# THE LONG-TERM EFFECTS OF CLIMATE CHANGE ON THE RIVER PROFILE AND BED SURFACE

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# PREFACE

This report is the result of my final thesis which is part of my bachelor program Civil Engineering at the Delft University of Technology. This research topic was introduced to me by Dr.ir. A. Blom and during eight weeks it made me more and more enthusiastic about the topic of river engineering.

Now, while looking back on a period of hard work, I realize how much I learned from setting up a research from the beginning on, doing literature studies and working with a numerical model in a program that I never had used before. At this moment I am still doubting which direction I want to continue with when starting my master program, but at least I got a very good impression of the interesting topic of river engineering.

I want to thank A. Blom and L. Arkesteijn for their support, advising me during the process and providing me of a lot of feedback. Because that is what you learn the most of in the end.

# SUMMARY

The goal of this research is to get a better understanding of the long-term changes of the river profile and bed composition of the Dutch Rhine for the coming 300 years, based on the effects of different changing boundary conditions. Predictions of the river behaviour, like the change of the river profile and bed composition, are necessary to foresee the risks, to design proper river management measures and to limit negative effects. The following three boundary conditions are taken into account: a change in discharge (upstream hydrodynamic boundary), a change in sea level (downstream hydrodynamic boundary) and a change in sediment flux (upstream morphodynamic boundary). To simplify the situation of the Dutch Rhine, this research focuses on a case loosely based on the Waal.

To model future scenarios for the river several assumptions have made. For this research alternating steady flow is assumed to be present. The morphodynamic steady state is given by the Exner equation and for the sediment transport relation Engelund-Hansen is chosen. The river branch is simplified as a uniform channel with a prismatic cross-section. Furthermore the influence of current and future interventions on the river is neglected as well as the effect of flood-plains.

To be able to understand the separate effects of changing boundary conditions, first a base case is defined. The base case is based on the current situation for the Waal and does not take into account any changes for the boundary conditions yet. By modelling the base case, it became visible that a period longer than 300 years is needed to reach the equilibrium state. During the transition towards equilibrium, at the downstream end sedimentation takes place, while further upstream degradation occurs. The wave of erosion slowly moves in downstream direction and the change of the bed elevation results in an decrease of the bed slope all along the river reach.

However, in reality, the boundary conditions are slowly changing and this results in a change of the river bed profile and bed slope. To investigate the effects of these changes towards the future, the rate of change is defined and for each boundary condition several scenarios are defined.

For more extreme discharges (higher maximum and lower minimum), the average discharge will increase since changes of the peak discharge have a greater effect than changes of the base discharge. An increase of the average discharge will result in a higher flow velocity and a higher sediment transport rate. Degradation will therefore take place all along the river reach. Due to the change of the bed level all along the river branch, the slope decreases for all scenarios. The average water surface elevation and water depth however both increase.

For the sea level rise something different happens. An increased water level at the downstream end results in a higher water depth at the river mouth and therefore a decrease of the flow velocity. A lower flow velocity results in a decrease of the sediment transport rate and aggradation all over the river reach takes place. But, when the sea level is rising too fast, the system is not able to adapt to the new situation in time. The system wants to increase the bed level at the downstream part, since the water level is increasing as well, but the river is reacting too slow. The sediment needed from upstream is not supplied in time, resulting in a relative low bed level at the downstream end and a relative big water depth. Furthermore, a bigger increase of the sea level rise results in a longer backwater curve and higher water levels in upstream direction.

The outcome of this research has provided insight in a rough approach of the river behaviour on long-term, but more research on this topic is preferable. It is still difficult to make realistic assumptions for the rate of change for the different boundary conditions, since the available information is quite inaccurate and the range of possible scenarios is large. Also a lot of assumptions have been made to schematize and simplify the situation. With respect to climate change it would be very interesting to see what happens to the river profile when the model is made more complex or when different scenarios and changing boundary conditions get combined.

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# 1. Introduction

## 1.1. Relevance of the research

All over the world, people prefer living in delta areas; although delta areas only comprise 0,5% of the land area, the human population of these deltas is about 5% of the global population, a factor 10 higher (Ericson et al., 2005). The same is visible in the Rhine-Meuse delta, which is the most densely populated and intensively used area of the Netherlands (Huismans et al., 2017).

The Rhine-Meuse delta is a complex network of many different river branches. The Rhine crosses the Dutch border at Lobith and splits at Pannerdensche Kop in the Waal and the Pannerdensch Kanaal. The Pannerdenschkanaal becomes the Nederrijn, while the Waal flows via Nijmegen and Tiel to Woudrichem. After passing Woudrichem, the Waal is called Boven Merwede and bifurcates several times before distributing its water to Haringvliet, Oude Maas and Nieuwe Waterweg. The Dutch Rhine provides water for agricultural, industrial, domestic and recreational use and is also an important waterway for inland navigation in Europe.

The Rhine has many different functions and users. It is therefore important to get a better understanding of the long term response of the river, not only to increase the knowledge about its behaviour, but also to make right decisions according to river management. Predictions of the river's behaviour, like the change of the river profile and bed composition, are necessary to foresee the risks, to design proper management measures and to limit negative effects. In such a way it is possible to provide good navigability of the rivers, minimize the flood risk in the river surroundings and control the water quality and ecology now and in the future.

When the boundary conditions of rivers, like the upstream water discharge, upstream sediment discharge and the downstream base level that fluctuates around a constant mean value, do not change, rivers tend to a morphodynamic equilibrium state over time (Blom et al., 2017). However, due to continuously changing boundary conditions, the river will never reach its equilibrium state. If the change of the boundary conditions is sufficiently slow, the river is called to be at quasi-equilibrium state.

When focussing on the Dutch Rhine, changes in boundary conditions are already visible. Current bed degradation of about 1 to 2 cm per year is already causing problems for the navigability of the river and this erosion might be a direct effect of the changing upstream sediment discharge (Blom, 2016). Other expected changes are sea level rise and an increase of the maximum discharge, partly due to climate change (Van Tets, 2017).

What will be the effect of changing boundary conditions along the Rhine-Meuse delta on the river profile and bed composition? And how will this influence the river's functions like navigability or flood risk for cities? There is only a limited number of studies available about this topic. Therefore, this research will focus on collecting more information about the long-term behaviour and occurring changes of the Dutch Rhine.

## 1.2. Problem definition

At this moment it is difficult to predict the changing behaviour of the Dutch Rhine over a longer term (300 years from now). Changes in river profile and bed composition of the river are affected by different boundary conditions. To be able to make predictions of the future situation, an overview of the boundary conditions is required, as well as an expectation of the way these boundary conditions will change.

The first and most obvious condition related to erosion and sedimentation is the sediment flux in the river. Bed degradation takes place if more sediment is transported downstream than is supplied from upstream. The change in sediment transport and supply is caused by two processes; (1) narrowing and shortening of the Dutch Rhine has resulted in an increase of the flow velocity and therewith an increase in the sediment transport capacity and (2) a coarsening of the sediment supply has taken place due to erosion upstream in the

Rhine, the cutting of Pleistocene soil layers and artificial supplies with coarse sediments at several places along the river. (Blom, 2016)

Sediment transport also has a strong correlation with discharge. An increase of the discharge and the flow velocity results in an increase of the sediment transport capacity. Not only more but also coarser sediments get transported by the river when the discharge increases. Natural fluctuations in the discharge are normal, but there are reasons to expect a long-term change due to climate changes resulting in more extreme discharge peaks.

Since the focus is on long-term changes, also climate-related changes like sea level rise should be taken into account. The sea level is the downstream boundary for the river system. Sea level rise will result in a decrease of the flow velocity and an increase of sedimentation at the downstream delta area. This sedimentation wave will slowly proceed in the upstream direction.

This results in three varying boundary conditions: a change in discharge (upstream boundary), a change in sediment flux (upstream boundary) and a change in sea level (downstream boundary). However, it is still difficult to make realistic assumptions for the future situation, since the available information about the current sediment transport is quite inaccurate and the range of possible discharge scenarios is very large. Also with respect to a predicted sea level rise along the Dutch coast, many different numbers can be found (Van Tets, 2017). This results in some challenges for predicting the long-term morphodynamic behaviour of the Dutch Rhine.

Besides that, it is also still unknown how these changing boundary conditions will interact. These changes in the upstream and downstream boundaries will result in, sometimes contradictory, changes of the river profile and bed composition. Sea level rise will for example result in an initial increase of the water depth at the mouth of the river, therewith a decrease in flow velocity and sediment transport and finally aggradation slowly moving upwards until it meets a structure in the river. At the same time, it is expected that the peak discharge at the upstream boundary will increase, which will probably result in a lowering of the riverbed and a decrease of the bed slope (Van Tets, 2017). A better understanding of the effects of the individual changes in the boundary conditions but also the different scenarios and combinations of these would contribute to a more future-proof river management.

## 1.3. OBJECTIVE

The goal of this research is to get a better understanding of the long-term changes of the river profile and bed composition of the Dutch Rhine for the coming 300 years, based on the effects of different changing boundary conditions.

## 1.4. RESEARCH QUESTIONS

To simplify the situation of the Dutch Rhine, this research will focus on a case loosely based on the Waal. The objective of this research will be achieved by answering the following research question:

- ❖ What is the expected change of the river profile and the bed surface texture with respect to changing boundary conditions in the coming 300 years?

This research question is subdivided into the following sub-questions:

1. What are the characteristic parameters needed to schematize the Waal, from Pannerdensche Kop til Woudrichem, in a schematized 1D model?
2. How are the current hydrodynamic and morphodynamic boundary conditions (discharge, sediment flux and sea level) expected to change over time in the coming 300 years?

3. What is the individual effect of each changing boundary condition on the river profile and bed surface texture when assuming different scenarios for the future situation?

## 1.5. Method of research

To provide insight in the morphodynamic behaviour of rivers, it is possible to use very complex models. However, due to the limited time and depth of this Bachelor thesis project, it is chosen to simplify the situation. Instead of analysing the complex network of the Rhine delta, this project will only focus on the river branch the Waal. For the schematization of the river different hydrodynamic and morphodynamic models, like the sediment transport relation, are selected used. These models are explained in Chapter 2.

Chapter 3 will give an answer on the first sub-question; how to schematize the Waal in a simplified model. Based on literature study and by doing the essential assumptions the characteristic parameters and initial boundaries are defined. This is done for a base case which functions as the zero-scenario for this research.

A numerical model is used to run the base case. For a period of 300 years from now the changes for the bed elevation, bed slope and water level are modelled and visualised in different figures. The observed changes are evaluated in Chapter 4.

For this research, three varying boundary conditions are taken into account: a change in discharge (upstream hydrodynamic boundary), a change in sediment flux (upstream morphodynamic boundary) and a change in sea level (downstream hydrodynamic boundary). Chapter 5 explains how a prediction for the long-term changes of these boundary conditions is made. Based on existing literature, a selection of the possible rates of change is made resulting in two till four scenarios for each boundary condition.

Chapter 6 will give an answer on the third sub-question by modelling the effects of the individual changing boundary conditions and analysing the changes of the river profile and bed composition. The results are discussed and compared with the base case.

The accuracy of the used information and the made assumptions within this research is discussed in chapter 7. The final conclusion and recommendations for further research are given in chapter 8.

# 2. MODEL DESCRIPTION

To model future scenarios for the Dutch Rhine some assumptions of the system have to be made. This chapter will give an overview of the background theory about flow models, morphodynamics and the sediment transport relation used within this research.

## 2.1. FLOW MODEL

For analyses and computations of one-dimensional long-wave phenomena, the equations of Saint-Venant are used. These equations are also known as the shallow water equations, since they can be applied on situations in which the depth is assumed to be very small compared with typical length dimensions. This is also the case for this research in which the Waal is approached by a long prismatic channel. The Saint-Venant equations describe the conservations of mass and momentum of the flow in a one-dimensional flow and are given by the continuity equation and the momentum balance. The momentum balance is built up of four terms; the local acceleration term, the advective acceleration term, the influence of gravity and the resistance term.

There are different simplifications by which the unsteady behaviour of a flow can be approached. For a *quasi-steady* approach, the influence of the inertia term on the momentum balance is neglected which means that the influence of the gravity equals the resistance experienced by the flow. For an *alternating steady* approach, next to this, also the discharge is considered to be constant during each time-interval. A third approach is the *steady flow* approach which assumes the discharge to be constant over time and space. This reduces the continuity equation since the time depending term gets neglected and the momentum balance also gets simplified.

Soci (2015) and Van Weerdenburg (2016) both state that an alternating steady flow model yields a satisfying approximation of the predictions by an unsteady flow model. The propagation velocity of the disturbances predicted by an alternating steady flow model are not even 1% off from the prediction based on an unsteady flow model (Van Weerdenburg, 2016).

For this research the data used for the discharge through the Waal is not constant over time, which makes it in the first place impossible to use the steady flow assumption. But, since earlier simplifications have shown satisfying results, it is possible to assume alternating steady flow. Alternating steady flow is almost comparable to steady flow, but instead of assuming the total time, alternating steady flow splits the total time into several time intervals *dt*. For each time interval the discharge is assumed to be constant and therewith the flow to be steady.

## 2.2. MORPHODYNAMIC MODEL

The morphodynamic steady state of a river is given by the Exner equation [2.1]. The Exner equation is based on the conservation of sediment mass. Applying this equation makes it possible to determine the equilibrium channel slope, the flow depth and the possible bed level steps.

$$c_b \frac{\partial z_b}{\partial t} = -\frac{\partial s}{\partial x} \qquad [2.1]$$

with s = volume of transported sediment per unit width and time
$z_b$ = mean elevation of bed surface
$c_b$ = sediment concentration within the bed ($c_b$= 1-λ, where λ = porosity)

As long as the transport rate does not vary spatially, the bed level will not change. In a steady state the river bed has adjusted such that it can transport all sediment supplied by the river from upstream in downstream direction. When the volume of transported sediment upstream is not equal to the volume transported downstream, degradation or aggradation takes place.

Within this research a distinction between suspended sediments and bed load sediments is made. The transported sediment is given by the bed material load which includes both the bed load materials (sand, fine and coarse gravel) and the suspend sand concentration but not the wash load.

## 2.3. Sediment transport relation

For the sediment transport relation a choice between many different relations had to be made. These relations are quite similar, but a simple method is the semi-empirical relation of Engelund-Hansen (1967). This is a relation that does not include a critical value for the initiation of sediment transport.

The Engelund-Hansen equation is based on the shear stress approach and can be written as:

$$S = B\, m\, u^n \qquad [2.2]$$

With:

$$m = \frac{0.05 c_f^{\frac{3}{2}}}{(\Delta g)^2 D_{50}} \qquad [2.3]$$

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w} \qquad [2.4]$$

$c_f$ = friction coefficient [-]
n = 5 [-]
g = 9,81 [$m^2/s$]
$D_{50}$ = media of the particle size distribution [m]
u = flow velocity [m/s]
S = sediment bed load transport rate [$m^3/s$]

# 3. SCHEMATIZATION OF THE RIVER

The Rhine-Meuse delta is a complex network of many different river branches. To simplify this research and to make the outcome applicable for other delta areas with comparable conditions, it is chosen to focus on a case loosely based on the river branch the Waal which is part of the Rhine-Meuse delta. This chapter will give an answer on how to schematize a river branch like the Waal in a simplified model and how to translate this to a base case with its own characteristics, boundary conditions and initial conditions.

## 3.1. THE WAAL BRANCH OF THE RHINE RIVER

The Rhine crosses the Dutch border at Lobith and bifurcates in the Waal and the Pannerdensch Kanaal. Since this research has the main objective to clarify more about the effects of changing boundary conditions on the river profile and bed compositions and not to focus on the full interaction of different river branches, it is chosen to only assume one river branch. The case within this research is loosely based on the Waal from Pannerdensche Kop till Woudrichem (figure 1). Except of the Amsterdam-Rijnkanaal there is no water subtracted from the Waal over this distance. Since the discharge through the Waal is significantly larger than the discharge that flows towards the Amsterdam-Rijnkanaal it is chosen to neglect this channel within this research. This schematisation is important to be able to simplify the river branch as an uniform channel with a prismatic cross-section and a constant width, as is done within this research.

Two more simplifications are done regarding the river branch. Firstly it is chosen to neglect the influence of flood-plains. When including flood-plains in the situation an distinction between conveying width and normal width has to be made. Besides that, the friction coefficient for the flood-plains differs from the friction coefficient in the main channel due to vegetation and also the specific discharge is affected. This results in different flow velocities and water depths during high water discharges. To keep the problem simple it is therefore chosen to neglect the flood-plains within this research.

Secondly, the current ongoing and future interventions on the river are as well neglected. At the moment some adjustments are made with respect to the 'Room for the River' project for the Dutch delta area. The adjustments for example include the displacement of dikes and groynes and the construction of longitudinal dams. However, including these interventions would make the research to complex, especially since this research focuses on a rough estimation of the future changes only.


*Figure 1: The Waal from Pannerdensche Kop til Woudrichem.*

The development of the bed level and water level between Pannerdensche kop (Rhine-km 867) and Woudrichem (Rhine-km 951) is given in figure 2. The bed level varies over space, but it is possible to approach it with a linear slope. The water level slope decreases more towards the downstream boundary where the river reaches the sea.

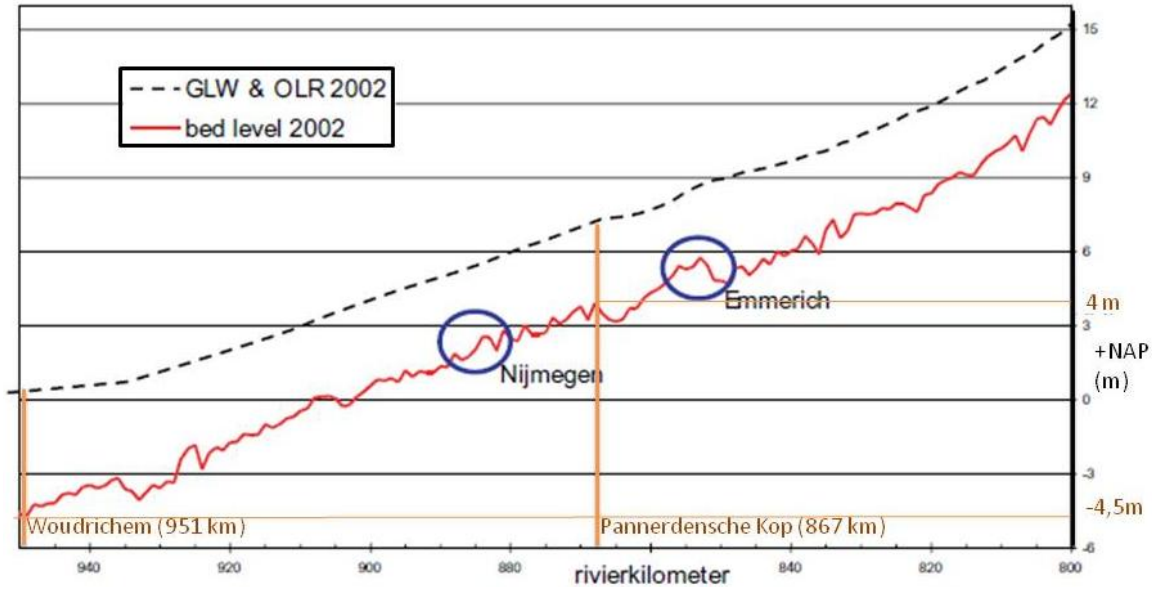


*Figure 2: Waterlevel and bed level between Pannerdensche Kop (867km) and Woudrichem (951km) (Sieben, 2009)*

## 3.2. Settings of the base case

To be able to understand the effects of changing boundary conditions, it is important to start modelling with a base case. For this research the base case is based on the current situation for the Waal (t=0) without assuming any changes for the initial and boundary conditions yet. However, it is important to realise that the initial conditions for the current situation like the bed slope do not equal the equilibrium state for the Waal, since the river still is adapting to modifications like river narrowing and shortening during the 19th and 20th century. For the base case future interventions and the effects of current projects, like the 'Room for the River' project, are neglected. This means for the base case that the river will reach its equilibrium state over time. Below, the chosen characteristic parameters, initial conditions and boundary conditions for the base case are explained.

### 3.2.1. Characteristic parameters

The Waal river starts at Pannerdensche kop (Rhine-km 867,5) and ends at Woudrichem (Rhine-km 951). This results in a total length of 83,5 km (Hillebrand, Frings, 2017, p. 146). The length of the backwater curve is expected to be longer than the length of the Waal itself. Therefore, to make sure that all changes on the river bed are visible and within the chosen range, the defined length of the base case is increased till a total length of 200 km. This is still in the same order of magnitude.

Considering the width of the river, the Waal has a width differing between 250 and 315 meter with an average of approximately 270 meter (Hillebrand, Frings, 2017, p. 156). For this research a constant width of 270 meter is assumed over the total length.

### 3.2.2. Boundary conditions

For the base case, the friction coefficient is larger than the bed slope ($c_f > i_b$) which means that the slope of the river bed is mild and the flow is subcritical. To determine the hydrodynamic state of a subcritical channel system an upstream and downstream hydraulic boundary condition are needed. A third boundary condition is needed related to the morphodynamics.

#### Upstream hydrodynamic boundary condition

The upstream hydrodynamic boundary condition is given by the water discharge. This data is used since there is much more data available about the water discharge at Lobith than for the Waal. But the discharge at Lobith does not equal the discharge in the Waal, due to the split at Pannerdensche Kop. Based on discharge measurements from 1971 to 1995 (figure 3), it is visible that the percentage of the total Rhine discharge that flows towards the Waal at Pannerdensche Kop decreases for higher discharges, but it never drops below 64% (Ogink, 2006). Another widely used approximation for estimating the discharge to the Waal is 2/3 (66%) of the total discharge at Lobith (Sieben, 2009). For further calculations within this research the value of 2/3 will be used. For the base case the discharge for the coming 300 years is assumed to be the same as the past 100 years.

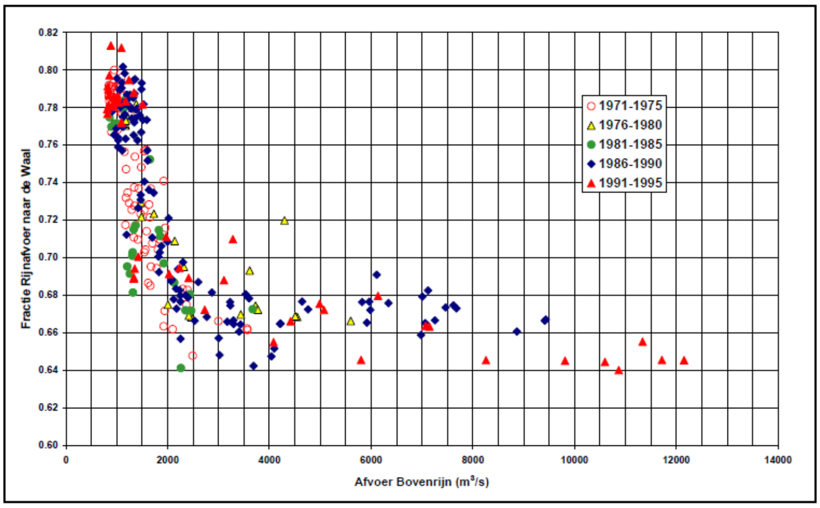


*Figure 3: Percentage of the total Rhine discharge that flows via the Waal at the branching at Pannerdensche Kop (Ogink, 2006)*

### Downstream hydrodynamic boundary condition

The downstream hydrodynamic boundary condition is given by the water level at Woudrichem. For the base case the water level at this boundary is assumed to be a fixed level. This assumption ignores the daily variation in water level due to the tide and due to the variation of the discharge, since the long-term effects are of greater importance. Even though Woudrichem is not located directly along the coast, but approximately 50 km away from the sea, sea level changes are assumed to be the same at Woudrichem as at the coast. For the base case no sea level rise is assumed to take place.

### Upstream morphodynamic boundary condition

The third and last boundary condition has effect on the morphodynamic situation which is the sediment transport rate at the upstream boundary. At the upstream boundary of the Waal, the average annual transport rate per sediment type is 1.55 Mt/year for suspended clay and silt, 0.34 Mt/year for suspended sand, 0.07 Mt/year for bed load sand, 0.08 Mt/year for bed load fine gravel and 0.02 Mt/year for bed load coarse gravel and cobbles (Frings et al., 2014). The argumentation behind the sediment transport rate and the sediment flux distribution at Pannerdensche Kop is included in Appendix A 'Sediment flux'.

For this model only the bed material load is taken into account since the wash load (suspended silt and clay minerals) won't affect the river bed. The bed material load includes suspended sand, bed load sand, fine gravel and coarse gravel. This results in a total transport rate of 0.51 Mt/year. The sediment density is assumed to be equal for all sediments (2650 kg/m$^3$).

To simplify this research even more, it is chosen to limit the number of sediment types to only one sediment type. Since the biggest part of the transported sediment consists of sand particles, a unisize sediment with a grain size of 2 mm is selected.

### 3.2.3. Initial conditions

The current bed slope of the Waal is estimated based on information about the bed level along the river (figure 2). At Pannerdensche Kop the bed level is at approximately at NAP+4m and at Woudrichem the bed level is approximately at NAP-4,5m (Sieben, 2009). This results in a bed slope of $1*10^{-4}$ for the total river branch of the Waal at t = 0.

Since the Waal already is schematized a lot, it is no longer possible to approach the water depth at the river mouth by using the values given in figure 2. Instead it is better to calculate the expected water depth at this point by using the Van Bendegom & De Vries equations for alternating steady flow (Appendix B.2. 'Van Bendegom & De Vries equations'). Including the water discharges of the last 100 years, this calculation gives the following value for the water depth: $d_{e,\,mouth}$ = 11,5 m.

The friction coefficient is assumed to be 0.004. The bed porosity for the Rhine is not precisely known but according to Frings it can be estimated between 0.15 and 0.35 which is lower than the often-used value of 0.4 (Frings et al., 2008). The assumed bed porosity for this research is therefore chosen at 0.3. The river bed is assumed to be build up of only one sediment type.

The above defined parameters are summarized in table 1. These parameters form the basis for all calculations and modeling done in this research.

| **Parameter** | **Symbol (unit)** | **Value** |
|---|---|---|
| Length | L (m) | 200000 |
| Width | B (m) | 270 |
| Gravity | g (m/s$^2$) | 9,81 |
| Density water | Ρ (kg/m$^3$) | 1000 |
| Porosity | ϕ(-) | 0,3 |
| Grain size | $D_{50}$ (mm) | 2 |
| Bed slope | $I_b$ (-) | $1*10^{-4}$ |
| Friction coefficient | $C_f$ (-) | 0,004 |
| Bed level at Pannerdensche Kop | d (m) | N.A.P. + 4,0 |
| Bed level at Woudrichem | d (m) | N.A.P. - 4,5 |

*Table 1: Overview of the characteristic parameters of the schematized Waal*

# 4. Results of the base case

Based on the theory about a prediction of the expected result could be made. By doing so, it is possible to check whether the model behaves as expected. For the situation of the base case first a prediction of the outcome after 300 years is made. Afterwards the outcome of the model is discussed. The goal of running a base case model is to understand the equilibrium to which the system tends, without including the effects of changing boundaries yet.

## 4.1. Theory

For the base case it is expected that the river bed adjusts its level and slope to the equilibrium state since the river still is adapting to modifications like river narrowing from the past. During the transition to equilibrium state, often a backwater curve is be present. The different types of backwater curves are explained in Appendix B1 'Backwater curves'. To reach the equilibrium state and the corresponding values for flow depth and bed slope, aggradation or degradation of the river bed will occur. By using the Van Bendegom & De Vries equations for alternating steady flow, the values for equilibrium flow velocity ($u_e$), flow depth ($d_e$) and bed slope ($i_{be}$) can be found for the area upstream from the backwater zone. These equations are explained in Appendix B2 'Van Bendegom & De Vries equations'.

For the base case all boundary conditions are kept constant. Only the discharge is still varying since it is chosen to use a constant discharge hydrograph instead of one constant discharge. Adaptations for the bed level and bed slope are therefore expected to move in downstream direction along the river reach.

## 4.2. Modelling of the base case

For a period of 300 years from now the changes for the bed elevation, bed slope and water level are modelled and visualised in different figures. The observed changes are evaluated below.

### 4.2.1. Bed elevation

The river bed was assumed to be constant with a slope of $1*10^{-4}$, but towards the future, over a period of 300 years, some changes in the river bed elevation are visible (see figure 4). At the downstream end sedimentation takes place, while further upstream degradation occurs. The wave of erosion slowly moves in downstream direction. The transition point between degradation and aggradation can be found at approximately x=80km. The maximum aggradation at t=300 years results in a maximum bed elevation of approximately 2.9 meters at x=180km and at the downstream end the bed elevation is equal to 2.2 meter.

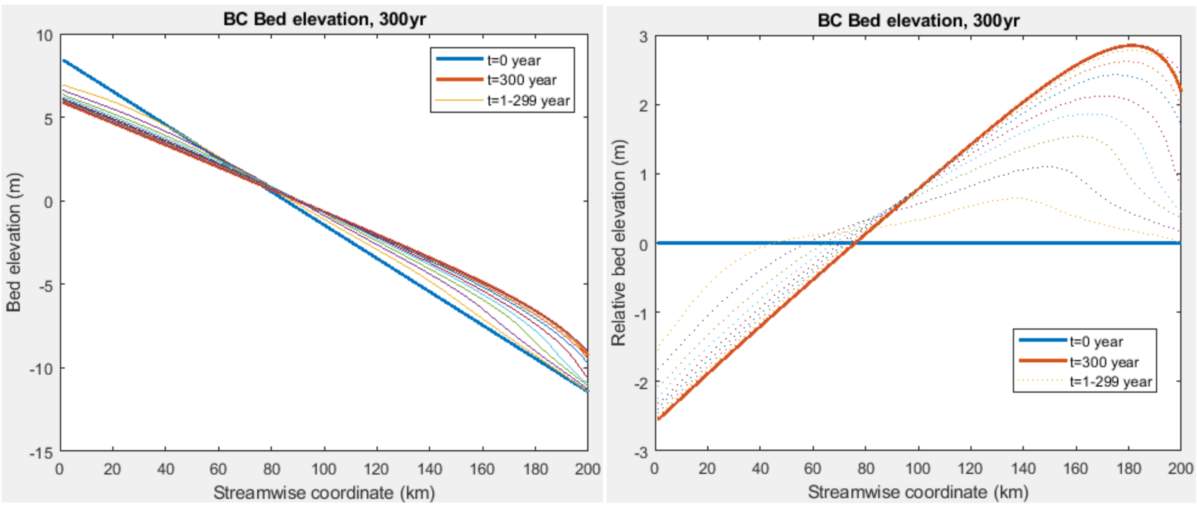


*Figure 4 (a, b): Bed elevation (a) and relative bed elevation (b) for the base case.*

### 4.2.1. Bed slope

The change of the bed elevation results in a decrease of the bed slope over almost the entire reach, see figure 5. A decrease of the bed slope leads to a decrease of the flow velocity and therewith a decrease of the sediment transport rate. A decrease of the sediment transport rate counteracts the ongoing degradation. After a sufficient long time the equilibrium will be reached and a new constant slope is established. As is visible in figure 5, at t = 300 years the equilibrium is almost reached at the upstream part of the river but not yet at the downstream part. The disturbance of the bed slope is slowly moving in downstream direction and after some more years (at t=1000) the equilibrium will be reached over the full length of the river.

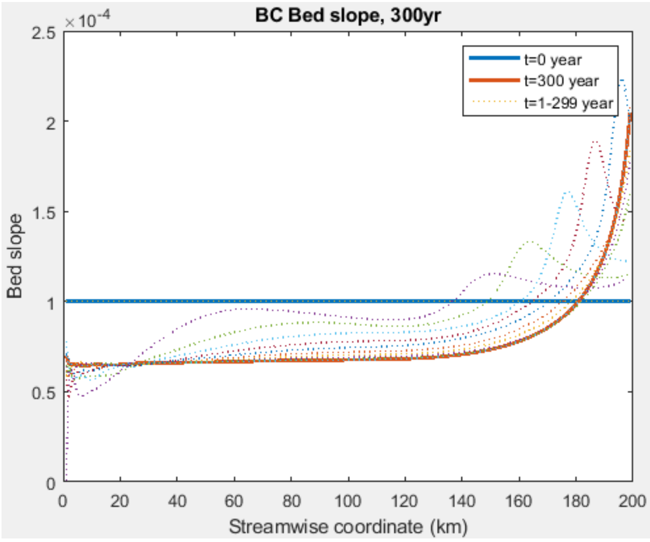


*Figure 5: Bed slope for the base case.*

### 4.2.1. Water surface elevation

The water surface elevation seems to have the shape of a M1-backwater curve (see figure 6), which means that the current water depth is bigger than the equilibrium water depth. However, some fluctuations are due to the fact that the discharge is not constant for every time step since the hydrograph consists of varying discharges. Every time-step in figure 5 covers 30 years, and they all belong to a different discharge at that moment of time. When also considering the water depth (figure 7) it gets visible that not only M1-backwater curves occur, but also M2-curves are present along the river branch.

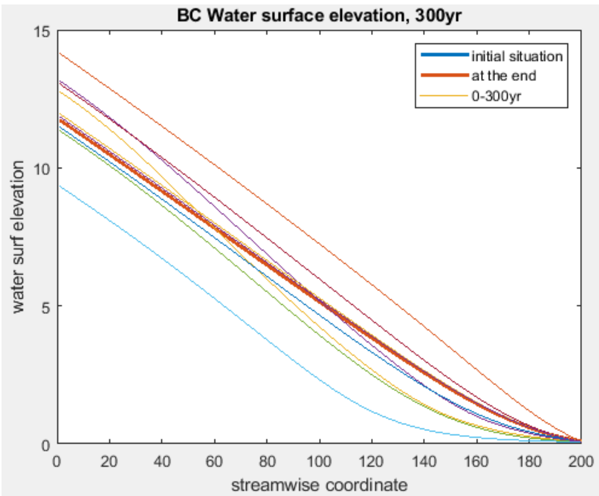


*Figure 6: Water surface elevation for the base case.*

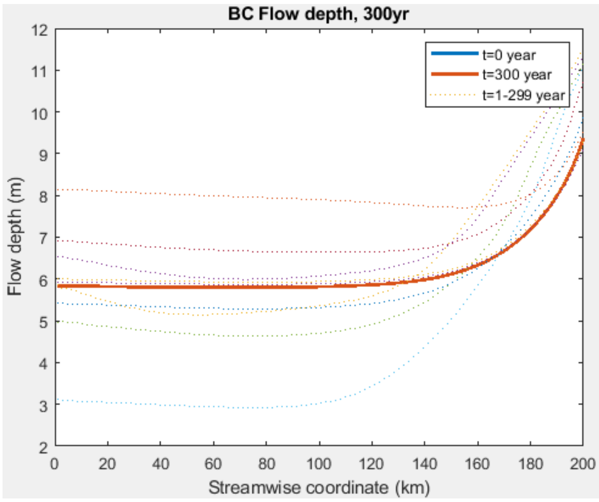


*Figure 7: Flow depth for the base case.*

# 5. SCENARIOS FOR THE BOUNDARY CONDITIONS

For this research, three varying boundary conditions are taken into account: a change in discharge (upstream hydrodynamic boundary), a change in sea level (downstream hydrodynamic boundary) and a change in sediment flux (upstream morphodynamic boundary). For the base case these boundary conditions were defined in a way equal to the current situation for the Waal and kept constant. However, for the long-term situation these boundary conditions will probably change. Before doing research on the effects of these changes, the future rate of change must be known for each boundary condition. Within this chapter, based on existing literature, a selection is made of the possible rates of change resulting in two till four scenarios for each boundary condition.

## 5.1. DISCHARGE

Prediction of the future water discharge is difficult because it depends on many estimations and uncertainties. Meteorological conditions have a great influence on temperature, precipitation and evaporation, but at the same time the precise effects of climate change on the discharge of the Rhine are hard to predict. Van Tets (2017) defined three scenarios for the water discharge statistics in 2250 at Lobith, based on the predictions for the year 2050 or 2100 based on four different studies by Te Linde, Görgen and Lenderink (Te Linde, 2006) (Te Linde et al., 2010) (Görgen, 2010) (Lenderink et al., 2007). For the predictions a distinction between summer months (Juny, July and August) and winter months (December, January and February) was made, since these are the periods in the year that include the minimum and maximum discharges. Due to climate change it is expected that the extremes will increase resulting in an increase of the mean water discharge in the winter months and a decrease of the mean water discharge in the summer months.

The three scenarios defined by Van Tets (2017) predict the possible change of rate for the discharge at Lobith, see table 3. The first scenario predicts an increase of +20% in the winter and -25% during the summer until the year 2100 and it assumes the discharge to stay constant between 2100 and 2250. The third scenario expects the same change until the year 2100 and between 2100 and 2250 the extremes get even bigger, resulting in an increase of the discharge of +40% in winter and a decrease of -50% in summer. The second scenario describes a more moderate change (between D1 and D3) for which the changes between 2100 and 2250 results in a winter discharge of +30% and a summer discharge of -38%.

| | 2100 - 2200 | | 2200-2300 | |
|---|---|---|---|---|
| D1 - Scenario 1 | +20% winter | -25% summer | +20% winter | -25% summer |
| D2 - Scenario 2 | +20% winter | -25% summer | +30% winter | -38% summer |
| D3 - Scenario 3 | +20% winter | -25% summer | +40% winter | -50% summer |

*Table 2: Discharge scenarios; change of the discharge during summer and winter time.*

The discharge hydrograph used for scenario D1, D2 and D3 is based on the discharge hydrograph of the past 100 years at Lobith, but it is adjusted for the situation with the Waal. For this research the discharge scenarios, as given in table 2, are used to predict the future situation. These scenarios are partly based on the scenarios defined by Van Tets.

## 5.2. SEDIMENT FLUX

There are different reasons to expect changes in the sediment flux for the coming years. The mean grain size of the sediment transported by the Rhine has increased, indicating coarsening of the river and a coarser sediment supply (Blom, 2016). However, the total sediment volume transported by the Rhine has not significantly changed (Frings et al., 2014).

Again, different scenarios are defined according to the change of the sediment flux for 300 years from now. Since it is expected that the coarsening trend will continue towards the future, the gravel content will increase for all scenarios.

For the first scenario it is assumed that the content of fine and coarse gravel will increase with 30% over a period of 300 years due to an decrease of the transported volume of suspended sand and bed load sand. The volume of gravel stays constant. For the second scenario again it is assumed that the content of fine and coarse gravel increases with 30% over a period of 300 years, but now due to an increase of the transported volume of gravel. The volume of sand stays constant, only the amount of gravel increases.

Table 3 gives an overview of the expected transport rates of the different sediment types for the two scenarios. These values include the fact that the transport rate of bed-load sediments towards the Waal is 86% of the total sediment transported by the Rhine at Lobith and for suspended sediments it is 70% (see Appendix A 'Sediment flux').

| | Base case (Mt/year) | F1 - Scenario 1 (Mt/year) | F2 - Scenario 2 (Mt/year) |
|---|---|---|---|
| Suspended clay and silt | 1.55 | 1.55 | 1.55 |
| Suspended sand | 0.34 | 0.22 | 0.34 |
| Bed load sand | 0.07 | 0.03 | 0.07 |
| Bed load fine gravel | 0.08 | 0.08 | 0.20 |
| Bed load coarse gravel | 0.02 | 0.02 | 0.05 |
| ***Unisize sediment (D =2 mm)*** | ***0.51*** | ***0.35*** | ***0.66*** |

*Table 3: Scenarios for the change of sediment flux (Mt/year) for the year 2300.*

Within this research it was chosen to only assume unisize sediment, so the sediment load for the unisize sediment still has to be defined. For the unisize sediment a diameter of 2 mm is chosen, just like for the base case, and the transport rate for this unisize sediment is a summation of the transport rates of the bed material load only which includes the suspended sand, and the bed load sediments.

## 5.3. SEA LEVEL

To predict the future sea level at the downstream end of the Waal not only information about the global expected changes is necessary, but more specific also for the North Sea. There are three reasons why the sea level rise at the North Sea probably differs from the global sea level rise. The first reason is that due to the melting of ice a flux of fresh water will be added to the oceans. This will probably change the ocean properties resulting in a difference in the ocean circulation and currents and therewith also effecting the regional sea depths (Stammer, 2008, Yin et al., 2009). A second reason is the effect of melting ice on land which has a direct effect on the gravitational field and shape of the earth. The third reason includes all possible local changes like a change in sediment composition or tectonic activity that might take place (Church et al., 2013).

Based on the fifth assessment report (IPCC, 2014) published by the IPCC (International Panel on Climate Change) and the expected regional sea level rise from 1970 to 2100 for IJmuiden in The Netherlands (Church et al., 2013) three scenarios for the sea level rise are approached by Van Tets (2017). A fourth 'worst case' scenario is based on a prediction of DeConto and Pollard (2016). For an overview of the scenarios see table 4.

| Scenario of this study | Scenario IPCC | Rate of sea level rise [mm/yr] |
|---|---|---|
| S1 - Positive scenario | High, RCP8.5 | 3.4 |
| S2 - Neutral scenario | High, RCP8.5 | 9.5 |
| S3 - Negative scenario | High, RCP8.5 | 15.6 |
| S4 - Worst case scenario | High, RCP8.5 | 30.0 |

*Table 4: Scenarios for sea level rise at the North Sea [mm/yr] based on a high IPCC scenario (Van Tets, 2017)*

The expectations given by Van Tets (2017) are all based on assuming a high scenario of the IPCC for the North Sea. The high scenario of the IPCC matches the Representative Concentration Pathway (RCP) scenarios RCP6.0 and RCP8.5 that describe the development of greenhouse gasses. It is still doubtful in which extent it is correct to assume a high scenario of the IPCC, but for now the positive scenario (S1, table 4) already matches the current situation in which we indeed notice an increase of 2-3 mm per year. All four scenarios from table 4 will be compared with the base case scenario.

# 6. Results: Individual effects of changing boundary conditions

## 6.1. Modelling the change of discharge

The discharge for the coming 300 years is given by four different data sets (Q0, Q1, Q2 or Q3) that all belong to one scenario. An overview of the boundary conditions for each single scenario is given in table 5 where the sediment flux and sea level are kept constant.

| | Discharge (data set) | Sediment flux in 2300 (with d = 2mm) | Sea level (mm/yr) |
|---|---|---|---|
| Base case | Q0 | 0.51 Mt/a | 0.0 |
| D1 - Scenario 1 | Q1 | 0.51 Mt/a | 0.0 |
| D2 - Scenario 2 | Q2 | 0.51 Mt/a | 0.0 |
| D3 - Scenario 3 | Q3 | 0.51 Mt/a | 0.0 |

*Table 5 - Scenarios related to a change of the upstream hydrodynamic boundary due to changes in discharge.*

For each scenario the bed elevation, bed slope, water surface elevation and water depth are modelled. The results are compared with the base case and the differences between the different scenarios are explained in the paragraphs below. See Appendix C.2. 'Results - discharge' for a complete overview of all figures that belong to scenario D1, D2 and D3.

### 6.1.1. Bed elevation

For more extreme discharges (higher maximum and lower minimum), the effect of the peak discharge is greater than for the base discharge. This is also visible in the equations of Van Bendegom & De Vries (Appendix B.2.) where the dominant discharge ($Q_{dom}$) has a larger value than the average discharge. An increase of the average discharge will result in a higher flow velocity and a higher sediment transport rate. Degradation will therefore take place and the degradation wave will travel from the upper boundary in downstream direction.

This change is as well visible in the figures for relative bed elevation of scenario D1, D2 and D3 (figure 8). During the first 100 years the discharge is the same for all scenarios. During the second decade the discharge increases with 20% during winter and decreases with 25% during summer. Also this is the same for all scenarios. The difference is visible for the last decade; for Q1 the discharge does not change anymore and the bed elevation after 300 years is therefore the most comparable with the base case. For Q2 the discharge increases up till 30% during winter and decreases with 38% during summer. For Q3 the changes get even more extreme; an increase of 40% during winter and a decrease of 50% during summer. The last scenario therefore results in the biggest changes with respect to the base case.

In figure 8 the development of the bed elevation per time-step of 30 years is given. The blue line equals the final bed elevation of the base case after 300 years. During the first 100 years the development of the bed elevation for scenario D1, D2 and D3 is the same as for the base case, since the discharge has not changed yet. During the next decades (year 100-300) the discharge for the three scenarios will however start to change with respect to the base case scenario. The final bed development (yellow line) shows a clear deviation of all scenarios compared to the base case. Furthermore it is visible that both the overall bed elevation and the maximum bed elevation are lower for the scenarios with more extreme discharges than for the base case. The transition point, which was located at x=80km for the base case, has moved in downstream direction and the bed elevation at both the upper and lower boundary have decreased.

When looking at the situation after 300 years, for more extreme discharges (D3) not only the maximum bed level has decreased compared to the base case, but also the area over which the bed level increases has become smaller. It is interesting to see that the bed elevation at the lower boundary is much lower for scenario D3 (+0.5m) than for the base case (+2.2m). This suggests that the peak of sedimentation not only has decreased but it also has become steeper. Besides that, also the location of the maximum bed elevation has moved in upstream direction compared to the base case. For scenario D2 and D3 the maximum bed elevation stops increasing after a certain time and then decreases again. Figure 8d shows that the bed elevation of scenario D1 relative to the base case decreases both over time as over space, where the biggest changes are visible at the downstream part.

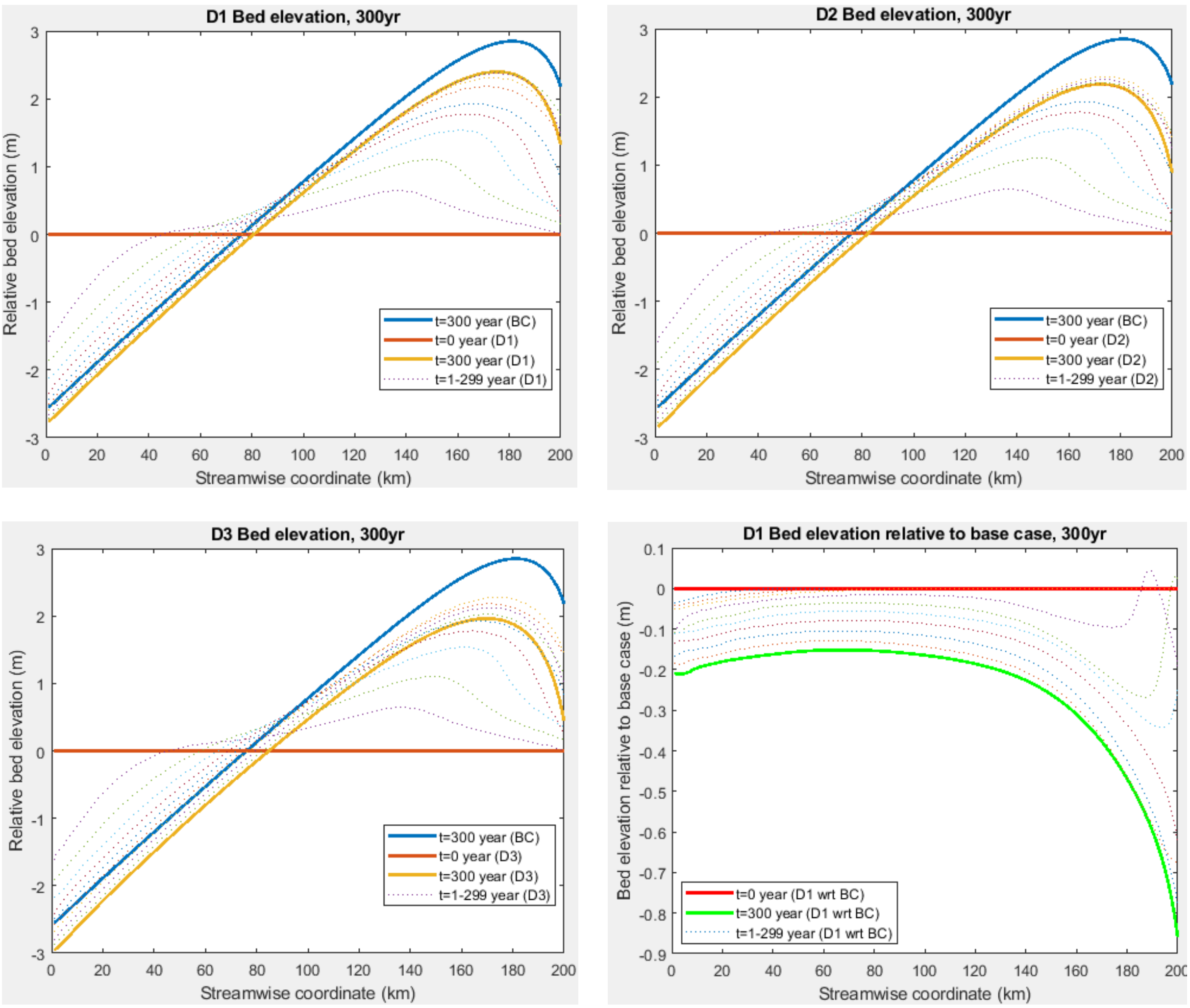


*Figure 8 (a,b,c): Relative bed elevation for  scenarios D1, D2 and D3 compared with the relative bed elevation of the base case.*
*Figure 8 (d):Relative bed elevation for scenario D1 relative to the base case.*

For even more extreme discharges the bed elevation is expected to decrease more compared to the base case. The maximum bed elevation will decrease and at the downstream boundary only a small or no bed elevation is expected.

### 6.1.2. Bed slope

Due to the change of the bed level all along the river branch, the slope decreases for all scenarios. The equilibrium to which the slope tends seems the same for the base case as for the scenarios D1, D2 and D3 and this is approximately $0.6*10^{-4}$ (figure 9). But, since the sedimentation peak, visible in figure 8, gets steeper for more extreme discharges, the maximum bed slope at the downstream boundary increases more for scenario D3 compared to the base case than for scenario D1 . Due to the change in discharge it will probably take longer for these scenarios to adjust the bed slope to the equilibrium and this won't happen as long as the discharge still is changing.

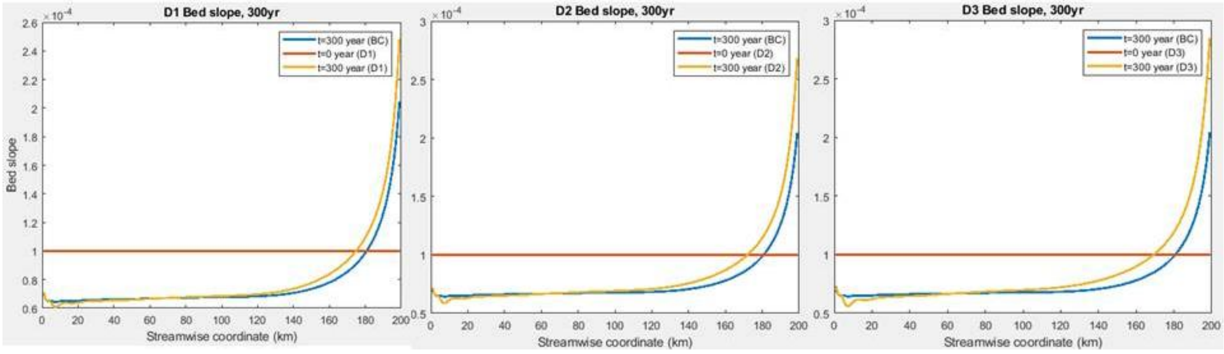

*Figure 9 (a, b, c): Bed slope for scenarios D1 (a), D2 (b) and D (c).*

### 6.1.3. WATER SURFACE ELEVATION

The shape of the backwater curves are not very different from the result found for the base case. The average water surface elevation however is higher for the scenarios D1, D2 and D3 than for the base case. The same is visible for the water depth. This is not surprising since the average discharge increases when the base and peak discharge get more extreme.

## 6.2. MODELLING THE CHANGE OF SEA LEVEL

The sea level will increase linearly with different slopes (mm/yr) for scenario S1, S2, S3 and S4. The boundary conditions for each scenario are given in table 6. The discharge hydrograph and sediment flux are kept constant. Compared to the base case only the downstream hydrodynamic boundary varies.

| | Discharge (data set) | Sediment flux in 2250 (with d = 2mm) | Sea level (mm/yr) |
|---|---|---|---|
| Base case | Q0 | 0.51 Mt/a | 0.0 |
| S1 - positive scenario | Q0 | 0.51 Mt/a | 3.4 |
| S2 - neutral scenario | Q0 | 0.51 Mt/a | 9.5 |
| S3 - negative scenario | Q0 | 0.51 Mt/a | 15.6 |
| S4 - worst-case scenario | Q0 | 0.51 Mt/a | 30.0 |

*Table 6: Scenarios related to a change of the downstream hydrodynamic boundary due to sea level rise.*

For each scenario the bed elevation, bed slope, water surface elevation and water depth are modelled. The results are compared with the base case and the differences between the different scenarios are explained in the paragraphs below. See Appendix C.3. 'Results - sea level' for a complete overview of all figures that belong to scenario S1, S2, S3 and S4.

### 6.2.1. BED ELEVATION

The initial changes at the downstream boundary for scenario S1, S2, S3 and S4 are relative small. A sea level rise of only a few millimetres will not affect the shape of the river bed a lot in the first years, compared to the found results for the base case. However, over time, the water level at the downstream end will increase more and more. This results in a higher water depth at the river mouth and therefore a decrease of the flow velocity. A lower flow velocity results in a decrease of the sediment transport rate and aggradation all over the river reach will take place.

For the base case after 300 years, an increase of the bed level was found for the downstream part from x= 80 km until the downstream end at 200 km. For the reach upstream of this transition point a decrease of the bed level was observed. For the scenarios S1, S2, S3 and S4 this turning point is found at a longer distance in upstream direction from the downstream boundary. For S1 the turning point is at x=70 km, for S2 at x=65 km, for S3 at x=55 km and for S4 at x=35 km. This can be explained by the fact that the increase of the sea level results in an increase of the river bed all over the reach.

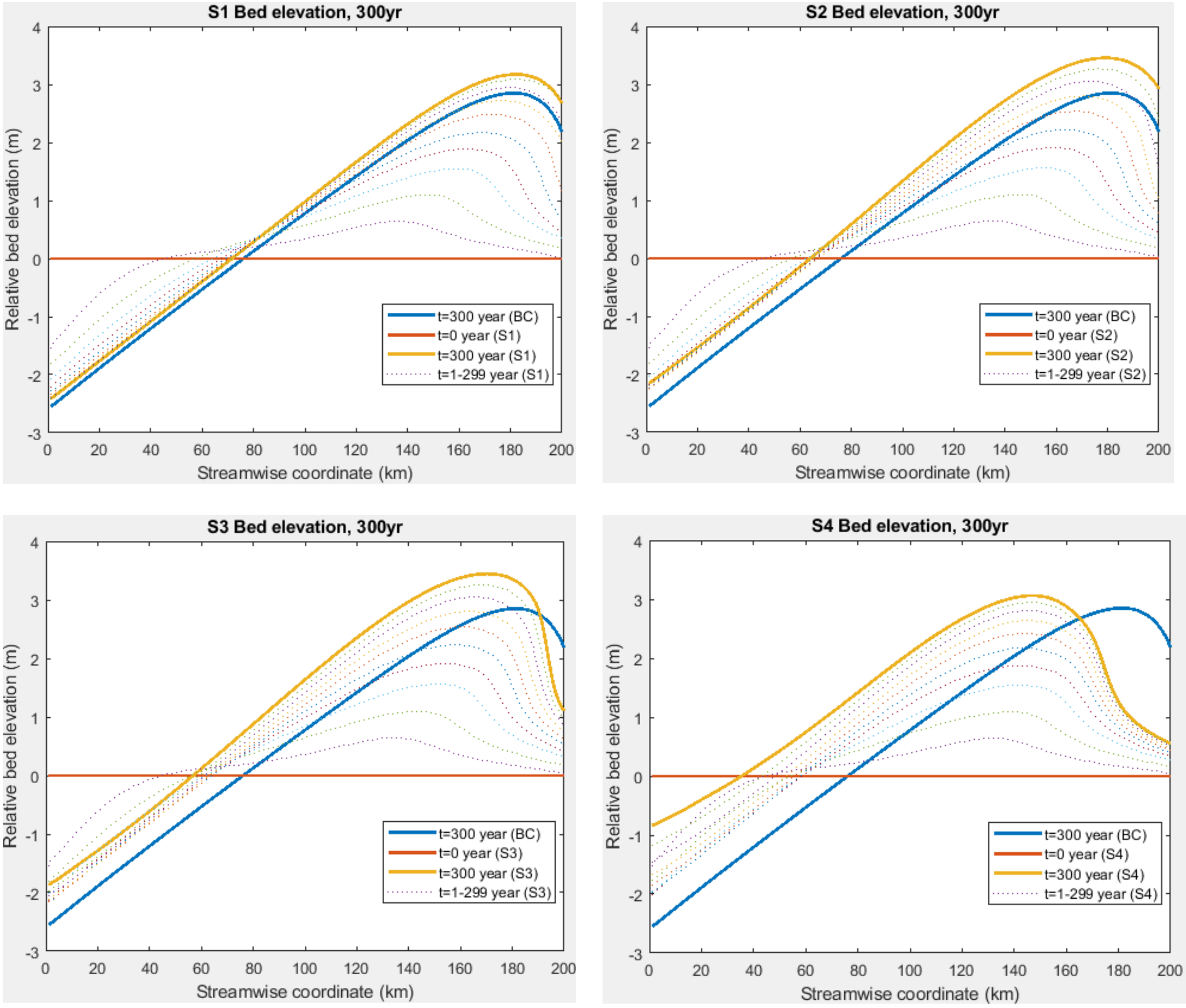


*Figure 10 (a, b, c, d): Bed elevation for Scenario S1 (a), S2 (b), S3 (c) and S4 (d).*

When looking at the bed elevation at the downstream boundary (x=200 km) something interesting happens. Not only the transition point is moving in upstream direction when comparing scenario S1 with S4, but also the position of the maximum positive bed elevation. For each individual scenario it is visible that the maximum bed elevation moves in downstream direction and increases over time. The position of this maximum has a big effect on the bed elevation at the downstream end. As can be seen in figure 10 the bed elevation at x=200 km is approximately 2.7 meter for S1 and only 0.6 meter for S4. The maximum value for the bed elevation at t=300 years does not change that much for the different scenarios and is always about 3.2 meter. The maximum value for bed elevation is slightly higher for S2 (3.4 meter) than for S1 (3.2 meter) but also decreases a bit again for S4 (3.1 meter). It is therefore difficult to find a clear relation between the maximum positive value for bed elevation and the different scenarios for sea level rise. However, when we compare the outcome with the base case it is possible to say something about the shape of the bed elevation.

For the base case no changes along the boundaries occurred and therefore the bed elevation slowly started to adjust towards the equilibrium state. Comparable to the scenarios in figure 10, also for the base case the maximum bed elevation slowly moved in downstream direction over time. When the sea level at the downstream boundary suddenly increases, the system still wants to adjust to an equilibrium state, but there is no time to do so since the boundary condition keeps changing and the sea level keeps rising. For scenario S1 and S2 the shape of the bed elevation is still comparable to the base case, but for scenario S3 and S4 the shape starts to deviate a lot. The system wants to increase the bed level at the downstream part, since the water level is increasing as well, but the river is reacting too slow. The sediment needed from upstream is not supplied in time, resulting in a relative low bed level at the downstream end and probably a very big water depth. The maximum bed elevation is still moving in downstream direction, but the increase of the sea level is just too fast.

### 6.2.2. Bed slope

At t=300 years the decrease of the bed slope for scenario S1 is almost the same as for the base case and it tends towards a value of approximately $0.6*10^{-4}$ (figure 11). But the more the sea level rises per year, the bigger the changes of the bed slope relative to the base case get. The biggest changes are visible at the downstream end since the steepness and location of the maximum bed level have a great influence on the bed slope. Figure 12 shows that the bed slope at t=300yr for scenario S4 does not match the base case anymore. However, if the sea level would not increase anymore, it is expected that the bed slope will change towards the equilibrium state as happened for the base case.

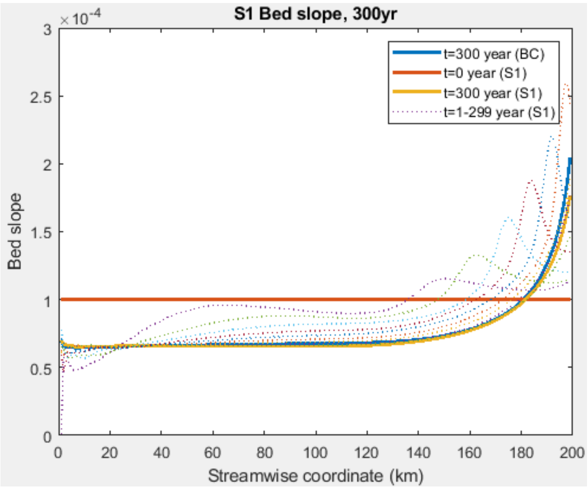


*Figure 11: Bed slope for Scenario S1, including the steps through time.*

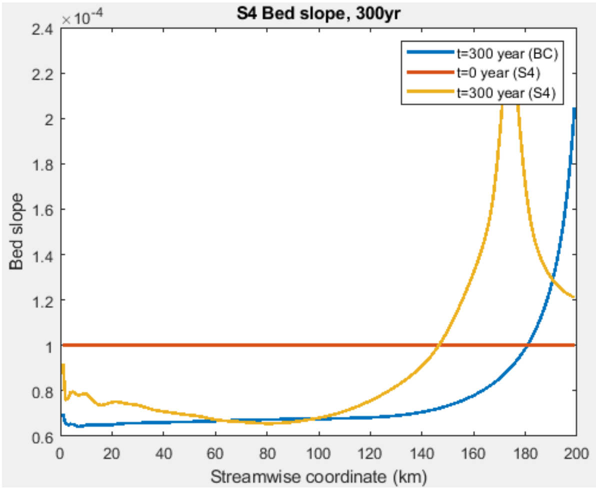


*Figure 12: Bed slope for Scenario S4*

### 6.2.3. Water surface elevation

As is visible in the figures of water surface elevation (figure 13), the plots of the different time steps are not parallel. This variation is caused by the fact that each plot belongs to another water discharge from the discharge hydrograph. However, it is still possible to get a rough impression of the behaviour of the water surface elevation and the length of the backwater curves.

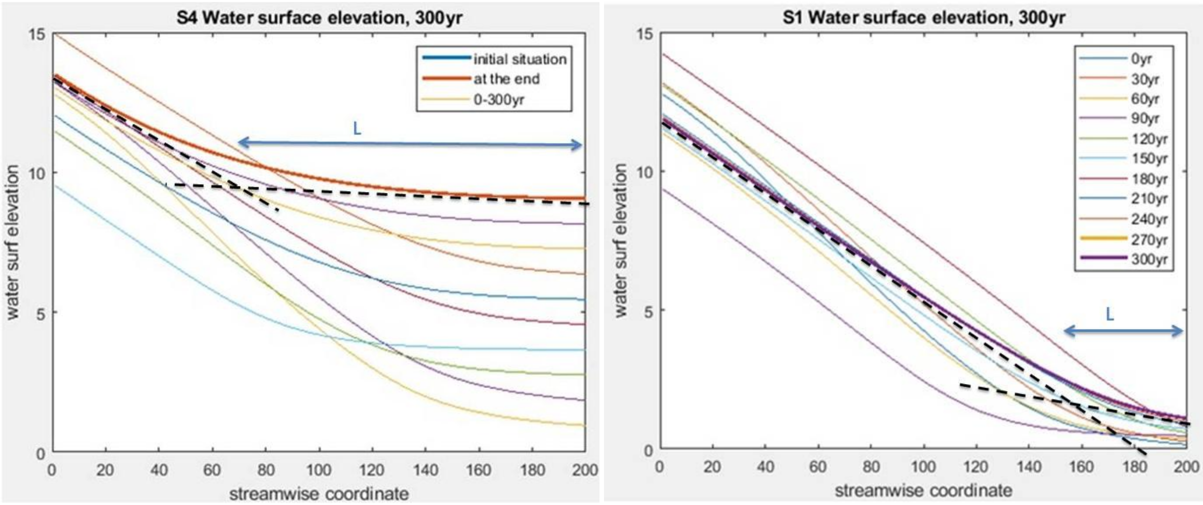


*Figure 13 (a, b): Water surface elevation and length of backwater curve for S1 (a) and S4 (b).*

The rise of the sea level has influence on the downstream part of the river. The length of the backwater curve varies for the different scenarios, see figure 11. A bigger change of the water level at the downstream end results in longer backwater curve. For S1 the backwater curve is approximately 50 km, while for S4 the backwater curve is more than twice as long.

When looking at the flow depth of the different scenarios after 300 years (figure 14) it gets visible that not only M1 backwater curves are present, but also M2 curves can be found. An extreme rise of the sea level, like for scenario S4, will result in very high flow depths at the downstream part of the river.

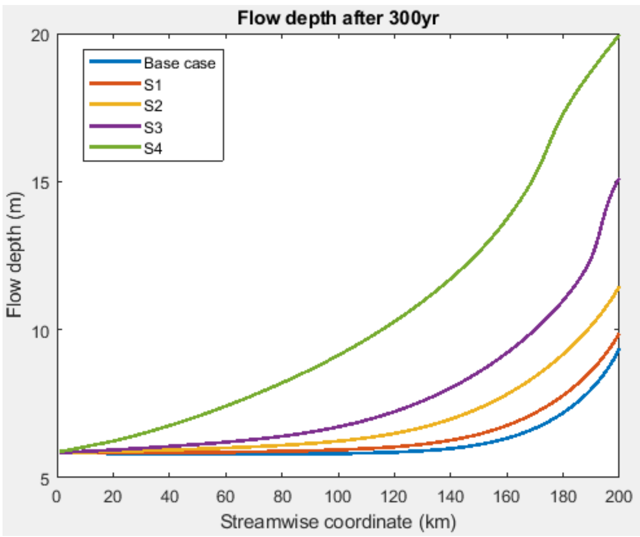


*Figure 14: Flow depth at t=300 years for the base case, S1, S2, S3 and S4.*

## 6.3. Modelling the change of sediment flux

Due to limitations of the model used within this research, it was not possible to visualise the changes due to changing sediment flux. To solve this, it is necessary to slightly redesign the model. Unfortunately to little time is available to work this out and therefore it is chosen to not go deeper into this boundary condition for now. For future research it would be interesting to investigate more about the effects of changing sediment flux.

# 7. DISCUSSION

For this study a lot of assumptions are made to be able to schematize the Waal in such a way that the future changes could be modelled by using a numerical model. It is however important to be critical according to the made assumptions. Therefore some of the assumptions are discussed below.

**High uncertainty scenarios**

It is difficult to make realistic assumptions for the rate of change for the different boundary conditions, since the available information is quite inaccurate and the range of possible scenarios is very large. For the discharge it is now assumed that the extremes will increase during the winter months and decrease during the summer. It is however also possible that only a few discharges per year increase/decrease a lot, instead of a whole season as is assumed here. Also for the sediment flux it is complicated to make good assumptions. The information about the current sediment transport is very limited and with a high uncertainty. Besides, predicting the rate of change towards the future on a very long-term has not done a lot before. Also with respect to a predicted sea level rise along the Dutch coast, many different numbers can be found. Scientists have not agreed yet on the rate of change for the sea level rise and some predictions are much more negative than others. Within this research many different scenarios are defined, but it is still impossible to predict which scenario will correspond most with the real future situation.

**Sediment transport relation**

For the sediment transport relation Engelund-Hansen was chosen because it is one of the most simple relations. Engelund-Hansen is a relation that does not include a critical value for the initiation of sediment transport. Since it is chosen to simplify the situation within this research to unisize sediment, this seems to be a valid choice. However, Engelund-Hansen is mainly used for sediments with a smaller size than the assumed 2 mm in this research. All tests with Engelund-Hansen are done for sediments in the range 0.19 mm $<D_{50}<$0.93 mm. It would be good to in the future repeat all modelling for another sediment transport relation to compare the results and check whether and how much the chosen sediment transport relation affects the results.

**Discharge towards the Waal is 2/3 of the total Rhine discharge at Lobith**

While formulating different scenarios for the discharge it would also be important to check whether the partitioning at Pannerdensche Kop affects the discharge rate towards the Waal when the extreme discharges get more extreme. Based on discharge measurements from 1971 to 1995 (figure 3), it was visible that the percentage of the total Rhine discharge that flows towards the Waal at Pannerdensche Kop decreases slightly for higher discharges, but it never drops below 64%. However, for lower discharges during summer relatively much more water flows towards the Waal compared to the Pannerdensch Kanaal, this amount increases quickly up to 80%. A decrease of the total discharge at Lobith of 25% will therefore have a smaller effect on the decrease of the discharge towards the Waal (only a decrease of 20%) since a greater part of the total discharge will flow to the Waal due to the low total discharge. Since this shift of the discharge ratio at Pannerdensche Kop only is valid for low discharges, the yearly effect will be small. Compared to the yearly average discharge, this difference in discharge for low extreme values is therefore not noteworthy and this means that the assumption that the Waal deals with 2/3 of the total discharge at Lobith is still valid. It is however important to realise that a small shift of discharge ratio at Pannerdensche Kop occurs.

**Sediment flux distribution for changing discharge scenarios**

The shift of the discharge ratio at Pannerdensche Kop will also affect the sediment flux. For low discharges almost 80% of the total discharge at Lobith will flow to the Waal, also transporting more sediments in this direction. This will result in a relatively higher sediment flux. However, this happens for low discharges only. When the discharge through the river is very low, the absolute amount of transported sediment is also much lower, especially compared to the yearly average. The effect on the results is therefore expected to be relative small and that allows us to neglect the effects of this discharge ratio shift for both the discharge and sediment flux for this research.

**Sediment assumed to be unisize**

For this research the sediment is assumed to be unisize with a grain size of 2 mm. But what would happen to the situation if we would consider the sediment to consist of different sediment sizes? The assumption of unisize sediments it not very realistic compared to the real situation, so assuming different sediments would be more realistic and it would probably result in a better prediction of the future situation. It would be interesting to see the effect of different sediments on the change of the river bed profile and bed slope.

**Neglecting future interventions and flood-plains**

The effect of flood-plains and interventions is probably relative big, but for this research it is chosen to neglect these effects to simplify the situation sufficiently. Due to all simplifications and schematizations the results found within this research does no longer represent realistic results for the Waal. But, it does give an impression of the behaviour of rivers of certain dimension and size. For future research it would be interesting to see what happens if the effects of flood-plains and interventions are taken into account as well.

**Predicting the future**

With respect to climate change it would be very interesting to see what happens to the bed elevation when both the discharge becomes more extreme and the sea level starts to rise. But since this research is based on different scenarios, all with their own uncertainties, it is really difficult to say something about the combination of the scenarios.

To give a short impression two plots are made below. Figure 15 shows the combination of discharge scenario D2 with sea level scenario S2 while figure 16 shows the combination of discharge scenario D2 with sea level scenario S3. For figure 15 the two scenarios almost cancel each other but for figure 16 the combination of the scenarios gives a big deviation for the bed elevation at the downstream end with respect to the base case scenario.

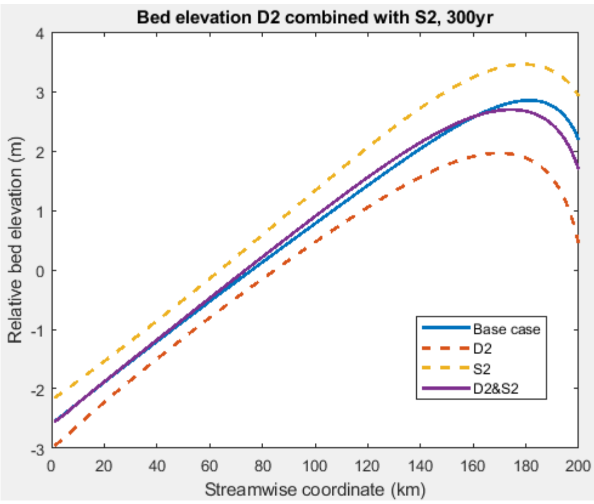


*Figure 15: Bed elevation for combination of D2 and S2.*

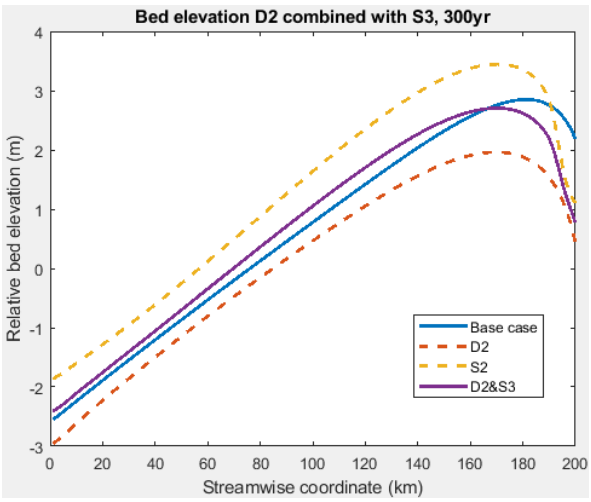


*Figure 16: Bed elevation for combination of D2 and S3.*

So even though this research is able to increase the understanding of the long-term changes of the river profile and bed composition for river branches like the Waal for the coming 300 years, it will never be able to predict the future. The uncertainties are just too high.

# 8. CONCLUSION AND RECOMMENDATIONS

## 8.1. CONCLUSION

The goal of this research was to get a better understanding of the long-term changes of the river profile and bed composition for river branches like the Waal for the coming 300 years.

For the base case, which is loosely based on the Waal and neglects changes for the boundary conditions, it is found that the river tends towards equilibrium state over time. By modelling the base case, it became visible that a period longer than 300 years is needed to reach the equilibrium state. During the transition towards equilibrium, at the downstream end sedimentation takes place, while further upstream degradation occurs. The wave of erosion slowly moves in downstream direction and the change of the bed elevation results in an decrease of the bed slope all along the river reach.

When changing the boundary conditions, new changes with respect to the river profile will occur. For more extreme discharges (higher maximum and lower minimum), the average discharge will increase since changes of the peak discharge have a greater effect than changes of the base discharge. An increase of the average discharge will result in a higher flow velocity and a higher sediment transport rate. Degradation will therefore take place all along the river reach and it will travel from the upper boundary in downstream direction.

When looking at the situation after 300 years, for more extreme discharges not only the maximum bed level decreases with respect to the base case, but also the area over which the bed level increases becomes smaller. The bed elevation after 300 years at the lower boundary is much lower for scenarios with more extreme discharges than for than for the base case. Due to the change of the bed level all along the river branch, the slope decreases for all scenarios. The average water surface elevation however gets higher for scenarios with more extreme discharges and the same is visible for the water depth.

For the sea level rise something different happens. An increased water level at the downstream end results in a higher water depth at the river mouth and therefore a decrease of the flow velocity. A lower flow velocity results in a decrease of the sediment transport rate and aggradation all over the river reach takes place. But, when the sea level is rising too fast, the system is not able to adapt to the new situation in time. The system wants to increase the bed level at the downstream part, since the water level is increasing as well, but the river is reacting too slow. The sediment needed from upstream is not supplied in time, resulting in a relative low bed level at the downstream end and a relative big water depth. Furthermore, a bigger increase of the sea level rise results in a longer backwater curve and higher water levels in upstream direction.

With respect to the climate change it would be very interesting to see what happens to the river profile and bed texture when both the discharge becomes more extreme and the sea level starts to rise. Given that sea level rise results in average to aggradation of the river bed and more extreme discharge results in degradation of the river bed, these two changing boundary conditions are theoretically able to cancel each other out. However, in reality one of the changes will always result in a bigger effect than the other. At the same time the range of possible scenarios is very large, which makes it hard to make a prediction for the future.

## 8.2. RECOMMENDATIONS

Even though this research has provided insight in the morphodynamic behaviour of rivers on the long-term, more research on this topic is preferable. The model used within this research was very schematized and simplified but to understand the real behaviour of rivers an extension of the research is needed.

In the first place it would be interesting to check the effects of changing sediment flux on the river profile and bed slope. Even though this was one of the goals for this research, the elaboration of this boundary conditions is not included fully within this report.

Furthermore, it would be good to increase the scope of the research by also including different sediment sizes in the model or by including the effects of flood-plains and (current and) future interventions. This makes the model significantly more complex, but therefore also more realistic.

Also it would be interesting to combine the different scenarios and see what the effect on the river profile is when several boundary conditions change simultaneously. To do so, it is very important to make a substantiated choice about which scenarios should be combined, since the range of possible scenarios is very large.

Overall it is very important to get a better understanding of the long term response of the river, not only to increase the knowledge about its behaviour, but also to make right decisions according to river management. More research on predicting the long-term response of rivers is therefore desirable.

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# APPENDIX A: SEDIMENT FLUX

The sediment flux has a great influence on the rate of sedimentation/erosion of the Waal. According to Frings (Frings et al., 2014a) sediment in the Rhine has three main sources; bed degradation, sediment supply from upstream and artificial supply for bed stabilization. About 50% is transported downstream and the rest is mainly deposited in ports, groyne fields and floodplains, see figure 3. These are however the estimations for the Rhine (640-865km) before it passes the split at Pannerdensche Kop and therefore not directly applicable for the Waal.

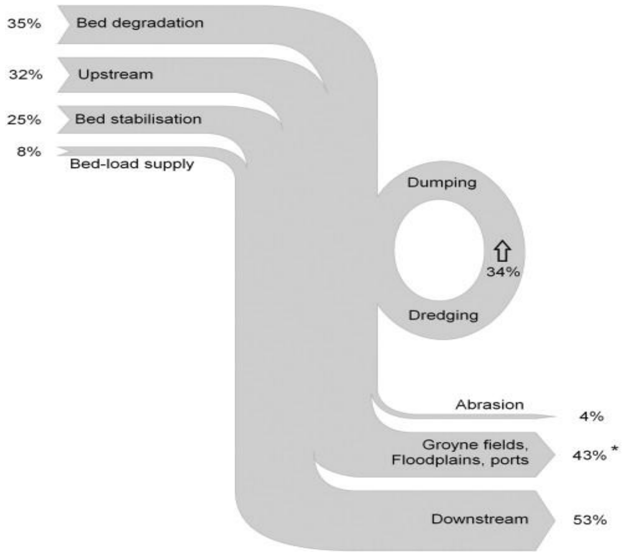



*Figure A1: Sediment budget for gravel and sand for the Rhine reach between km 640–865 (period 1991–2010) (Frings et al., 2014a).*

At the split at Pannerdensche Kop, about 2/3 of the water is distributed to the Waal. The sediment flux distribution is however not equal to the discharge. At Pannerdensche Kop 30% of the clay and slib is flowing towards the Pannerdenschkanaal and 70% enters the Waal. Relatively even more gravel and sand (86%) is distributed to the Waal at this point. (Hillebrand, Frings, 2017, p.152 and p.157).

The exact sediment flux at the upstream boundary of the Waal is not know, but there are measurements available about the average annual transport rate near Lobith, at Rhine-km 857.5. According to Frings (Frings, 2014a) sediment can be subdivided into five groups, based upon their grain size and mode. These groups are presented in table A.1. The sixth group contains all bed load particles together.

| ID | Mode | Sediment type | Grain size (mm) |
|---|---|---|---|
| F1 | Suspension | Silt, flocculated clay minerals | 0.006–0.063 |
| F2 | Suspension | Sand | 0.063–2 |
| F3 | Bed load | Sand | 0.063–2 |
| F4 | Bed load | Fine gravel | 2–16 |
| F5 | Bed load | Coarse gravel, cobbles | 16–125 |
| F6 | Bed load | Sand, gravel, cobbles | 0.063–125 |

*Table A.1: Division of sediment according to the grain size fraction of the particles and whether they are in suspension or not (Frings et al., 2014a).*

Near Lobith, the average annual transport rate per group is: 2.22 Mt/a suspended clay and silt (F1), 0.48 Mt/a suspended sand (F2), 0.08 Mt/a bedload sand (F3), 0.09 Mt/a bed load fine gravel (F4) and 0.02 Mt/a bed load coarse gravel and cobbles (F5) (Frings et al., 2014a).

Combining these numbers with the sediment flux distribution at Pannerdensche Kop results in the following sediment flux at the upstream boundary of the Waal, see table A.2.

| **Sediment type** | **Mode** | **Grain size (average) (mm)** | **Transport rate at Lobith (Mt/a)** | **Distribution rate towards the Waal** | **Transport rate into the Waal (Mt/a)** |
|---|---|---|---|---|---|
| Silt, flocculated clay minerals | Suspension | 0.006-0.063 | 2.22 | 70% | 1.55 |
| Sand | Suspension | 0.063-2 | 0.48 | 70% | 0.34 |
| Sand | Bed load | 0.063-2 | 0.08 | 86% | 0.07 |
| Fine gravel | Bed load | 2-16 | 0.09 | 86% | 0.08 |
| Coarse gravel, cobbles | Bed load | 16-125 | 0.02 | 86% | 0.02 |

*Table A.2: Average annual transport rate and distribution per sediment type, at Lobith and at the Waal (Mt/a)*

At the upstream boundary of the Waal, the average annual transport rate per sediment type is 1.55 Mt/a for suspended clay and silt, 0.34 Mt/a for suspended sand, 0.07 Mt/a for bed load sand, 0.08 Mt/a for bed load fine gravel and 0.02 Mt/a for bed load coarse gravel and cobbles (Frings et al., 2014a).

# Appendix B: Additional theory

## B.1. Backwater curve

For the future it is expected that the river bed will adjust its level and slope to the equilibrium state, since the river still is adapting to modifications like river narrowing and shortening during the 19th and 20th century. When reaching the equilibrium state, the water depth will become equal to the equilibrium water depth ($d_e$). Equation B.1 shows that the equilibrium water depth depends on the friction coefficient ($c_f$ = 0,004), the specific discharge (q), the river bed slope ($i_b = 1{,}0*10^{-4}$) and the gravitational acceleration ($g = 9{,}81\ m/s^2$). The equation for the equilibrium depth only holds for the area with quasi-normal flow.

$$d_e = \left(\frac{c_f q^2}{i_b g}\right)^{\frac{1}{3}} \qquad [B.1]$$

Even if the river has not yet reached its equilibrium, the river is always striving to reach the normal flow situation in which the bed slope and friction slope are equal. This transition is visible by a backwater curve. For large Froude numbers the adaption occurs faster (see equation B.2) .

$$\frac{dd}{ds} = \frac{i_b - i_w}{1 - Fr^2} \qquad [B.2]$$

For the Waal river the friction coefficient is larger than the bed slope ($c_f > i_b$) which means that the slope of the river bed is mild and the flow is subcritical. A backwater curve for a river profile with a mild slope and a subcritical flow is called a M-curve and it can be divided in three different types; M1, M2 and M3.

1. M1-type: the initial water depth is larger than the normal water depth. The water depth will slowly decrease towards the equilibrium in upstream direction.
2. M2-type: the initial water depth is smaller than the normal water depth but higher than the critical water depth. The water depth will slowly increase towards the equilibrium in upstream direction.
3. M3-type: The water depth is smaller than the critical water depth. This would mean that the flow is supercritical (Fr>1) while the river actually has a subcritical flow. Therefore the M3-type will never occur.

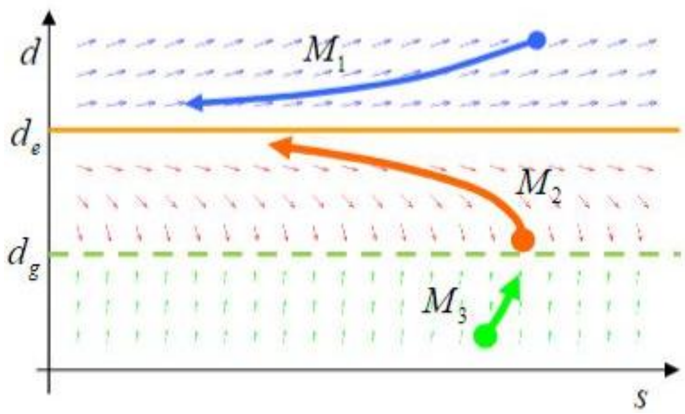



*Figure B1: M-type backwater curve, with normal water depth (d), the equilibrium water depth ($d_e$) and the critical water depth ($d_g$).*

To find the adaption length over which the river adapts towards normal flow Bresse method can be used, but this a very complicated method. Instead a 1st order approximation can give a insight in the adaption length without being very accurate. An empirical fit to Bresse is even more accurate than a 1st order approximation and is therefore better to use. To get the most accurate, fast and detailed solution, a 1D or 2D numerical model should be used.

The empirical fit to Bresse is given by equation B.3 and B.4:

$$d(s) = d_e + (d_0 - d_e)2^{\frac{s-s_0}{L_{1/2}}} \quad [B.3]$$

$$L_{1/2} = 0.24\frac{d_e}{i_b}\left(\frac{d_0}{d_e}\right)^{4/3} \quad [B.4]$$

## B.2. Van Bendegom & De Vries equations

The Van Bendegom & De Vries equations continue on the knowledge from the Exner equation, the conservation of mass equation and the belanger equation and results in three equations describing the flow velocity, the flow depth and the channel slope for steady state conditions (figure B2). To solve these equations the values for S (transported sediment), Q (discharge), B (width), $c_f$ (friction coefficient) and m (from Engelund-Hansen) must be known.

For variable flow, different from steady flow, the water discharge varies with time. When the discharge varies, the sediment load will also vary since the sediment transport rate depends on the discharge and flow velocity.

To understand the channels response to variable flow, it is possible to use the PDF (Probility density function) of the discharge. The PDF can be simplified for a two-mode water discharge when only a base and peak discharge occur, but it can also become more complex when including several different discharges. By doing so $Q_{dom,d}$ can be found. $Q_{dom,d}$ is the characteristic discharge that equals the value of a steady discharge which provides the same slope as the full PDF of water discharges.

$$Q_{dom} = \left[\alpha Q_{base}^{\frac{n}{3}} + (1-\alpha)Q_{peak}^{\frac{n}{3}}\right]^{3/n} \quad [B.5]$$

$$Q_{dom,d} = \left[\alpha Q_{base}^{n} + (1-\alpha)Q_{peak}^{n}\right]^{1/n} \quad [B.6]$$

Again using the Van Bendegom & De Vries equations, it is possible to create three new equations that are valid for alternating steady flow. These equations can however only be applied for quasi-normal flow segments (upstream from the backwater zone).

The Van Bendegom-De Vries Equations

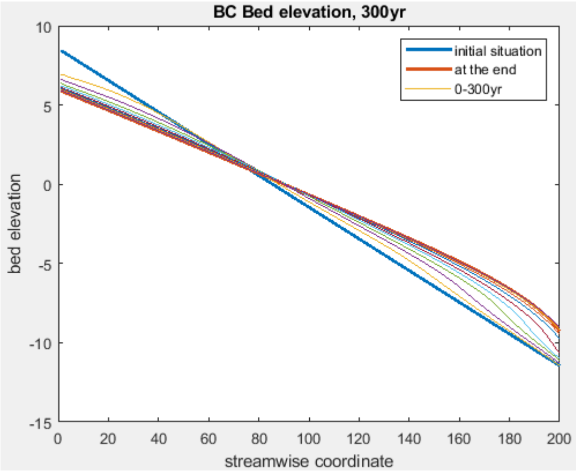
| | Steady discharge | Alternating steady discharge |
|---|---|---|
| Flow velocity | $u_e = \left(\frac{S}{Bm}\right)^{1/n}$ | $u_e(t) = \left(\frac{Q(t)}{Q_{dom}}\right)^{1/3}\left(\frac{E(S)}{Bm}\right)^{1/n}$ |
| Flow depth | $d_e = \frac{Q}{B^{1-1/n}}\left(\frac{m}{S}\right)^{1/n}$ | $d_e(t) = \frac{Q_{dom}^{1/3}Q(t)^{2/3}}{B^{1-1/n}}\left(\frac{m}{E(S)}\right)^{1/n}$ |
| Slope | $i_{be} = \frac{c_f B^{1-3/n}}{gQ}\left(\frac{S}{m}\right)^{3/n}$ | $i_{be} = \frac{c_f B^{1-3/n}}{gQ_{dom}}\left(\frac{E(S)}{m}\right)^{3/n}$ |

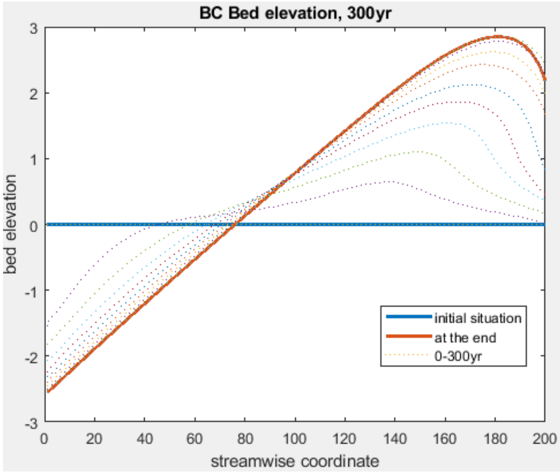
*Figure B.2: The Van Bendegom and De Vries equations for steady discharge and alternating steady discharge.*

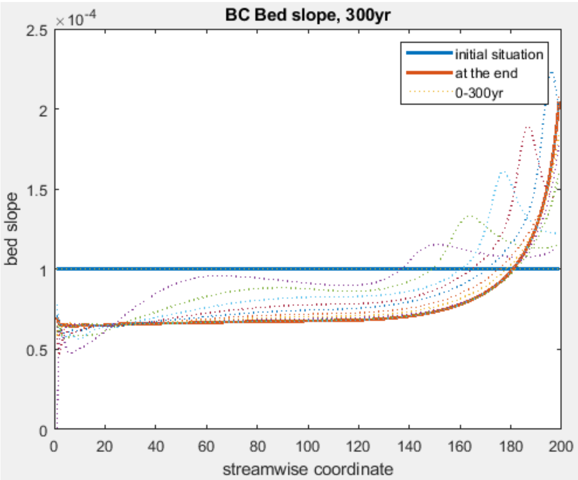
# Appendix C: Results

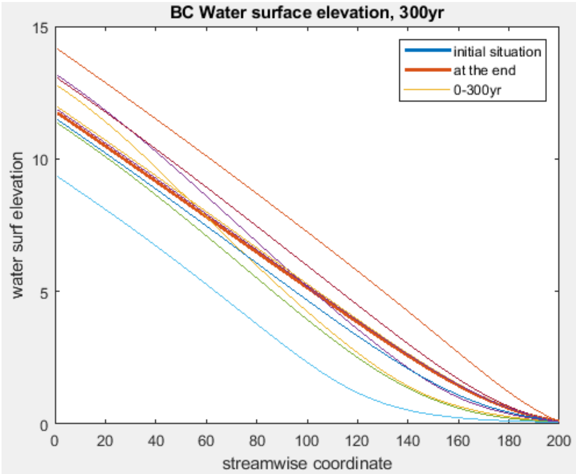
## C.1. Base Case

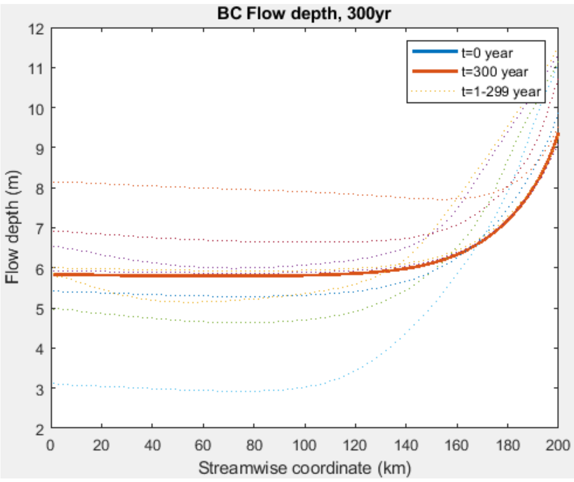
### Scenario Base Case - Figures



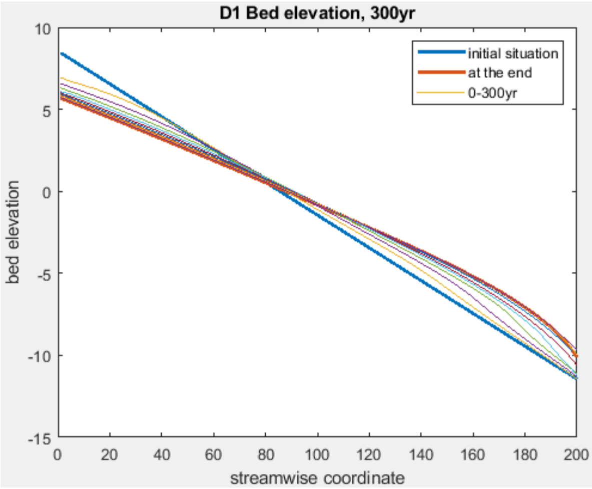



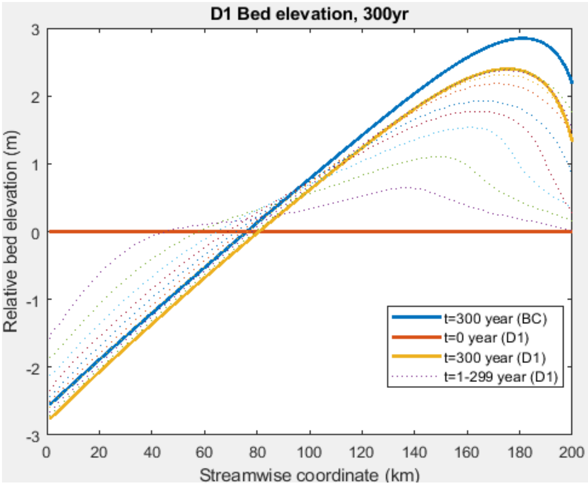



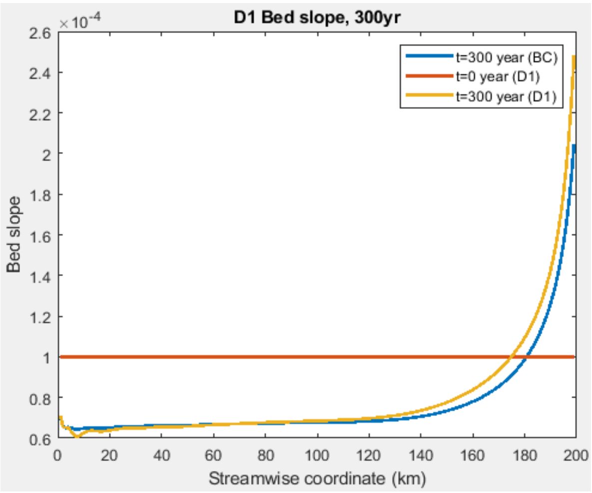



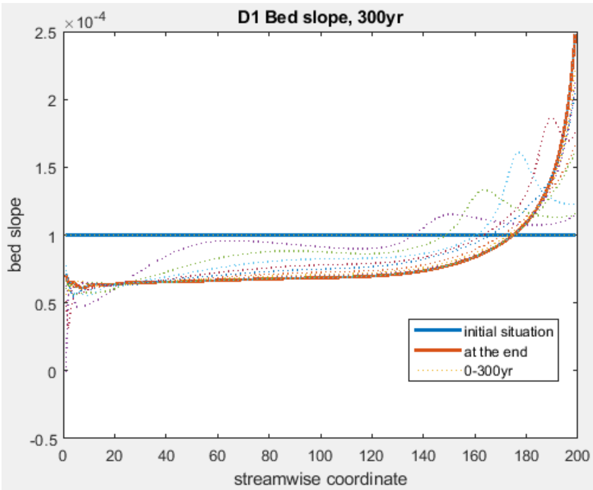
## C.2. Discharge

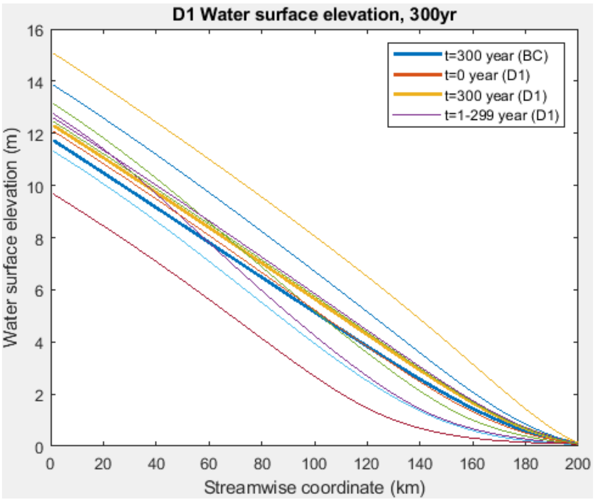
### Scenario D1 - Figures

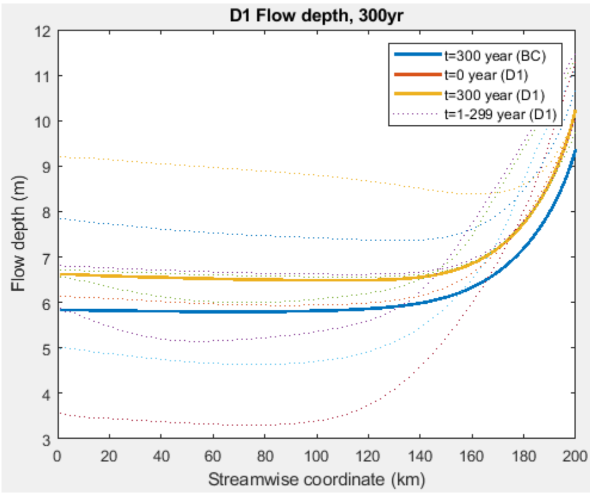


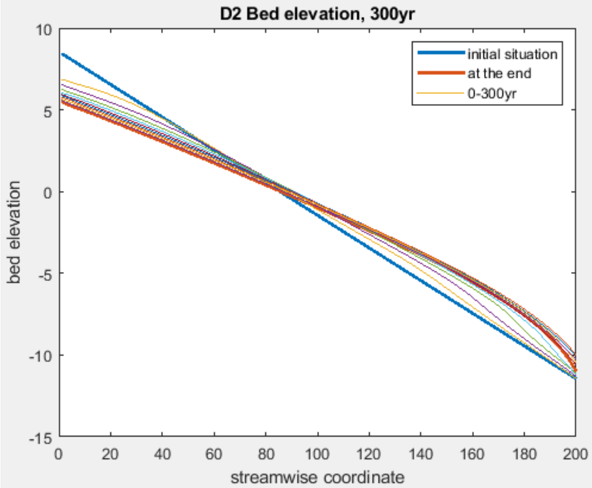



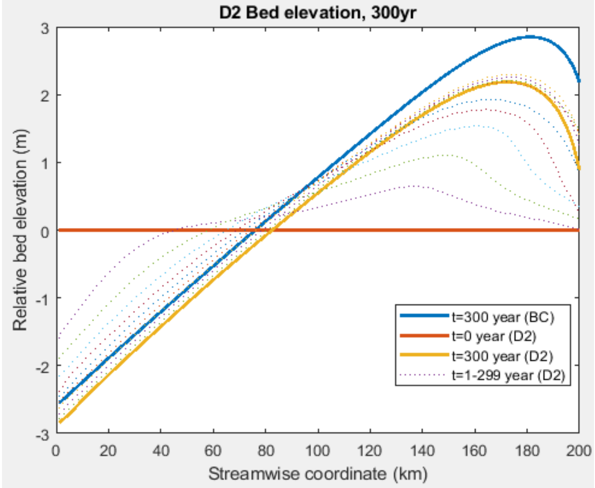



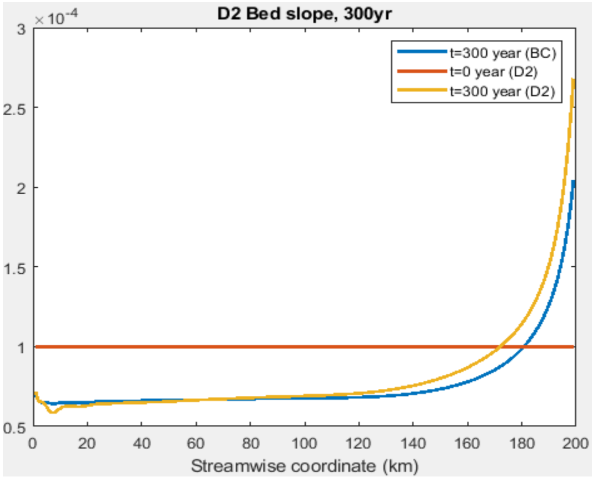



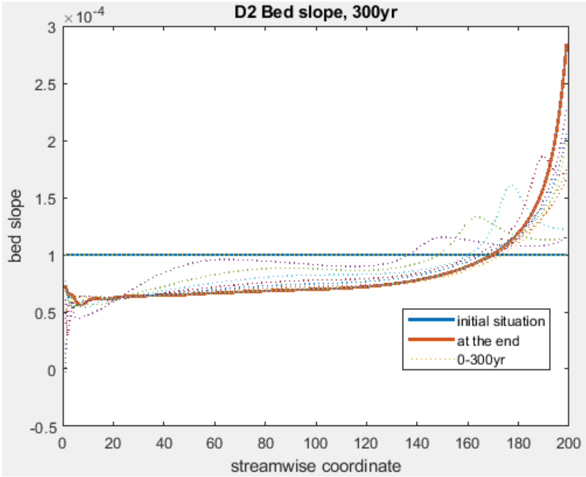



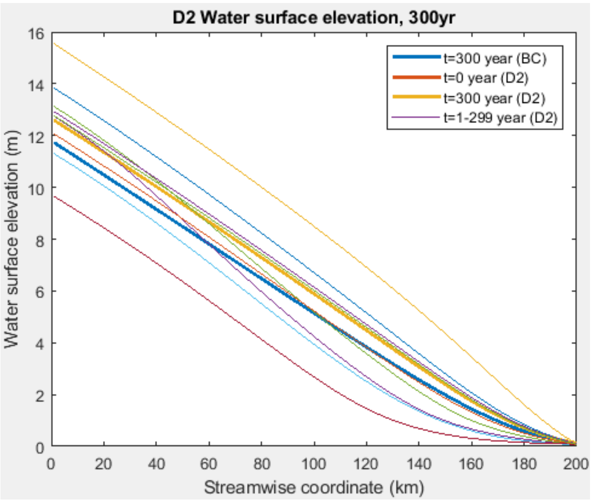
## Scenario D2 - Figures

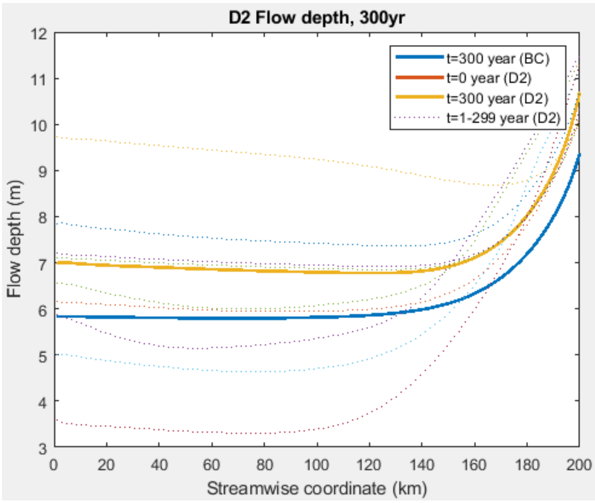


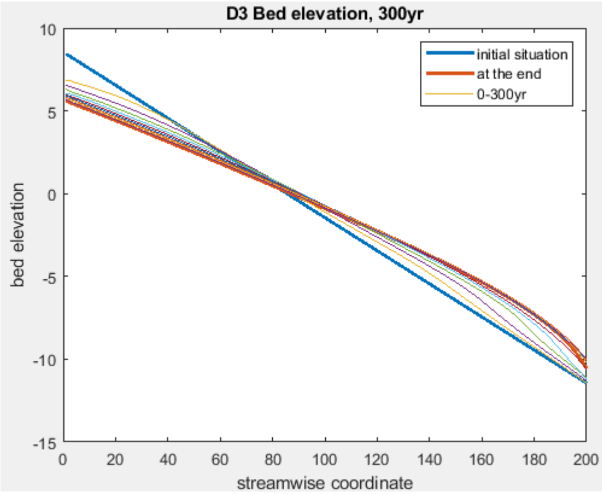



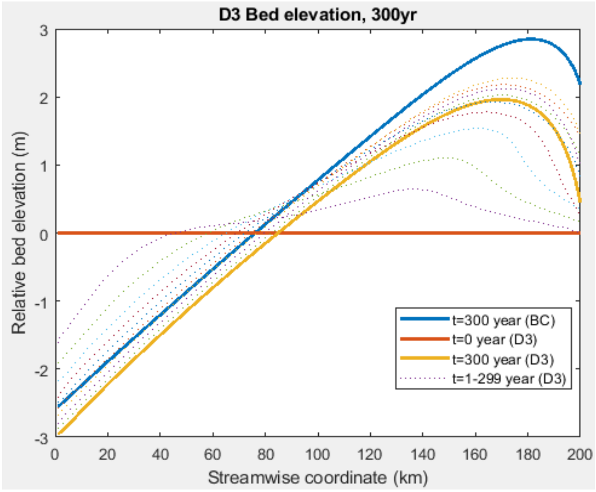



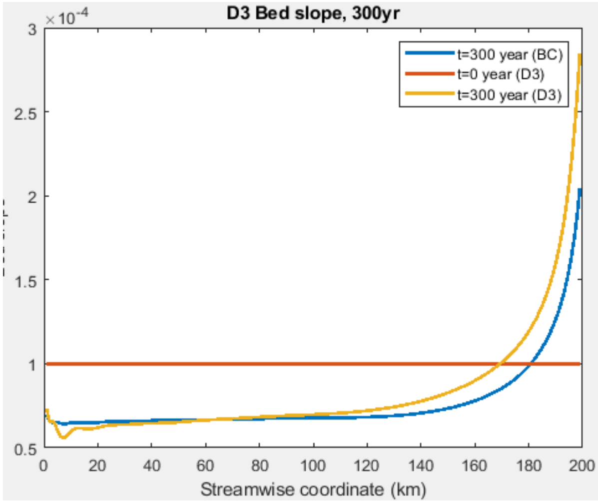



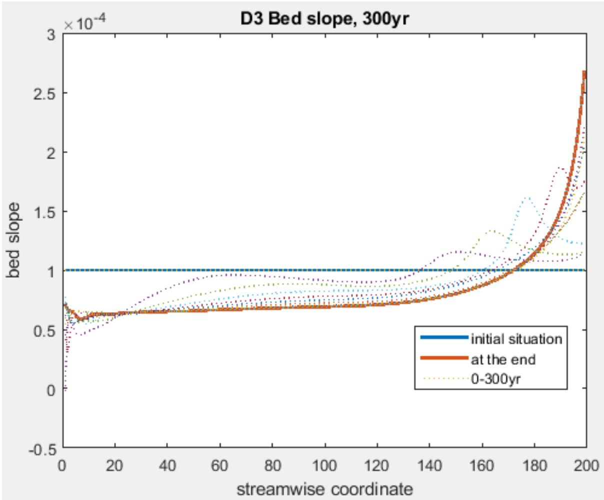



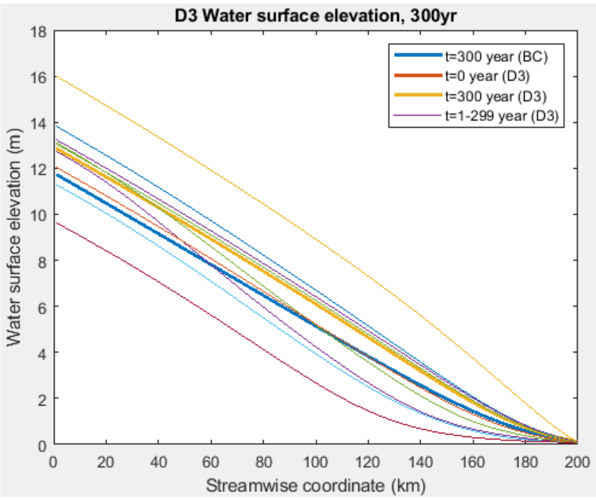
## SCENARIO D3 - FIGURES

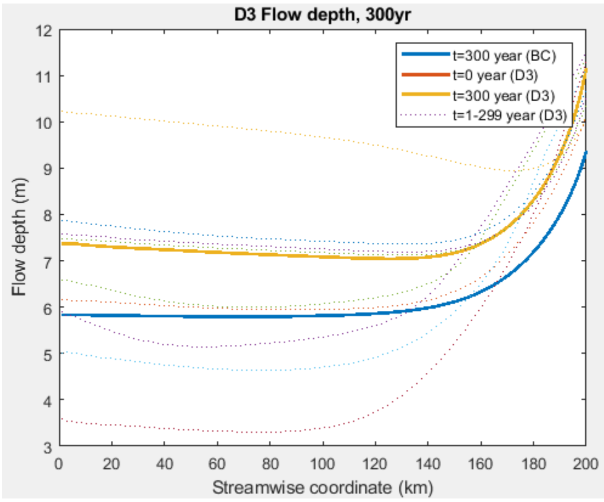


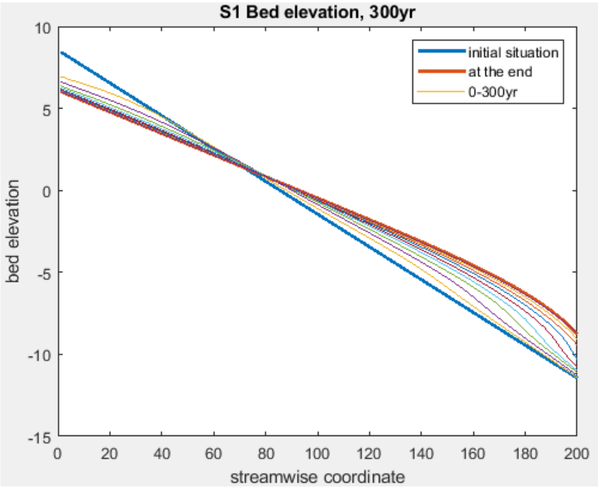



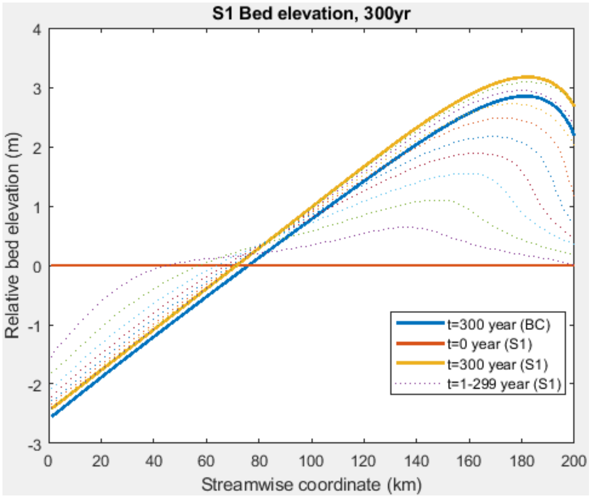



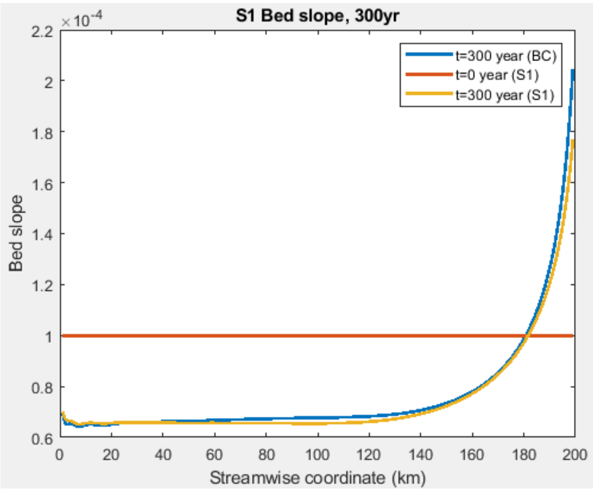
## C.3. Sea level

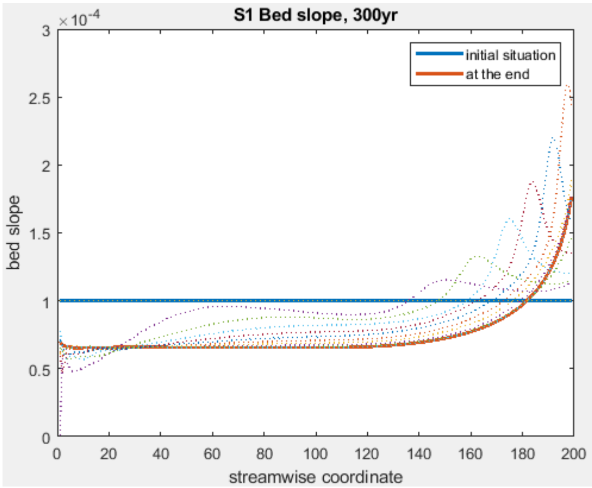
### Scenario S1 - Figures

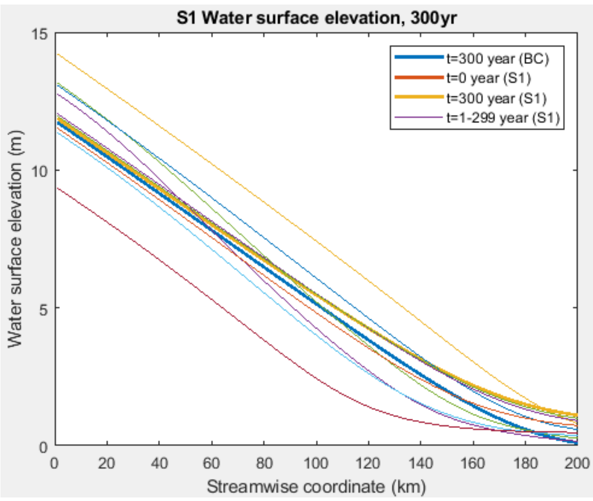
Sea level 3.4 mm/yr (positive scenario)

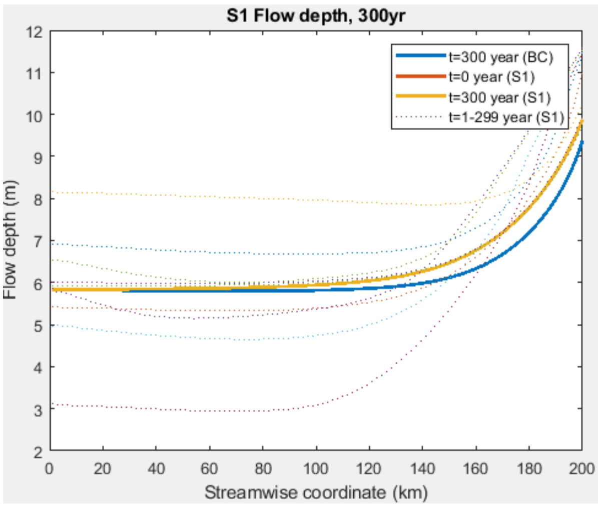


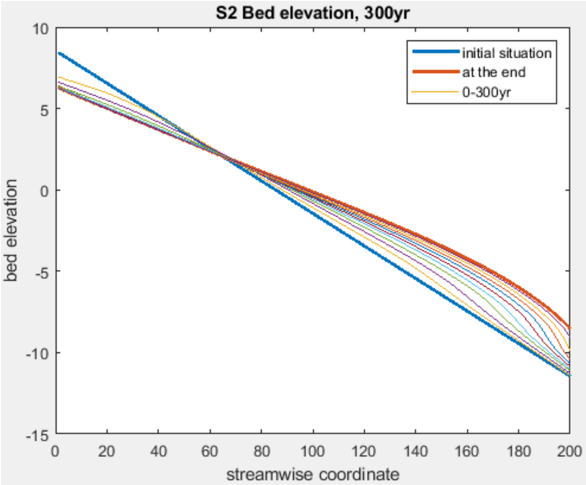



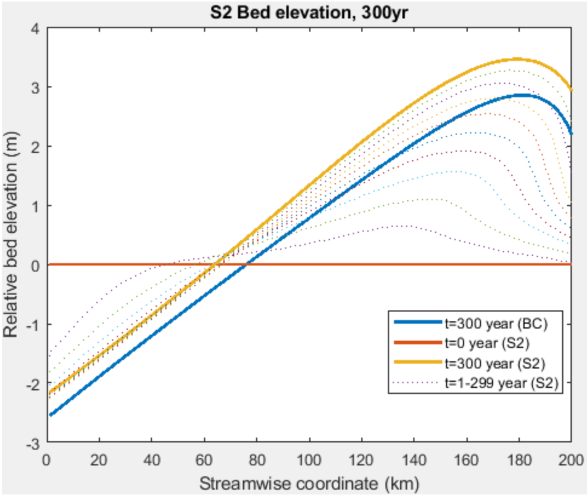



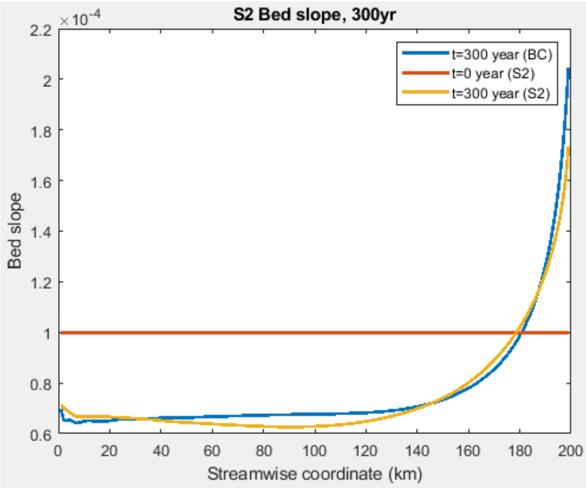



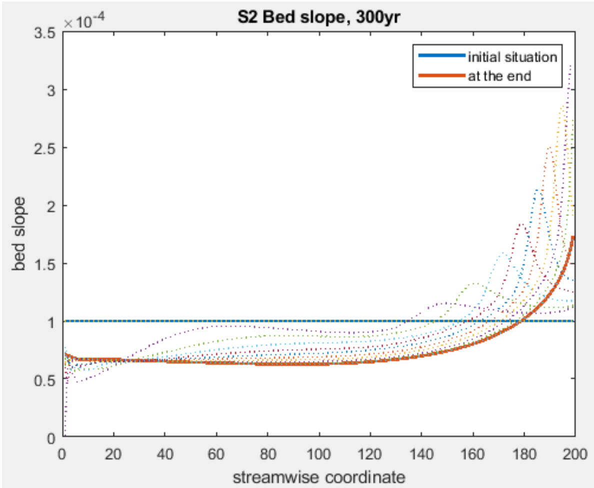
## SCENARIO S2 - FIGURES

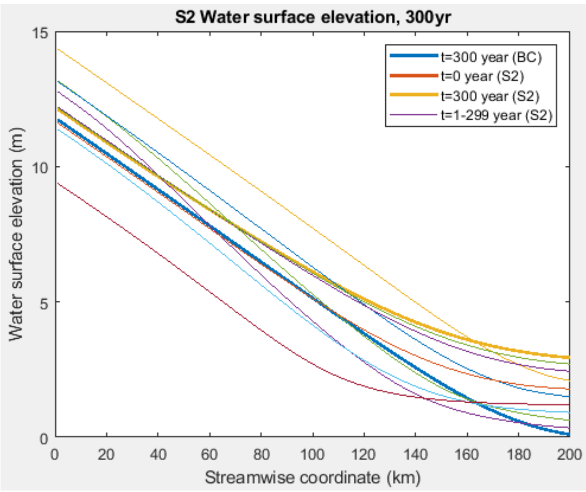
Sea level 9.5 mm/yr (neutral scenario)

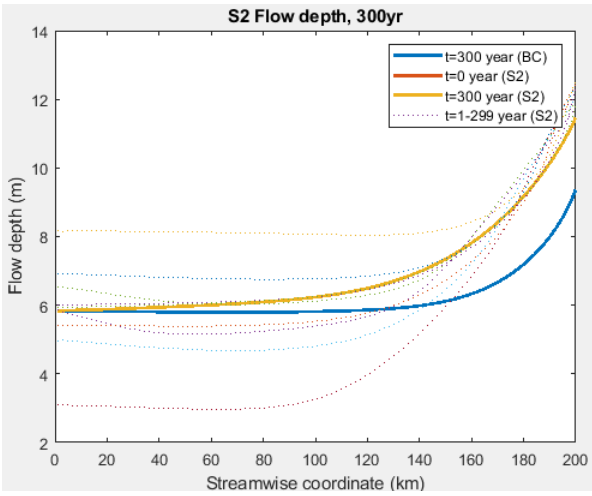


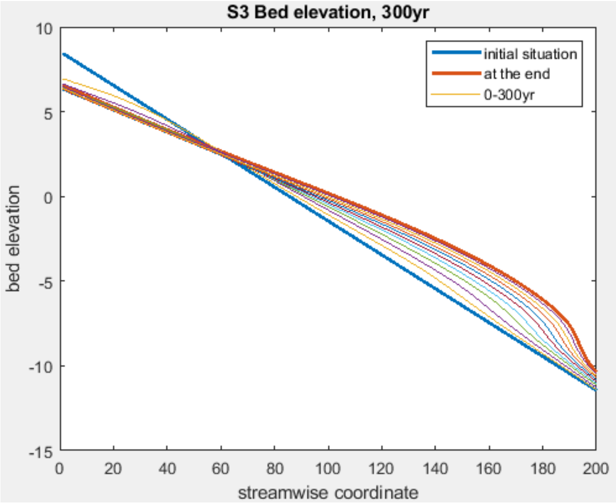



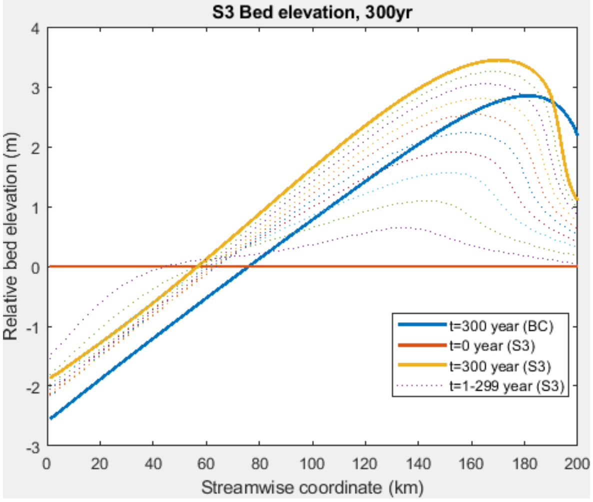



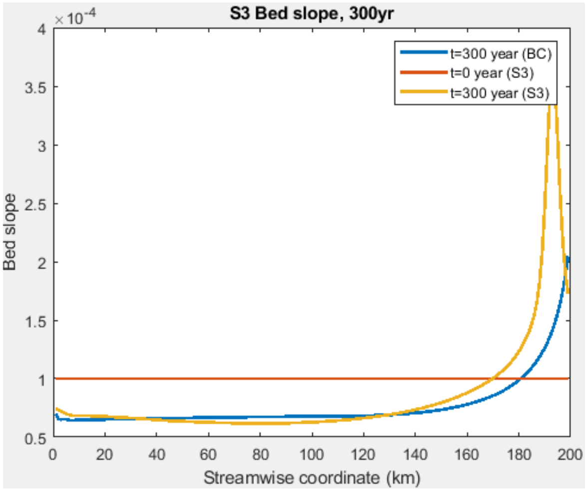



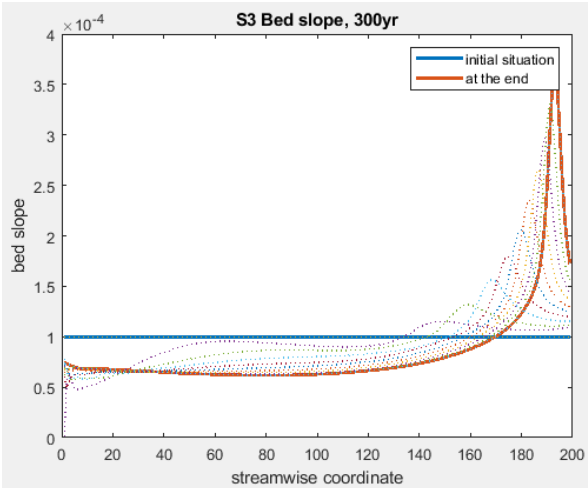
## Scenario S3 - Figures

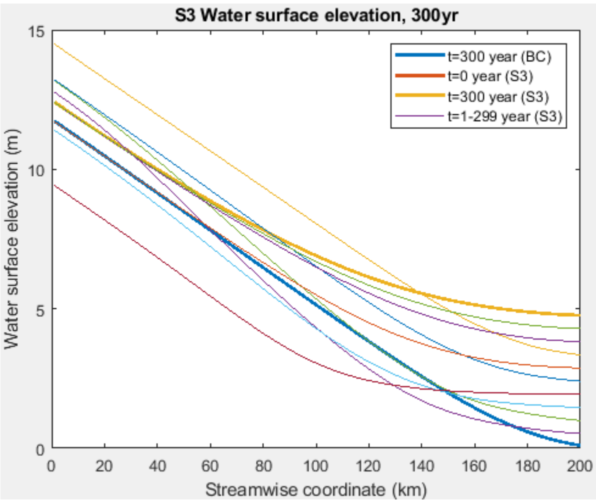
Sea level 15.6 mm/yr (negative scenario)

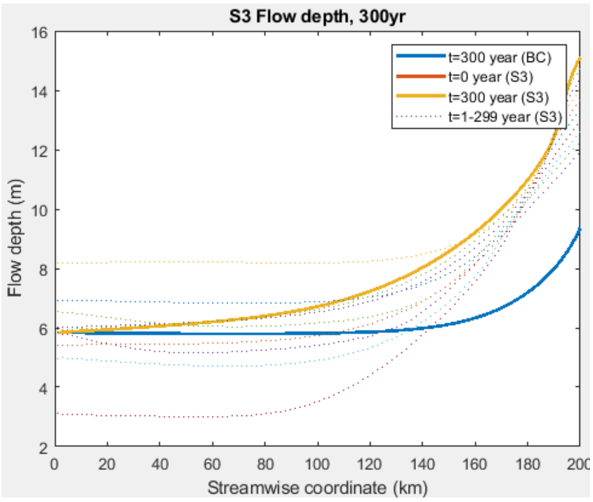


## Scenario S4 - Figures

Sea level 30.0 mm/yr (worst case scenario)