	-0.02	0.004	-0.013	-0.006

may increase the erosion in both the current situation as well as after implementation of the RfLR interventions, the underestimate of the downstream water levels will lead to an overestimate of the erosion. To which extent these biased compensate each other must be pointed out by further research. Not adapting the boundary conditions between simulated scenarios implies that the interventions do not influence the boundary conditions. For the upstream condition this is clear, but the downstream conditions may change as the discharges in each branch may change over time. However, Figure 21, shows that the change remains limited. Therefore, the effects of the constant downstream with respect to the reference scenario remain negligible.

Next to model based uncertainties, the level of generalisation influences the results as well. As this is still an exploratory study and the Room for Living River interventions have not been drawn up in detail, the interventions are implemented on a coarse level of detail. In reality, the measures will be implemented on a more detailed scale (i.e. it will not be possible to excavate the floodplains uniformly along the complete river Waal). When the interventions are applied in reality, the effects of the interventions on the hydrodynamics will probably reduce. As a result, the morphodynamic response in this study will most likely show an overestimate of the reduction in erosion, since the the measures are implemented in the model on a larger scale than it might be possible in reality. This does not imply however, that the Room for Living Rivers as currently proposed will have no effects.

As mentioned earlier, the Dutch Rhine branches cannot be regarded as individual river branches. Therefore, the interventions may affect the river's (hydraulic) behaviour at the upstream bifurcation (Pannerdensche Kop) (Gensen et al., 2021) and thereby the discharges and bed development in the Pannerdensch Kanaal and possibly even further downstream branches. This is highly undesired as the change in discharge may affect the flood safety. Although this is not part of the scope of this study, a global insight in the effects of the interventions can be made. The interventions do not show to affect the development of the discharge distribution significantly (Figure 21). The interventions do influence the bed level development in the channel. However, the additional induced erosion and sedimentation remain within 5 cm over a period of fifty years, with an exception downstream where the additional erosion reaches 10 cm (Figure 22). Compared to the simulated autonomous erosion, the effects remain limited.

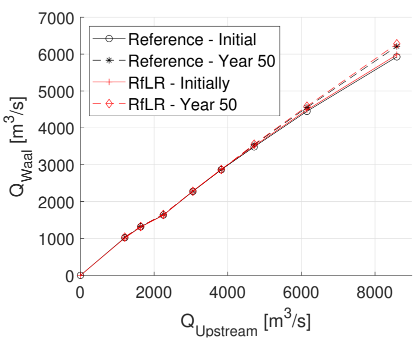

Figure 21: The discharge distribution at the Pannerdensche Kop initially and after fifty years for both the reference and the RfLR scenario.

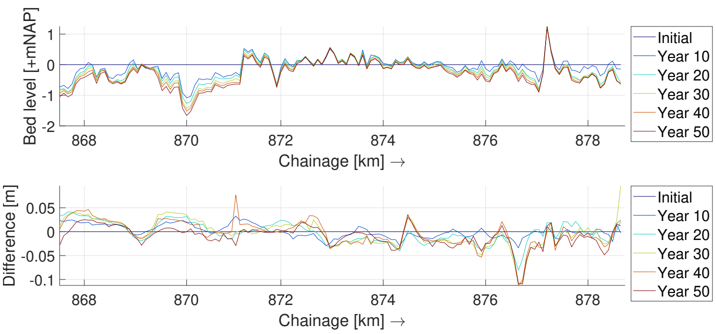

Figure 22: Top: width averaged bed level in the Pannerdensch Kanaal initially and after each ten years in the reference scenario. Bottom: difference in width averaged bed level in between reference and RfLR scenario. A positive value indicates less erosion in the RfLR scenario.

One of the special features of the DVR model, the dredging module, has not been used in this study. By excluding the dredging module from the simulation, recent nourishments in 2016 and 2019 in the Bovenrijn (rkm 862 - 864.5) have not been included in the simulations. As these nourishments have been carried out with coarse sediments, the expectation is that they will lead to stabilisation of the bed in the Upper-Waal within the studied period (Sloff et al., 2014). Other studies using the DVR model have shown that the nourishments will elevate and stabilize the bed level in the period after the nourishments in the Boven-Rijn (Van Vuren et al., 2015; Flierman, 2017; Ottevanger et al., 2015b). However, the nourishments may also influence the discharge distribution at the bifurcation Pannerdensche Kop, leading more discharge into the Waal (Ottevanger et al., 2015b). It remains unclear if the exclusion of this effect of the nourishments in this study leads to an under- or overestimate of the effects of RfLR. As the discharge distribution only changes slightly, the effects are not expected to be large.

If the findings in this research are compared to the 1D study by Barneveld et al. (2019), the general conclusions coincide; RfLR can reduce the ongoing erosion in the long-term, but the erosion will not be stopped. It is difficult however, to make a detailed qualitative comparison. Mainly this is due to a difference in trajectory length where the interventions have been incorporated as Barneveld et al. (2019) also applied the interventions to the Upper-Waal (rkm 868-890). It should also be noted that the shown results are after hundred years in the study by Barneveld et al. (2019), while the 2D model shows results after fifty years. Besides, both models use different schematizations describing the river at different moments in time. This becomes clear in Figure 23, which shows that even the initial bed level differs greatly between both studies. This could be feasible as the study by Barneveld et al. (2019) makes use of the bed level of 2017. However, it would be expected that the initial bed level in the 1D study would be below the initial bed level in this study, as the observed erosion would have led to a decrease in bed level. Why this initial discrepancy is present, remains unclear. Comparing the local trends induced by the interventions in the Middle-Waal between both studies, both models predict the erosion between rkm 891 and 903 already present in the reference case. Whereas the 2D model shows the RfLR measures to mitigate the erosion, this effect is less visible in the 1D study. Further downstream, between rkm 905 and 923, the 1D model shows that the RfLR induce additional sedimentation compared to the reference case, while the 2D model only shows a reduction in erosion.

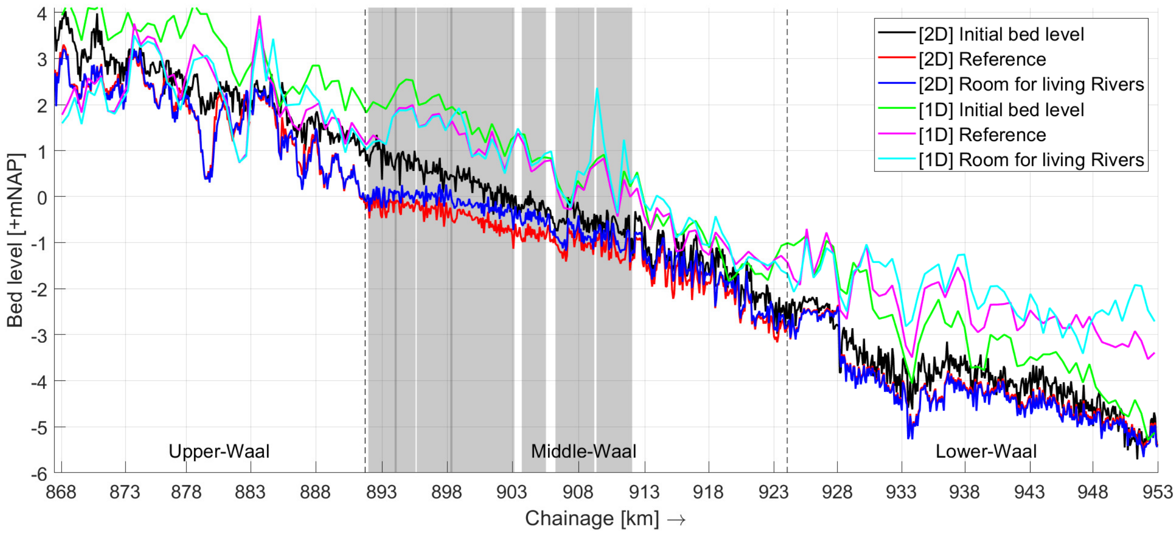

Figure 23: Initial bed level and bed level after 50 years for the two scenarios in the current 2D study compared to the modelled bed levels initially and after 100 years of an earlier 1D study by Barneveld et al. (2019).

Another difference between the 1D and 2D study, is that the 2D model is able to capture transverse variability in the bed level. Figure 7b for example shows that the river bed in the river bends next to the fixed layers erodes, as the fixed layers only cover half of the main channel. The 1D study shows no bed degradation at these locations (Figure 23), as it is not possible to schematize this transverse difference in bed composition in 1D. In this study it was also found that at the up- and downstream connection of the side channels, spatial patterns are found (Figure 17), which are induced by secondary flow. Again, this also is a 2D physical process, which is not possible to capture in 1D. In the latter, discharge is simply extracted, which makes it hard to model side channels and longitudinal dams (Barneveld et al., 2019).

5 Conclusion & Recommendations

Within this research, the objective is to gain insight in the effects of the Room for Living River vision on mitigating erosion when modelled in 2D. Using the DVR model, which is based on the Delft3D computational core and additional Python scripts, the morphological development with and without the proposed interventions have been modelled. Using steady-state conditions in combination with a discretized hydrograph and a morphological factor, it was possible to assess these effects over a period of fifty years within a reasonable period (two weeks). In this chapter, first, the conclusion of this research is presented, after which recommendation are given on morphological modelling with the DVR model and the Room for Living Rivers vision in general.

Conclusion

This study shows that the Room for Living River interventions show potential in their ability of mitigating the ongoing bed erosion in the Middle-Waal. The reference scenario shows that the current trend of bed erosion will continue in the coming fifty years without a change in erosion rate. This suggests that even after fifty years a stable (dynamic) equilibrium bed slope is not yet reached. This increases the necessity to intervene in the river to mitigate the erosion and its resulting problems for nature and society.

The interventions, as they are implemented in this study, are not capable of stopping the erosion completely along the river Waal. Although they reduce the erosion, the effects remain local and close to the interventions. In order to reduce the bed degradation over a longer distance, the interventions should thus also be carried out over a larger trajectory. At the end of the interventions, the sediment deficit in the flow is compensated for by additional erosion. This is foreseen in the Lower-Waal, as the interventions restrict the supply of sediments from the river bed along their trajectory. Although the interventions are thus capable of reducing the erosion, they enhance the ongoing erosion downstream.

Assessing the bed level response to the interventions in time, two developments stand out. First, both simulations show a significant bed level degradation in the first five years. Since this behaviour is encountered in both scenarios, this is expected to be induced by the model configuration itself, rather then by natural processes. Same results have been found in other studies using the same model (Sloff et al., 2014; Flierman, 2017). In further use of the model it is recommended to investigate, and when possible eliminate, this behaviour. Incorporating additional spin-up time for the morphodynamics may be a first solution. For now, it remains unknown how this strong behaviour in the first years affects the results. Second, in the first years after the implementation of the interventions, large bed differences between both scenarios have been found. If the side channels overlap (i.e. continuously extract discharge from the main channel), less erosion compared to the reference is the dominant response. However, if the discharge from both channels first confluences before the next side channel bifurcates again, a scour hole will occur enhancing the already present erosion. This study shows that the additional erosion due to the initial morphological response to the interventions is undone after 24 years. Thus, after 24 years, the interventions lead to a reduction in erosion along the complete trajectory of the interventions.

Regarding the connection of the side channels, another response is found. The 2D results show that the connection of the side channels to the main channel may induce secondary flow, creating local shallows over the width of the main channel. Especially where side channels confluence in river bends, the bed flow effects may be enhanced, causing more erosion. Opposite, at the bifurcation of a side channel, sediment bumps may form when the side channel is not connected at the right elevation. In future design it is thus advised to pay attention to the connection of these side channels.

The added benefit of this 2D approach to an earlier 1D study by Barneveld et al. (2019), is that the just mentioned effects of the interventions on the transverse variability can be estimated. These results are not found by Barneveld et al. (2019), as the underlying physical processes cannot be captured in a 1D model. However, the general conclusion, that the RfLR vision reduces but not stops the erosion, is shared by the 1D outcomes. Whereas Barneveld et al. (2019) concludes that the RfLR should be implemented over a long trajectory while a uniform pattern of erosion and sedimentation should be pursued, this study adds to this that processes such as secondary flow can cause large transverse gradients at the up- and downstream connections of the side channels; the location and connections of the side channels thus should be taken into account. As the main findings between both the 1D and 2D comply, the benefits of a 2D model do not outweigh the additional computation time (several days versus several weeks) in an exploratory study where different scenarios are evaluated. In a later stage where the vision is reviewed with a greater level of detail regarding the interventions, 2D morphological modelling is found to provide additional value, as the measures have shown to induce large transverse gradients in the river bed, which may interfere with the objectives of the RfLR vision.

Recommendations

Based on the findings in this research, recommendations are made regarding the used modelling approach (method) and the Room for Living Rivers vision.

Recommendations on morphological modelling using the DVR model

The tool used to conduct the morphological modelling, the DVR model, is based on the generally used Delft3D computational core supplemented by additional Python scripts. Although this has been the prescribed computation tool for this scale of morphological modelling of the River Rhine branches by the Dutch government for quite some time, parts of the model are starting to become outdated. Since a few years now, a new generation of morphological models for the Dutch part of the River Rhine is being developed. This new generation introduces new functionalities to the model, such as the possibility to use an unstructured grid and thereby local grid refinement. Besides, the model will be calibrated on updated bathymetry and spatial characteristics. Thus, it is recommended to evaluate further (more detailed) Room for Living River visions using the new generation models when they become available.

However, using a new generation model does not prevent further recommendations based on the current findings. Independent of the used computational software, it is recommended to have a more detailed look into the strong erosive behaviour which is found in the first years of simulation. It remains unclear if this is solely a numerical artefact or if a physical process is the underlying cause. Further evaluation of this cause can put the found extend of the erosion into perspective. Possible methods to address this matter might be to compare the bed composition with more recent measurements or by incorporating a certain spin-up time where the bed level is kept in place.

Finally, it is recommended to increase the used resolution of the numerical grid. Since a spatially varying data in the schematization is projected on the grid, increasing the grid resolution makes it possible to better represent the river's bathymetry and roughness. As the cell density is already high in the main channel, a further increase in cell density in the floodplains will be beneficial for further studies. This is mainly because the interventions will lead to increased flow velocities outside of the main channel. Besides, reducing the grid cell size in the floodplains will make it possible to better represent (the shape of) the side channels. A downside of increasing the numerical grid, is that it might increase the computational time. The earlier mentioned new generation models may provide outcome, as the incorporated unstructured grid makes local grid refinement possible.

Recommendations on the Room for Living Rivers vision

In this research, the Room for Living River vision is only applied to the Middle-Waal. However, the Room for Living rivers encompasses interventions along all three major River Rhine branches in the Netherlands. As seen in this study, the interventions are able to mitigate erosion along the trajectory where they are implemented, while they induce additional erosion everywhere downstream and locally upstream. A strong recommendation for further research is to assess the bed development in case the RfLR vision is applied to all three River Rhine branches in the Netherlands.

A final, more general recommendation, is to assess the effects of the RfLR vision on other river functions. The troublesome bed degradation present in the river is partly due to a long period of intervening in the river system, while only focussing on one river function at a time. Within the current IRM, this scope has changed. Combining this with the upcoming new generation of riverine models, it becomes easier, and therefore recommended, to assess the effects of RfLR on different river functions altogether.

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A Overview Baseline schematizations

In this appendix, an overview is given of all interventions for which a permit was issued, and were thus incorporated in the used Baseline schematization.

As a starting point, the model uses three different Baseline schematizations. The schematization of the Niederrhein is adapted from the so-called 'Grensproject Bovenrijn'. For the other domains, excluding the Merwedes, the schematization 'baseline-rijn-Ref2015' is used. At last, the Merwedes is schematized using 'baseline-rmm-beno12_5-v1'. Additional measures have been mixed into this base model. The name, type and location of these measures is shown in Tables 5 and 6.

Table 5: Overview of included Room for the River and Water Framework Directive measures in the model. Adapted from (Sloff et al., 2014).

Nr.	Description	Intervention	River branch	Start [rkm]	End [rkm]
1	Millingerwaard	Construction channels	Waal	876.6	873
2	Bemmelsche Waarden	Floodplain lowering	Waal	878.2	881.4
3	Lent	Construction side-channel and dike relocation	Waal	881.5	886.6
4	Groyne lowering Middle-Waal	Groyne lowering	Waal	886.8	914.7
5	Afferdensche en Deetsche Waarden	Construction channel and floodplain lowering	Waal	898.5	903.2
6	Longitudinal Training Dams Tiel	Construction longitudinal Training Dams at inner bend and groyne lowering at outer bend	Waal	911.5	921.5
7	Groyne lowering Waal Fort St. Andries	Groyne lowering	Waal	914.7	934.2
8	Groyne lowering Lower-Waal	Groyne lowering	Waal	934.3	953.6
9	Munnikenland	Construction channels and dike relocation	Waal	947.6	952.6
10	Avelingen	Construction channel	Boven Merwede	955.8	957.5
11	Noordwaard	Construction flood area (NL: doorstroomgebied)	Nieuwe Merwede	963.0	979.7

Table 6: Overview of Water Framework Directive measures in the model. Adapted from Ottevanger et al. (2015a).

Measure	Abbreviation	Start [rkm]	Length [m]	Left/right bank	Foreshore
Winssensche Waard	wl_winw_z1	895.2	135	L	no
Ochtendse Buitenpolder	wl_ocht_z1	902.4	190	R	no
Dreumel	wl_heerw_z1	981.9	380	L	no
Heerewaarden	wl_zuil_z1	922.8	410	L	no
Zuilichem	wl_dreu_z1	943.5	140	R	no

B Elaboration on implementation of interventions

The normal procedure for this in Delft3D 4 would be to make use of Baseline. By doing so, one would first schematize an intervention in GIS according to the most recent Baseline protocol. After this, the intervention would be mixed in (i.e. merged into) the most up-to-date schematization of the river. The new situation will then be projected on the predefined grid and converted to Delft3D input files, again using Baseline. For this study however, the original Baseline model used for the reference case was not available. To overcome this problem, the interventions have been implemented directly in the Delft3D input files. In the sections below, an elaboration will be given on the used procedure to implement the proposed interventions: the construction of side channels and lowering of the floodplains.

Construction of side channels

The key element in the RfLR vision is the construction of side channels to reduce the flow velocities in the main channel. A first and coarse design of the location and geometry of side channels in the Middle-Waal has been made by ARK Natuurontwikkeling and Bureau Stroming (2020), see Figure 1. This has been the starting point for incorporation in the model. However, as the model is bound to the existing computational curvilinear grid, a one-on-one projection of the sketch on the modelinput is not possible. Therefore, the sketch has to be discretized to comply with the model input such that is the corresponding input files can be adapted accordingly. This incorporation consisted of the following steps, of which the first three have been carried out in ArcGIS and the latter three in the FME software suite:

1. Project the sketches by ARK Natuurontwikkeling and Bureau Stroming (2020) (Figure 1) on the model grid
2. Trace the outline of the new side channels
3. Project the outline on the grid and select corresponding cells
4. Lower the bed level in the selected cells to OLR
5. Change the bottom roughness in the side channels accordingly
6. Remove all weirs and dams within the side channel

Using the incorporated toolboxes in ArcGIS, the sketches have first been georeferenced, such that the location and dimensions of the sketch match reality and thus the model dimensions (Figure 24(a)) . From here, the outlines of the sketched side channels have been traced. If these outlines are then projected on top of the computational Delft3D grid (Figure 24(b), (c)), it becomes visible that it is rather difficult to capture the curvature of the side channels in the defined grid. To overcome this, the outlines have been manually snapped to the computational grid. During this snapping, the following constraints have been take into account (Table 7):

- The width of the side channel may not exceed $85m$ and the cells should be connected in at least U- or V-direction (i.e. not only connected diagonally).
- The local cell size within the grid. Due to the nature of the curvilinear grid, which is more coarse in the floodplains, especially the cell dimensions in the outer bends outside of the main channel are large. This both implies that the width of the side channels may take on sub-grid dimensions and that the Courant number increases if they are located too far away from the main channel due to the increase in flow velocity. Therefore, the side channels may be located closer to the main channel compared to the sketch.
- The new side channel may not be connected to the main channel, except for the up- and downstream channel end. As there is no distinct differentiation between the main channel and floodplains, cells within the main channel have been defined as all cells within the current definition of the summer bed by Rijkswaterstaat extended by a $50m$ buffer. This buffer has been created in order to take into account the groyne fields, which remain unaltered in this study.

The results of the snapping procedure can be seen in Figure 24(c) and are being used in steps 4-6. These steps all relate to changing the bathymetry in and around the side channels. First, the bed elevation in the side channel will be lowered to OLR acoording to the sketches, so the value of OLR must be

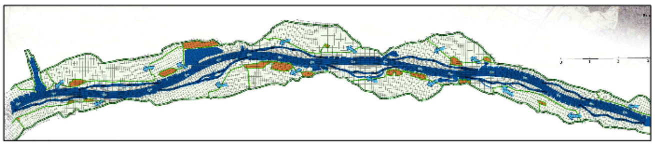
Table 7: Constraints used during implementation of side channels

Parameter	Value
Minimum width	65 m and 2 cells
Maximum width	85 m
Bed level	OLR (water level for $Q = 1020$ m^3/s at Lobith based on model)
New roughness code	105, corresponding to a roughness height of 0.20 m (complies with vegetatielegger)

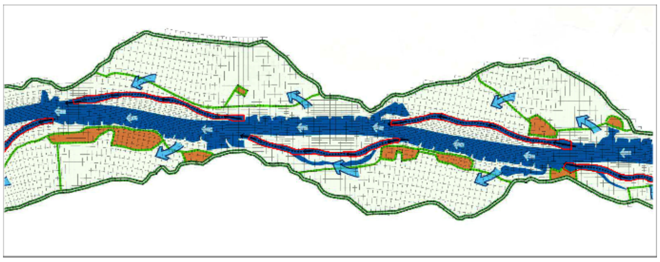
determined. OLR is defined as the water level corresponding with the OLA which is set at 1020 m^3/s at Lobith for the period 2012 - 2022 (Jans et al., 2018). The current OLR is thus defined in 2012, after which large scale interventions to the river have taken place. Since the defined OLR will possibly change in the near future, the OLR has been redefined in this study, by running the reference model with an upstream discharge of OLA (i.e. 1020 m^3/s. The obtained water level is considered as OLR further in the report.

Next, the bottom roughness in the new channels must be redefined. As mentioned earlier, this bottom roughness is based on trachytopes, which corresponds to a pre-defined roughness classification within Delft3D (Deltares, 2020; Rijkswaterstaat Waterdienst and Deltares, 2013). According to Rijkswaterstaat Waterdienst and Deltares (2013), the created side channels are classified as 'sandy side channels', which are attributed roughness code 105. In the model, this corresponds to a constant Nikuradse roughness height of $0.20m$.

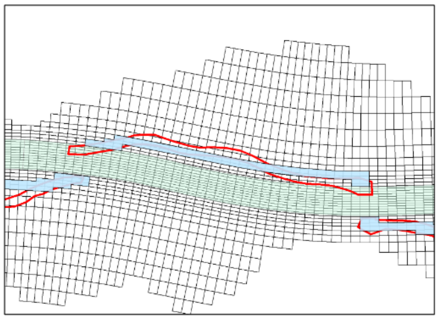
The last step in the implementation of the side channels, is to remove all constructions and groynes in the channel. This again has been done using FME, where all present groynes and thin dams within the shapefiles of the side channels have been removed from the input files.



(a) Model grid with georeferenced sketch by ARK Natuurontwikkeling and Bureau Stroming (2020).



(b) Zoom of model domain. In red the outline of the new side channels is traced.



(c) Model grid with sketched side channel outline (red), schematized side channel (blue) and main channel (green).

Figure 24: Different stages in the process of implementing side channels in the Delft3D input files.

Lowering of floodplains

A second proposed measure is the lowering of the floodplains. As this study aims to get first insight in the morphological response of the river Waal, the lowering of the floodplains is implemented on a coarse level of detail. Analogous to the approach by Barneveld et al. (2019), the floodplains in the model are in principle lowered by 2 meters. As it is undesired that the floodplains become (locally) below OLR, leading to an even further reduction of OLR, a restriction is applied such that the new floodplain level may not be located below OLR. To maintain the integrity of present dikes, the area within the so-called 'keurzonering' (i.e. the protected area around the dikes) has been kept untouched. To do so, all grid cells with their center within 100 m of the winter dike have been excluded in the lowering. Also the area between the main channel and the newly constructed side channels have been excluded in the lowering, as otherwise these areas would be lowered such that it would no longer create a boundary between both channels. The resulting schematization is shown in Figure 25.

Groyne lowering and removal of summer dikes

As explained in Section 1, the lowering of groynes is also part of the RfLR vision. In the current proposed design, the new height of all groynes in the river Waal should become equal to OLR. As the groynes in the Middle-Waal have already been lowered to OLR as part of the Room for the River measures, which are already incorporated in the reference scenario (see Appendix A), no model adaptations have to be made for this measure.

The removal of the summer dikes is done by spatially selecting all sub-grid structures (weirs and thin dams) located within 50 m of the outside of the groyne fields and excluding them in the new input files.

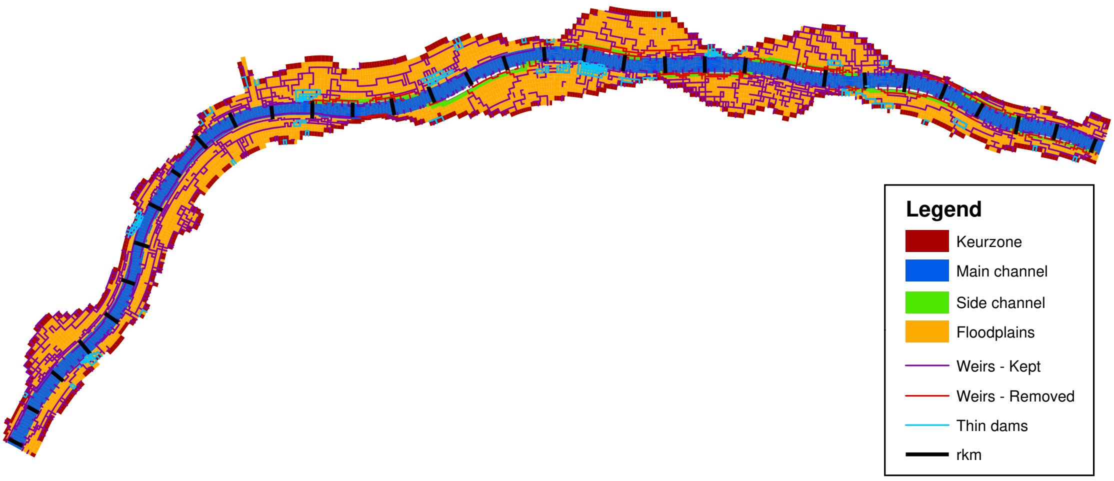
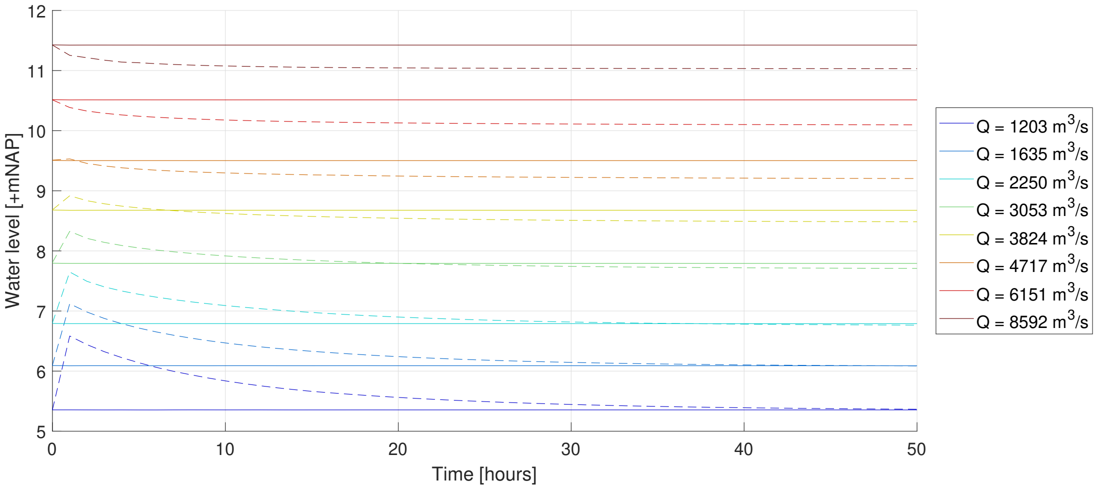


Figure 25: Room for Living River schematization regarding classification of cells and sub-grid structures.

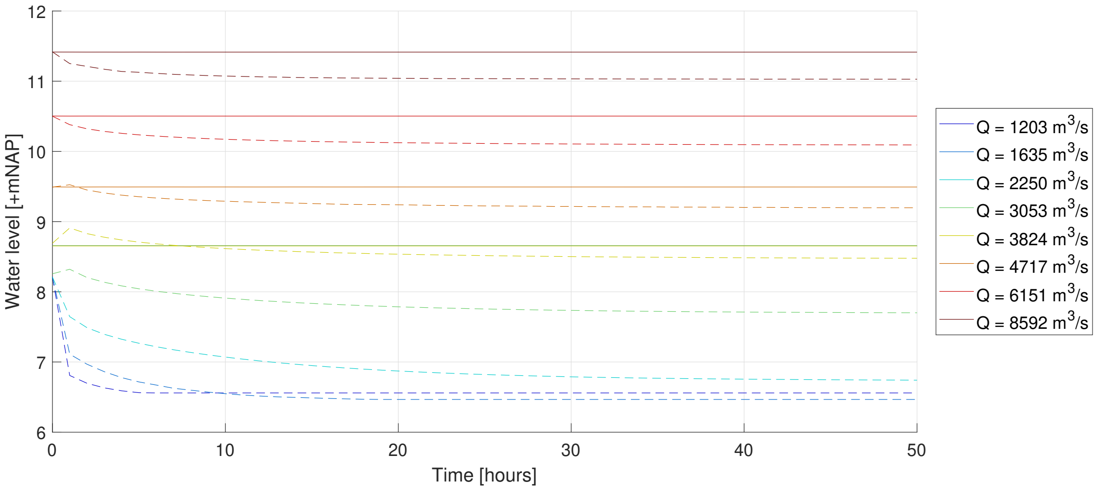
C Verification of spin-up time

In this appendix, verification of the chosen initial period at the start of the simulation is provided. In Figures 26 and 27, the development of the water level and flow velocity are shown over time respectively. The parameters have been visualized on on two locations, in the main channel and halfway the most upstream side channel (both at rkm 893 in the Middle-Waal) and for both simulations.

Regarding the water levels, Figure 26 shows that in the reference scenario, the water level in both the main and side channel remains equal to the initial specified value during the complete simulated time period. This validates the choice of applying no additional spin-up time at the start of the reference scenario simulation: as the initial water levels comply to the steady-state for each discharge, no additional time is needed to reach the steady-state. In the RfLR simulation, the figure shows that the water levels do need to adapt to the new river bathymetry. Although the water levels in the main channel increase before the decrease in the first hours of the simulation for discharges below 6051 m^3/s, they converge towards new steady-state conditions over time. After 50 hours of simulation the water level differences have become so small at both locations and for all discharges, that it can be assumed that the steady-state configuration are approached enough the purpose of this research.



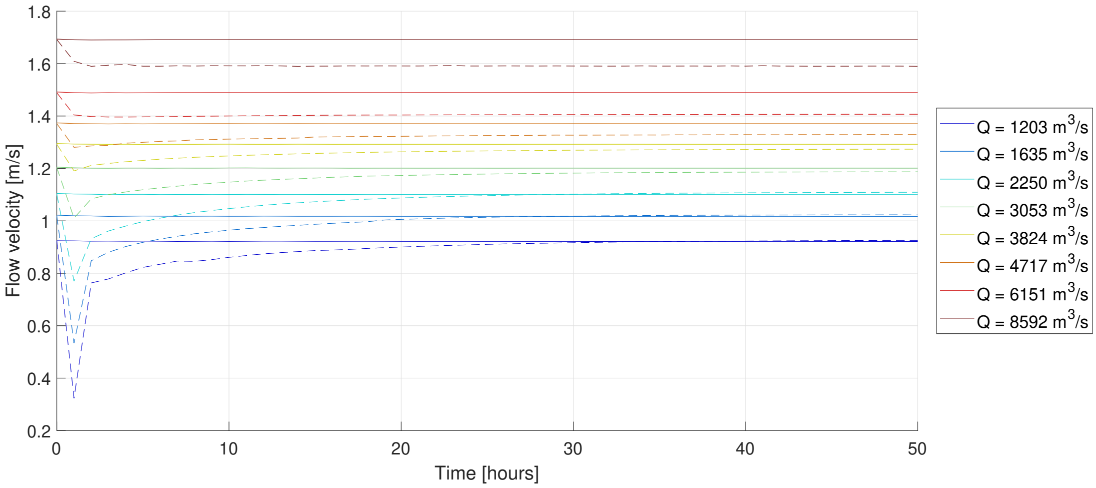
(a)



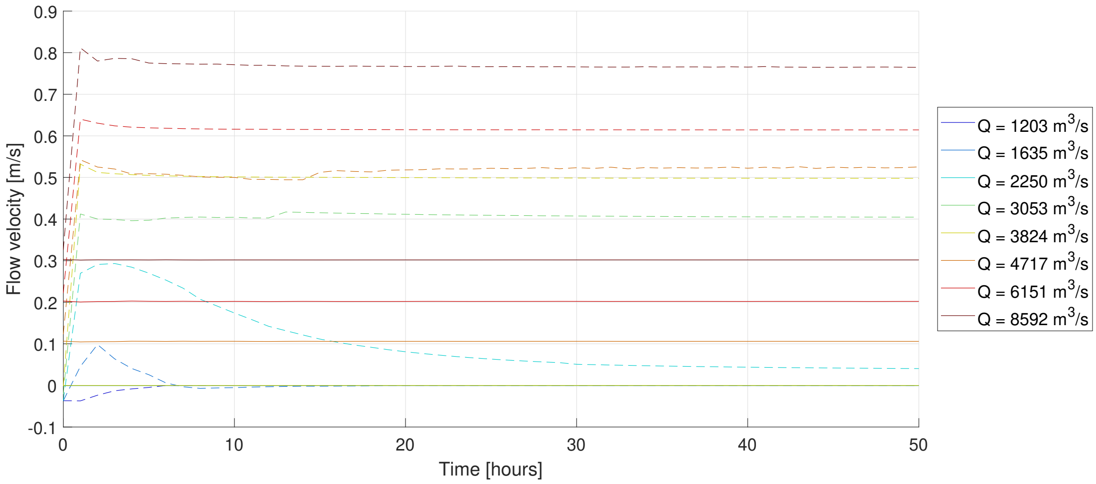
(b)

Figure 26: Simulated water levels over time without morphological development for all simulated discharges (a) at rkm 893 in the main channel and (b) in the newly incorporated side channel. The solid and dashed lines represent the reference scenario and the RfLR scenario respectively. No water levels are shown for discharges below 3053 m^3/s for the reference scenatio in (b), as this location is a non-inundated floodplain in the reference scenario.

Regarding the flow velocities, the same conclusions can be drawn. Again, the initial flow velocities in the reference scenario correspond with the steady-state conditions, thus eliminating the necessity of an additional spin-up time. The implementation of the side channels also clearly influences the steady-state conditions of the flow velocity, as can be seen the best in the side channels (Figure 27b). In line with the conclusion regading the water levels, after 50 hours, the change in flow velocity is limited to such extend, that it can be assumed that they correspond to the steady state conditions.



(a)



(b)

Figure 27: Simulated flow velocities over time without morphological development for all simulated discharges (a) at rkm 893 in the main channel and (b) in the newly incorporated side channel. The solid and dashed lines represent the reference scenario and the RfLR scenario respectively. No flow velocities are shown for discharges below 3053 m^3/s for the reference scenatio in (b), as this location is a non-inundated floodplain in the reference scenario.

D Width averaged flow velocities individual simulations

In this appendix, the width averaged flow velocities in the main channel for both the reference and the RfLR scenario are shown. For clarity, the simulated discharges are divided into the lowest four (Figure 28) and highest four discharges (Figure 29).

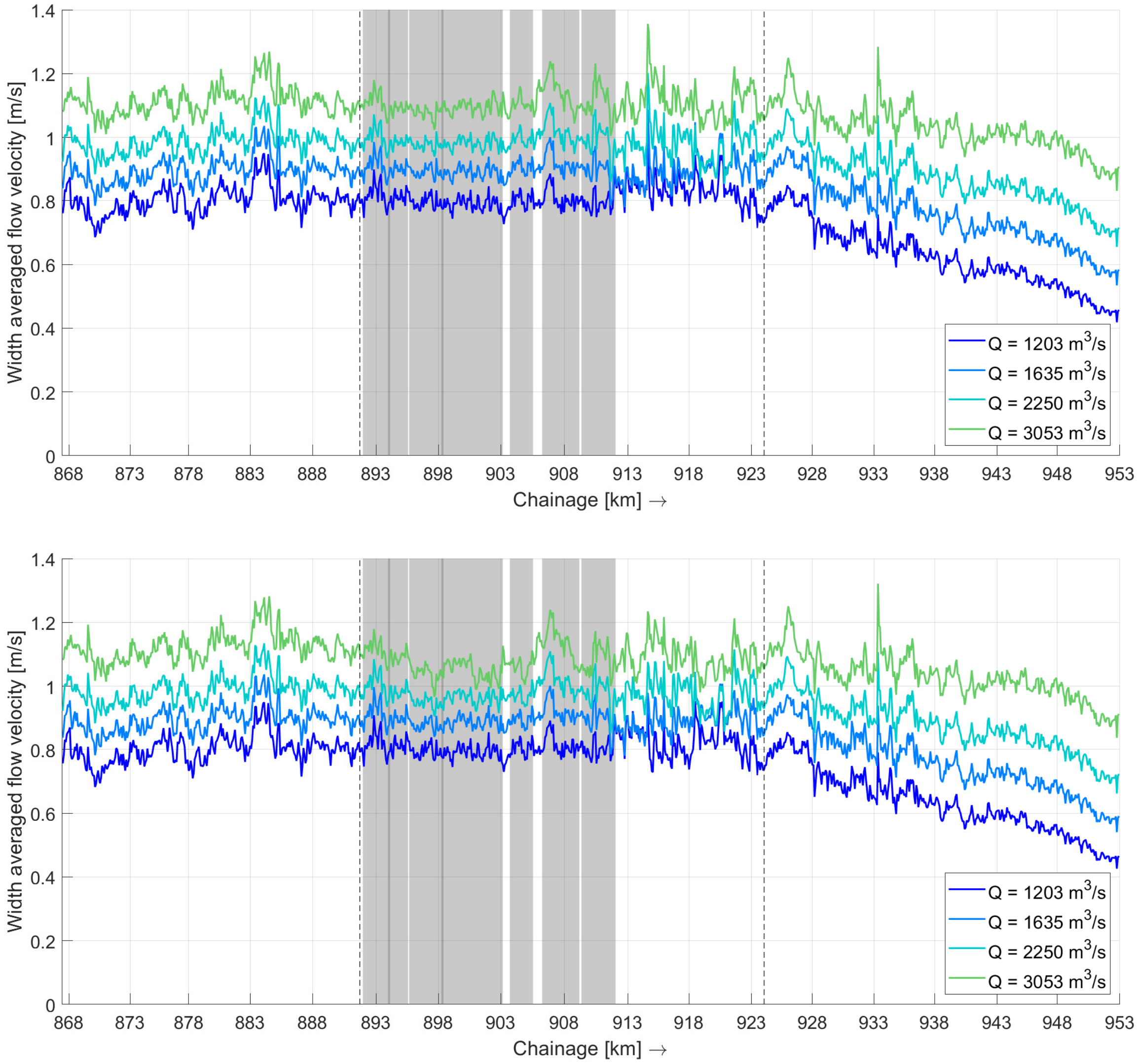


Figure 28: The width averaged flow velocities in longitudinal direction for the lowest four discharges. Top: the reference scenario. Bottom: Room for Living Rivers scenario. Each steady-state condition is based on the initial bed level at $t = 0$ in each scenario, excluding morphological changes. Grey areas show the locations of the implemented side channels, while the black dashed lines indicate the boundary of the floodplain lowering. The discharges shown in the legend correspond to the discharge at the model upstream boundary in the Niederrhein at Xanten.

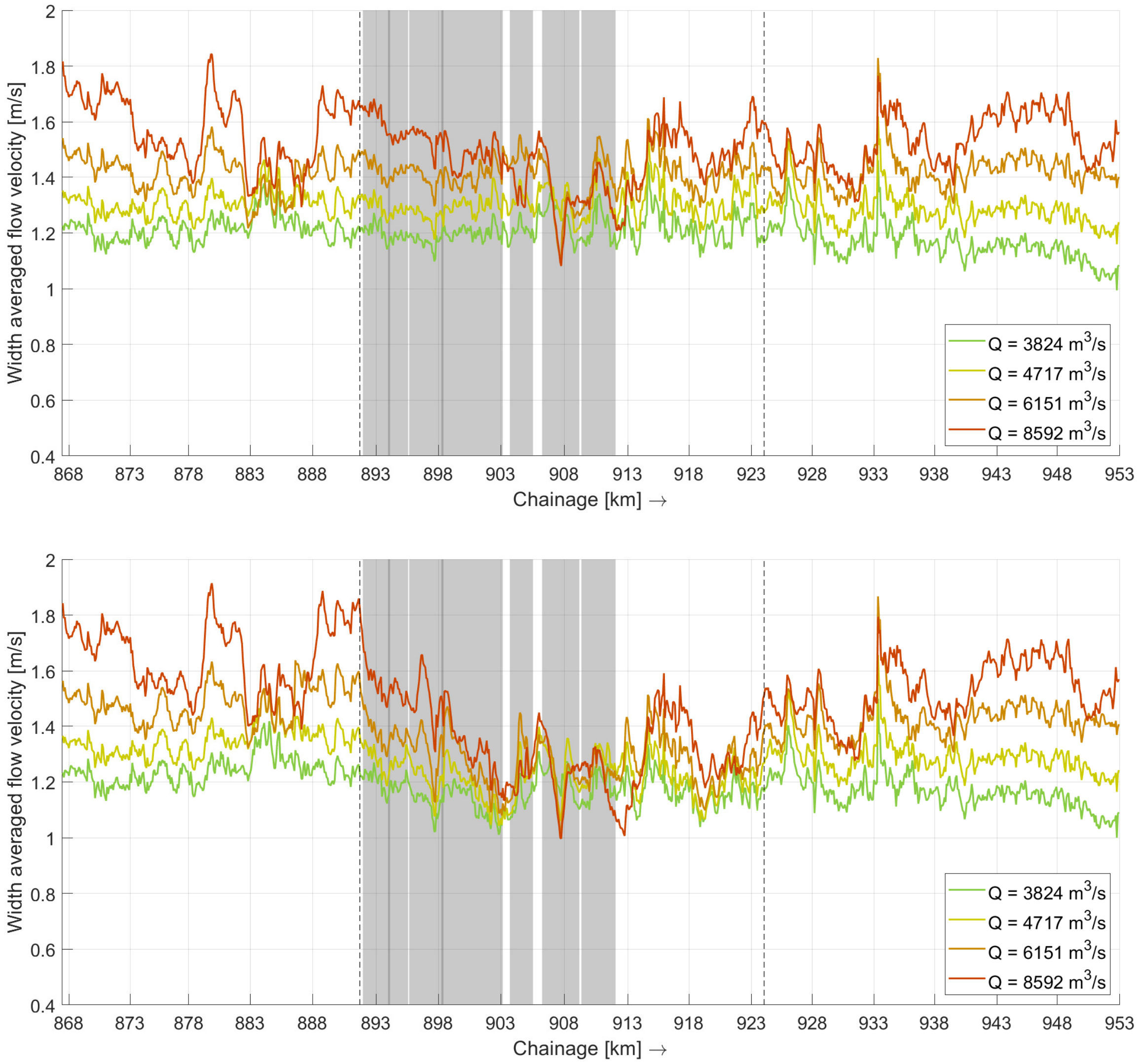


Figure 29: The width averaged flow velocities in longitudinal direction for the highest four discharges. Top: the reference scenario. Bottom: Room for Living Rivers scenario. Each steady-state condition is based on the initial bed level at $t = 0$ in each scenario, excluding morphological changes. Grey areas show the locations of the implemented side channels, while the black dashed lines indicate the boundary of the floodplain lowering. The discharges shown in the legend correspond to the discharge at the model upstream boundary in the Niederrhein at Xanten.