Long-term morphologic development and the effect on hydraulic load

Scenarios for long-term riverbed development in the main channel of the Dutch Rhine system and their impact on hydraulic load

Master Thesis
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Cover photo: At Pannerdense Kop into the direction of the Waal, M.M. Hendriksen, April 2017

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Scenarios for long-term riverbed development in the main channel of the Dutch Rhine system and their impact on hydraulic load

By

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in partial fulfilment of the requirements for the degree of

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at the Department of Rivers, Ports and Waterways,
Faculty of Civil Engineering and Geosciences,
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Final report

Preface

This thesis is the final part of my master Civil Engineering at Delft University of Technology. With this this thesis, I will finish my graduation project and study.

I have learned a lot during my study and graduation and I would like to thank a few people for their support and contribution. First, I would like to thank my graduation committee; Matthijs Kok for chairing the committee and making time for short and efficient conversations; Saskia van Vuren for her trust and enthusiasm. Astrid Blom for here critical view and motivating words; and Andries Paarlberg, for his support, shared knowledge and always clarifying conversations. It was refreshing to have a brainstorm session with you sometimes! I also would like to thank HKV consultants for the project opportunity and all river experts who were willing to participate in this research.

Finally, I would like to thank my family and friends for their support and sometimes welcome distraction from all the work, and in particular Joost for his continuous support, faith and patience during my study and graduation.

Merel Hendriksen
Delft, July 2018

Summary

High safety standards against flooding are required in the Netherlands and the design of a flood defence has a lifetime of around 50 years. The guideline for design of flood defences, OI2014, prescribes a guideline for climate change, but not for riverbed development. Unforeseen, underestimated or neglected developments of the riverbed may lead to different hydraulic conditions in the river like the water level and discharge distribution. Different hydraulic conditions may result in a different flood safety along the river.

The aim of this thesis is to derive potential long-term riverbed developments in the main channel of the Dutch Rhine, determine the effect of long-term riverbed development on hydraulic load in the Waal and analyse if the long-term effect on hydraulic load is relevant to include in the guideline for the design of flood protection structures. The main question of this research is ‘What are scenarios of long-term riverbed development in the main channel of the Rhine system and what is the impact on hydraulic load?’.

Relation between riverbed characteristics and hydraulic load: Hydraulic load is related to the water level and is influenced by variation in the riverbed characteristics. Riverbed characteristics in the main channel that affect the hydraulic load are the bed slope, bed elevation, bed composition and bed roughness. The variation of the riverbed characteristics is induced by various controlling variables in the river. The controlling variables are the human interventions, upstream discharge, downstream water level, subsidence of the ground and sediment supply.

Historical and present development: Human interventions have had a large contribution to the development of the river Rhine. The upstream discharge, downstream water level and subsidence of the soil have had a contribution as well, but this was an order of magnitude smaller than the observed development of the bed elevation. The contribution of the sediment supply to bed characteristic development is unknown.

Data analysis in this study showed that the development of the branch-averaged bed elevation in the Pannerdensch Kanaal is -1.0 cm/y for the period 2002-2015. In the Upper- and Lower part of the Bovenrijn, it is +0.4 and -0.4 cm/y and in the Upper- and Middle-Waal it is respectively -1.5 and -0.9 cm/y for the period 2000-2015. The development in the Lower-Waal is observed to be +0.4 cm/y, but this could be a trend or a temporary development. The bed slope for the same time period as the bed elevation development is stable in Pannerdensch Kanaal and develops towards a steeper slope in the Bovenrijn and towards a milder slope in the Waal. This corresponds with the development of the bed elevation. Some coarsening is observed in the Bovenrijn and upper part of the Waal. It is unknown whether this coarsening is also observed downstream in the Waal. The information and data on the development of bed roughness in the past is inadequate and outside the scope of this thesis.

Scenarios of long-term riverbed developments in the main channel: Based on historical data, scenarios are generated over 50 and 100 years. The eroding trend is likely to be reduced or stopped in the future by human interventions or in a natural way, but until that time, the eroding trend is assumed to continue with the same speed. It is also expected that no new interventions are applied that can accelerate the erosion again, but the observed coarsening might expand and this phenomena accelerates erosion downstream. The derived developments in this research have led to three scenarios of the bed elevation in the Waal and Pannerdensch Kanaal:

1. The bed elevation continues to erode with the present rate.
2. A solution is possibly found within 50 or 100 years and erosion is stopped.
3. Erosion might even be increased due to coarsening upstream and associated decrease of sediment supply downstream.

The bed elevation scenarios are varied by the integration of the artificial armoured layers in the river and by uncertainty in the upstream boundary condition.

Effect of bed elevation scenarios on hydraulic load: This is studied for bed elevation scenarios of the Waal over 50 years. The derived scenarios lead to bed elevation lowering of resp. 0.750, 0.375 and 1.000 m at the upstream boundary of the Waal. The results of scenario modelling in this research show the effect on the water level. The influence on the discharge distribution is not included, but it is likely it has an influence and this will change the water level downstream.

The effect of bed elevation lowering in the main channel with a bandwidth of 35.1 – 93.5 cm upstream in the Waal (872 kmr) is a lowering of the water level with a bandwidth of 6.9 – 21.1 cm. The water level effect is equal for flow through the floodplains at each location.

In combination with lowering of the armoured layer, the water level effect of the bed elevation scenarios is increased upstream of the layer. In other words, the armoured layer in its present condition reduces the influence of the bed degradation on the water level. The increased effect has a bandwidth of 0.9-2.8 cm near the armoured layer (883 kmr) for a bed lowering of a bandwidth of 25.9 -68.9 cm. Near the bifurcation (872 kmr) the effect is smaller, a bandwidth of 0.2-1.9 cm.

Variation in the upstream boundary due to uncertainty in discharge distribution over the bifurcation Pannerdense Kop of ±250 m^3/s for 16.000 m^3/s at Lobith results in a water level uncertainty of around 12.0-15.0 cm for the reference bed scenario in the Waal.. This uncertainty increases in millimetres for a larger bed lowering.

Relevance of the effect of potential long-term riverbed development in the main channel on hydraulic load: The water levels relevant for hydraulic load are the levels that induce a water level above the summer dikes and flooding of the floodplains. The bed elevation scenarios are relevant to include in the guideline for the design of flood protections when the effect on the water level is in the same order of magnitude as the uncertainty factor of 0.3 m for hydraulic load. The effect of the bed elevation development on the water level is concluded to be relevant. The effect of the armoured layer in the bed elevation scenarios is an order of magnitude smaller than the uncertainty factor and concluded to be irrelevant. The effect of the bed elevation scenarios on water level uncertainty due to uncertainty in discharge distribution is concluded to be irrelevant compared to effect the bed elevations scenarios. However, this analysis is without consideration of the response of the discharge distribution on the change in water level.

Several recommendations are given based on this thesis. A recommendation is to do more research to the consequences of bed elevation development on the discharge distribution and therefore associated water levels. It is also recommended to determine a methodology to derive the potential future development of the bed composition and roughness and to compare the effect on the water level with the results of this thesis.

Abbreviations

GRADE – Generator of Rainfall and Discharge Extremes

HL – Hydraulische belasting (NL) // Hydraulic load (UK)

KNMI – Koninklijke Nederlandse Meteorologisch Instituut

Kmr – Kilometerraai (NL) // River kilometre (UK)

LMW-station – Landelijk meetnet water-station (NL) // National monitoring network stations for water (UK)

MSL – Mean Sea Level

OI2014 – Ontwerp Instrumentarium 2014 (NL) // Design Instrument (UK)

RftR – Room for the River

USPB – Upper Stage Plane Bed

Table of contents

1. Introduction

This chapter gives an overview of the reasoning behind this research with information on the functions of the river, policy related to flood safety in the Netherlands, morphologic development of the riverbed and application of long-term riverbed development in the design of flood defences. The problem description of this research is given as well and the research objective and research question are defined. Finally, the methodology and thesis outline are given.

1.1. Background

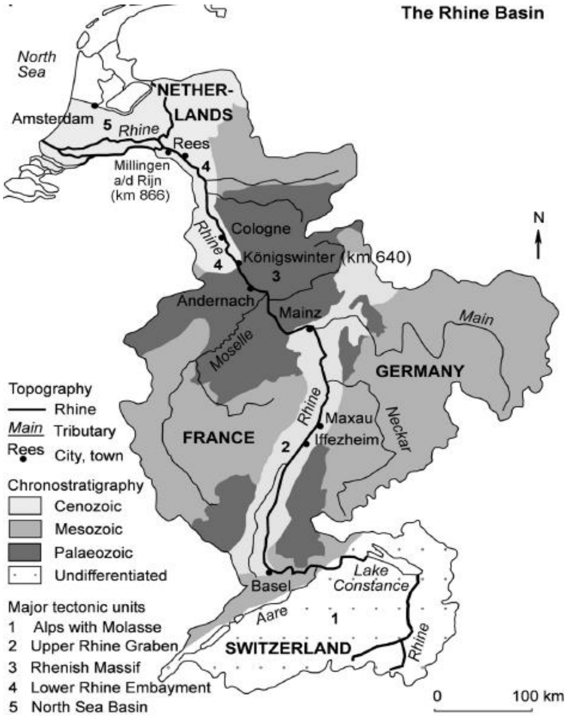

Figure 1 Topography of the Rhine basin (Frings, et al., 2013)

The Rhine basin covers 185.000 km^2 and around 58 million people live nearby and are vulnerable to flooding of the river (Frings et al., 2013). The upper part of the basin is located in Switzerland, the middle part in Germany and the lower part in the Netherlands. Downstream, the river flows into the North Sea basin (see Figure 1). The Rhine crosses the border between the Netherlands and Germany at Lobith. The upstream part of the Dutch Rhine is divided into four (main) branches by two bifurcations. The first bifurcation Pannerdense Kop is located around 5 km from Lobith and divides the Bovenrijn into the Waal and Pannerdensch Kanaal. The Pannerdensch Kanaal has a length of around 10 km and flows into the Nederrijn and IJssel at the second bifurcation IJsselkop.

The river Rhine discharges rain water, melt water, sediment and ice. During autumn and winter, mostly rain water is discharged, since snow is captured in the mountains. During spring and summer, mostly a combination of rain and melting snow is discharged.

High discharges cause high water levels along the river. The Rhine has a long history of floods and measures against it. Many people live in the basin of the Rhine and therefore high safety against flooding is required. Economic development along the river suffers from flooding as well. Management of the river is important and required to decrease the flood probability and to provide safety of society and economy.

River functions of the Rhine

A river function of the Rhine is transport of water, sediment and ice. Functions related to the river are flood safety, navigation and ecology. In this study, these functions are referred to as river functions as well. Functions along the river are agriculture, recreation and housing. Changes in the flow conditions might affect these river functions and management is required to maintain each river function.

Changing flow velocities and water levels might affect flood safety as it influences in the probability of flooding. Riverbed changes might affect flood safety as well by influence on the water level, but also by influence on the stability and functionality of hydraulic structures like weirs, flood defences, groynes and inlets. Navigation may be affected by changes in navigation depth due to changes in bed elevation or in return frequency of the discharge. This also affects the ecology in the river due to changes in the frequency of floodplain flooding and changes in the characteristic conditions. Transport of water and sediment is affected by changes in river geometry and hydraulic conditions.

Changes in the river can also affect the groundwater level near the river and cables and pipelines below the riverbed. Bed development causes different water levels and that results in a changing groundwater level along the river. Bed erosion decreases the thickness of the cover layer above cables and might induce the cables to become a bottleneck for navigation due to surrounding degradation.

The morphological changes in the river also influences riverbed properties and/or river geometry around a bifurcation point. This influences the water and/or sediment distribution over the bifurcation. A different discharge distribution results in different water levels downstream and this influences the river functions as well. It also leads to different sediment transport conditions and sediment distribution resulting in different morphologic conditions.

Policy for flood safety

Policy guides the management of river functions. Flood safety is a river function implied by the water law and quantified by the risk of flooding during peak flow. Risk is the consequence of a flood event times the probability of a flood to happen as a combination of different failure mechanisms. The probability of flooding depends on the strength of and hydraulic load on a flood defence system (Rijkswaterstaat, 2017b). The strength is based on multiple failure mechanisms, such as overflow, overtopping and stability mechanisms (e.g. piping, macro-stability). Hydraulic load is based on the height, period and duration of the water level and wind wave parameters. Hydraulic load, and therefore flood safety, is related to long-term riverbed development, because of its impact on the water level along the Rhine.

The safety requirement of the flood defence system along the Rhine is a probability of flooding between 1:3000 and 1:10.000 year, dependent on the location (Rijkswaterstaat, 2017c). Mostly, river flood defences are designed with a lifetime of 50 years and hydraulic structures with a lifetime of 100 years. At the end of this lifetime, the safety of the flood defence should be just below the maximum permissible probability of flooding. This implies that uncertainties, like climate change and riverbed development, to be included to determine design conditions for over 50 years or more. The design rules for flood defences are given within the design guide OI2014 (Rijkswaterstaat, 2017b). OI2014 covers the model and statistical uncertainties within an uncertainty factor of 0.3 m for the Dutch rivers. It also provides a guideline for climate change, but not for the uncertainty in bed development in the future.

Policy considers the climate scenario ‘W_+‘ as valid for assessment of flood safety[1] and implies a maximum flow discharge of 18.000 m^3/s at Lobith (Rijksoverheid, 2014; Rijkswaterstaat, 2017b). For higher discharges, flooding upstream of Lobith is expected and this reduces the amount of peak discharge towards the Netherlands. For extreme discharge events, >16.000 m^3/s at Lobith, a fixed distribution over bifurcation Pannerdense Kop is imposed by policy, distributing around 1/3 of the discharge towards Pannerdensch Kanaal and 2/3 towards the Waal. This distribution is maintained with a regulation structure near Pannerdense Kop (Pannerdensche Overlaat) and near IJsselkop (Hondsbroeksche Pleij). It is uncertain whether this distribution can be maintained and this uncertainty increases for higher discharges (Paarlberg et al., 2010; Kleinhans et al., 2013; ten Brinke, 2013). More information about the regulation structures to control the discharge distribution can be found in Appendix I. The government considers the policy on extreme discharge distribution to be valid at least until 2050 (Rijksoverheid, 2014), while it is uncertain if the regulation system reacts as expected under these conditions and if it feasible to adapt the system periodically during an extreme discharge, since this must be performed manually.

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[1] The ‘W+’ climate scenario consists of the expectation of a high temperate development (W) and a high development of the air circulation pattern (+) resulting in higher precipitation

Morphologic development of the river Rhine

A river has a natural dynamic morphologic equilibrium for which riverbed characteristics are balanced with the water and sediment discharge. The bed characteristics have a short-term and long-term response to perturbation of the river equilibrium, with consequences for the flow conditions and management of the river functions. After permanent perturbation, it can take centuries for the river to reach a morphologic equilibrium again (De Vries, 1975). This will probably never occur due to continuous interventions by human to maintain the river functions (Frings et al., 2013).

Riverbed adaptation is an uncertain development since not every process in the river is well understood and modelled. Short-term response of the riverbed is the initial response of the riverbed towards temporary conditions and it varies over time with the discharge variation. This variation causes fluctuation of the bed elevation by bed forms in the river like ripples and dunes, and sedimentation/erosion waves through the system, see also Figure 2. The long-term response of the riverbed is a slow process of adaptation of the bed characteristics towards the (dynamic) morphologic equilibrium of the system, see also Figure 2. The equilibrium is disturbed by changes in the river characteristics due to climate change and human interventions.

Climate change affects the downstream water level by sea level rise and the upstream discharge regime by changing weather conditions. Human interventions can be a change in the characteristics of the bed or in the regulation of water and sediment flow. Both climate change and human interventions affect the river characteristics in various ways and this differs in time and space. Many interventions like normalisation of the River, dredging, armoured layers and dams are applied to the Rhine in the past, see also paragraph 3.1.

Long-term riverbed trends in the main channel of the Rhine are observed from long-term measurements of riverbed characteristics like bed composition or bed elevation. The bed composition of the Rhine mainly used to be a sand river, but nowadays it has become more of a gravel river in the upper part of the delta and a sand river in the lower part (Frings et al., 2013; Blom, 2016). A bed degradation rate of 1-4 5 cm/y is noticed in the Rhine, varying per river branch and time period (Sieben et al., 2012; Frings et al., 2013; Blom, 2016; Sieben, 2016).

Bed degradation reduces the water levels, but unequal development of the riverbed in the downstream branches of the bifurcation point influences the discharge distribution as well. It is uncertain how the riverbed development develops, and influences the distribution and uncertainty in distribution under extreme discharge events (Sieben et al., 2012; ten Brinke, 2013). Variation in the discharge distribution affects flood safety. The levees downstream of the bifurcation are designed with a hydraulic load depending on the water level induced by the opposed ‘fixed’ discharge distribution. If the bed is not lowered equally in the entire branch for instance due to stabilization of the downstream reach, the increased discharge causes an increased water level locally downstream and therefor an increased load on the levees and a decreased flood risk.

The water and sediment distribution at a bifurcation are affected by local properties of the river. The water distribution depends on the river geometry, gradients and morphology downstream of the bifurcation and the regulation system along the Rhine. The sediment distribution depends on the geometry, transport capacity and morphodynamics upstream (Kleinhans et al., 2013). The morphodynamics around a bifurcation can be very irregular under high discharge events and this causes irregular hydraulic roughness (Warmink et al., 2007). The morphodynamics might affect the stability of the bed around the bifurcation. The stability is induced by the coarse bed, but it is unknown if this would maintain under extreme discharge events. It might come in suspension due to large shear stresses (Sieben et al., 2012; Kleinhans et al., 2013). That can lead to large erosion around and instability of the bifurcation, but this also depends on the sub-layers and the amount of erosion. This phenomena and process is highly uncertain.

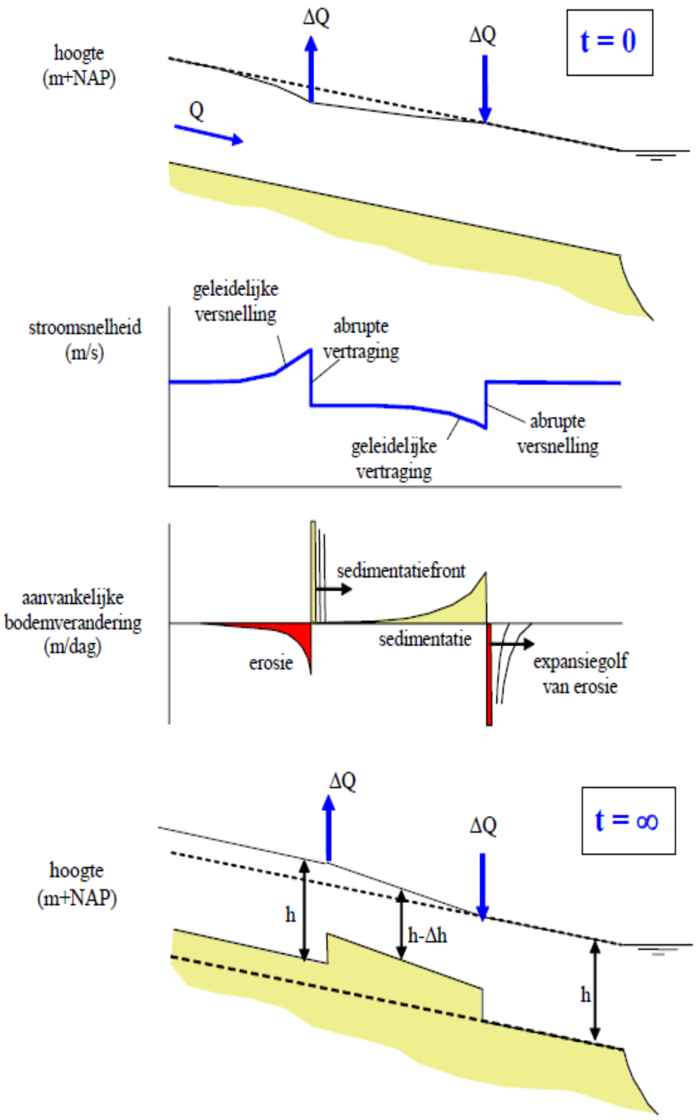

Figure 2 Morphologic response on short (t=0) and long (t=∞) term to riverbed widening (e.g. replacement of dikes, side channel), the first and second step show the hydraulic consequence of the intervention, the third step shows the short-term response and the fourth step shows the long-term response of the river characteristics and the new equilibrium (Mosselman et al., 2007)

Application of long-term riverbed development in design of flood defences

The most recent riverbed of the main channel available in the models used for flood safety assessment is the riverbed of the Rhine measured in 2013 (Berends, 2014). The assessment is applied every 12 years and does not assess the development between two assessments (Rijkswaterstaat, 2017b). The assessed bed is probably different from the present bed in the river Rhine. The assessed bed is also different than the future bed. It changes due to the morphologic development of the riverbed, climate change and human interventions and it may lead to different hydraulic conditions.

The design conditions should include the river conditions within the 50 years lifetime, since safety of the flood defence system should be just below the maximum permissible probability of flooding at the end of the lifetime. The design guideline for flood defences (OI2014) prescribes the inclusion of model and statistical uncertainties within an uncertainty factor of 0.3 m and provides a guideline for climate change. However, it does not prescribe a guideline for implementation of potential future riverbed development or uncertainty in discharge distribution in the design.

The development and contribution of climate change and bed development to the design are dependent on the design lifetime. The longer the lifetime, the more uncertain the bed development will be. A shorter lifetime is a way to reduce the uncertainty in climate change and bed degradation development (Rijkswaterstaat, 2017b). Insight in how the bed might develop in the future and if it is positive or negative for flood safety might reduce the uncertainties as well.

The required design of a flood defence is different when bed development is included, but if other developments like change in bed composition are included. These developments may change the hydraulic conditions. Bed degradation decreases the water level and seems positive for flood safety, but it influences the discharge distribution as well and leads theoretically to an increased discharge towards the Waal. The increased discharge may lead for instance to higher water levels in the downstream reach of a river where less or no degradation occurred due to riverbed adaptation towards a milder bed slope.

The bed development can be determined by modelling. Modelling is often accompanied with assumptions to simplify physical processes and river characteristics, and this causes an uncertain result. The choice of riverbed application is important, because a different riverbed elevation at the start of an event can result in different water levels (Paarlberg et al., 2010). The choice of hydrograph in a numerical model influences the results as well (Van Vuren, 2005; De Vriend, 2010; Sloff et al., 2014). The upstream discharge is often applied as a characteristic (deterministic) hydrograph, while this is a dynamic variation dependent on inherent uncertainty and resulting in a different hydrograph each year (Van Vuren, 2005). The description of the discharge variation is complicated. Analytical reasoning and trend analysis of the bed in the river can give insight in the potential future development as well and can be determined without description of a hydrograph.

The fixed discharge distribution at the bifurcation Pannerdense Kop is imposed by policy for extreme discharge events and applied in modelling. It is uncertain whether this fixed distribution can be maintained under the extreme conditions, because the bifurcation might become unstable under extreme discharge conditions and that affects the distribution (Kleinhans et al., 2013). Instability of the bifurcation might occur due development of riverbed characteristics over time, the (uncertain) large morphodynamics under high discharge events and the behaviour of the coarse bed around the bifurcation under high discharge events. A change in distribution results in a different flood risk (Brandsma, 2016).

1.2. Problem description

Long-term riverbed development is adaptation of the riverbed towards the dynamic equilibrium of the river between the riverbed and discharge of water and sediment. This development can take centuries and it is difficult to predict. The guideline for design of flood defences, OI2014, does not include riverbed development or discharge uncertainty within the guideline. The assessment conditions might be different than the design conditions due to bed level change or change of the bed surface structure. Unforeseen, underestimated or neglected developments of the riverbed related to flood safety is likely to lead to different hydraulic conditions in the river like the water level and discharge distribution. That might pose an additional risk for society and economy and can lead to more costs as a result of a possibly conservative design, maintenance or consequences of flooding.

In the Netherlands, high safety standards against flooding are implemented for which flood defences are designed. For economic and safety reasons, the design of a flood defence has a lifetime of around 50 years and a hydraulic structure has a lifetime of around 100 years. The longer the lifetime, the more uncertain the bed development and climate change will be. A shorter lifetime is a way to reduce this uncertainty, but insight in the potential riverbed development in the future and if it has a positive or negative contribution to flood safety might reduce the uncertainties as well. This makes it relevant to determine the long-term development of the riverbed within this lifetime to determine the flood safety over 50 and 100 years.

1.3. Objective

Aim of this thesis

The aim of this thesis is to determine potential long-term riverbed developments in the main channel of the Dutch Rhine, what the effect is of the long-term bed elevation development on hydraulic load in the Dutch Rhine and if the long-term effect on hydraulic load is relevant to include in the guideline for the design of flood protection structures.

Research question

Main research question:

What are scenarios of long-term riverbed development in the main channel of the Dutch Rhine system and what is the impact on hydraulic load in the Waal?

Sub-questions:

Q1) How are riverbed characteristics and hydraulic load related?

Q2) What long-term riverbed developments, for the riverbed characteristics related to hydraulic load, are observed in historical and recent measurements in the river Rhine?

Q3) Which scenarios of long-term riverbed developments in the main channel might occur in the Dutch Rhine?

Q4) What is the effect of scenarios of long-term riverbed development in the main channel on hydraulic load in the Waal?

Q5) How relevant is the effect of long-term riverbed development in the main channel on hydraulic load in the design of flood defences along the Waal?

1.4. Methodology

The approach to be followed for answering the sub-questions and the research question is divided into six steps:

1) The type of riverbed characteristics in the main channel and their controlling variables is analysed. Also part of the analysis is the relation of these characteristics and variables with hydraulic load.
2) The past and present riverbed development of controlling variables and riverbed parameters in the main channel related to hydraulic load are analysed from literature and data.
3) An analyses to potential long-term development of the riverbed characteristics and controlling variables based on literature, extrapolation of the trends found in step 2 and information from conversations with river engineering experts in the Netherlands, to include their ideas and hypothesis on the future based on experience in this analysis.
4) Based on this analysis, riverbed scenarios of long-term riverbed development are generated over 50 and 100 years in the Rhine.
5) The scenarios for long-term riverbed development, generated in step 3 are used to determine the effect on the water level with a numerical simulation in SOBEK-3. The results of the simulation are analysed and interpreted.
6) The results and analysis in step 5 is used to determine whether the effect of the potential scenarios are relevant for hydraulic load on the flood defences along the Waal.

Scope and limitations

In this research the developments of controlling variables and bed characteristics are used to generate potential scenarios of long-term riverbed development. The relation between the riverbed characteristics and the hydraulic load is used to determine the effect of riverbed development on the water level. An overview of these relations and steps are given in Figure 3.

The influence of water level effect on the discharge distribution at the bifurcation points is not studied in this thesis, because it could be a research topic of its own. The determination of hydraulic load is limited to the water level; wind effects are assumed to remain unaffected by the riverbed scenarios and therefore to have no effect on the hydraulic load.

Scenarios are determined in the Waal and Pannerdensch Kanaal for 50 and 100 years ahead and dependent on the development of the river system. The long-term development of the riverbed is limited to morphologic development of the main channel. The floodplain is assumed to remain at the present level and present state.

The determination of the effect of the scenarios on the hydraulic load with SOBEK-3 is limited to the Waal, because of the uncertainty in discharge distribution upstream in the model by calibration and corrections. Model calculations of the discharge distribution with modified riverbed characteristics is not reliable, because the schematization of the Rijn is calibrated with roughness sections where multiple combinations of roughnesses are plausible. The upstream boundary is applied as a static discharge of >4.000 m^3/s at Lobith, because lower discharges are influenced by the weirs in the Nederrijn-Lek, maintaining a navigable water depth in the Waal, and higher discharges induce flooding of the floodplains, what results in hydraulic load on the levees. Tide and salt intrusion are not present at the study area section.

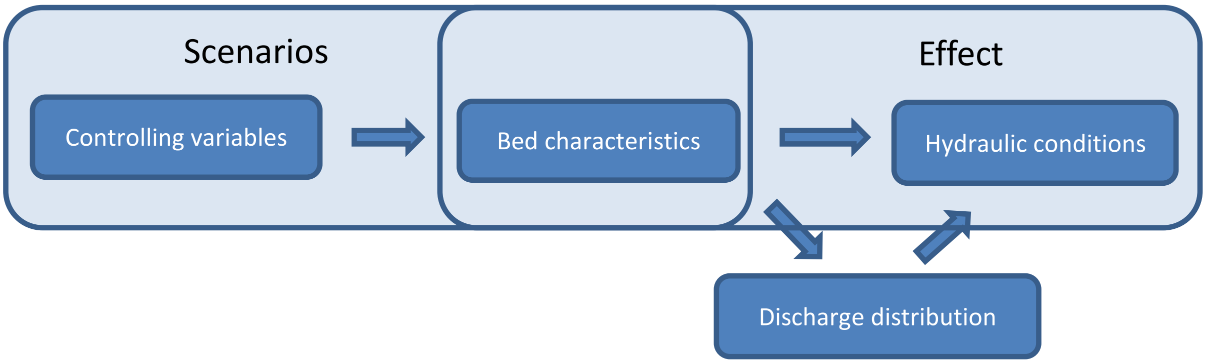

Figure 3 Relation between controlling variables, bed characteristics and hydraulic conditions used for the methodology in his thesis

1.5. Thesis outline

Chapter 2 is an analysis of the riverbed characteristics in the main channel of the river and the controlling variables of these riverbed characteristics. An answer is given to which riverbed characteristics and controlling variables are related to hydraulic load, so this chapter answers sub-question 1.

Chapter 3 answers sub-question 2 by analysing the past and present development of the relevant controlling variables and bed characteristics relevant to hydraulic load. Within this chapter it becomes clear whether development did occur in the past and whether it is relevant to analyse the future development of the controlling variable or bed characteristic.

Chapter 4 is an analysis of potential future development of the controlling variables and bed characteristics that were observed to be relevant in chapter 3. With this potential future development, scenarios of long-term riverbed development in the main channel of the Rhine are generated for over 50 and 100 years. This answers sub-question 3.

Chapter 5 gives an answer to sub-question 4. The procedure of modelling the effect of the riverbed scenarios on the water level related to hydraulic load is given and several necessary assumptions and decisions are clarified. The results are graphed and analysed in the final paragraph.

Chapter 6 is about the relevance of the effect of the bed elevation scenarios on the water level and hydraulic load. This chapter answers sub-question 5.

Chapter 7 treats the discussion on the method and results of this research. It also includes the conclusions of this research and answer to the research-question(s). Finally, recommendations on further research are given.

2. The relation between riverbed development and hydraulic load

This chapter is an analysis of the riverbed characteristics related to hydraulic load and their controlling variables. The first paragraph of this chapter describes the riverbed characteristics of the main channel. The second paragraph describes how these characteristics are controlled by variables of the river. The third paragraph describes how riverbed characteristics and controlling variables are related to hydraulic load. The final paragraph concludes which controlling variables and riverbed characteristics are relevant for hydraulic load.

2.1. Riverbed characteristics

The main channel of the river is characterized by the bed slope, bed composition, bed elevation and bed roughness. The bed slope of a river system can be divided in an upper-, middle- and lower reach. The bed gradually flattens in the downstream direction and the Dutch Rhine is located in the lower reach. The composition of the bed can vary in longitudinal, cross-sectional and vertical direction (top- and sub-layer). The surface sediment in the upper-reach is often more coarse than in the lower-reach through downstream fining (Frings, 2007). The bed elevation in the main channel varies around a dynamic equilibrium state with bed forms. The dynamic equilibrium state of the bed elevation might vary at branch-scale over a relatively large time scale.

Variation in the bed composition and bed elevation can lead to a variable roughness of the bed in time and space. The roughness relation is written by Van Rijn (1990) as $k_s = k_s' + k_s''$ with the roughness coefficient (k_s) divided into a roughness related to the bed grains (k_s') and to the bed forms (k_s'').The development of bed forms is related to the hydraulic conditions and grain size(Julien & Klaassen, 1995). In a moveable bed, the bed forms dominate the bed roughness due to turbulence at the downstream side of the dune (Wilbers & Ten Brinke, 2003). The grain resistance is often an order of magnitude smaller than the bed form resistance for alluvial channels (Van Rijn, 1982). In case of a plane bed, no dunes are present and the roughness is dominated by the grain resistance (Van Rijn, 1982).

An overview of the bed characteristics is given in Table 1. The riverbed characteristics are strongly related and often change mutual. For instance bed erosion results in a lower average bed elevation, a milder bed slope for large-scale erosion and perhaps exposure of a different sediment composition. A different bed composition is related to different bed forms (Julien & Klaassen, 1995) and therefore to the bed roughness as well. The relation between the bed characteristics is graphed in Figure 4.

Table 1 Overview of the riverbed characteristics

Bed characteristics
Bed slope
Bed composition
Bed elevation
Bed roughness

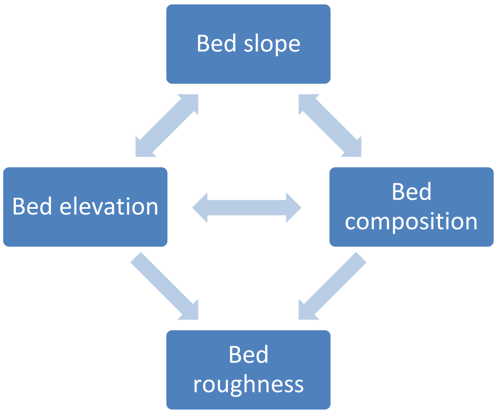

Figure 4 Relation between the riverbed characteristics, the bed roughness follows from the bed elevation, i.e. bed forms, and bed composition

2.2. Controlling variables of the riverbed characteristics

The main and natural function of a river is to transport water and sediment. There is a natural equilibrium between the riverbed and transport of water and sediment. This can be described with the mass and momentum balance of water and sediment (Jansen et al., 1979). The adaptation of bed characteristics is induced by variation in transport of water and sediment, because this causes an imbalance of the natural equilibrium. The variation results in erosion and sedimentation of the riverbed to adapt the riverbed characteristics towards a new equilibrium state that corresponds with the water and sediment conditions.

Steady flow and riverbed conditions lead to a static equilibrium of the riverbed. River flow is unsteady, because the discharge is variable due to seasonal variation in run-off, and results in a dynamic equilibrium of the riverbed. This means an equilibrium state with (small) fluctuations around the equilibrium bed elevation related to the yearly average discharge (Jansen et al., 1979).

From De Vriend (2015) is known that the adaptation of bed characteristics is controlled by the variables water discharge, downstream water level, consolidation of the ground and sediment supply. Human intervention is a control variable of the riverbed characteristics as well, but it also influences several other controlling variables.

- Variation in water discharge influences the flow capacity over time, with associated varying flow velocities and sediment transport capacity. The variable flow rate of the yearly discharge hydrograph induces the equilibrium bed slope. The river balances the riverbed characteristic with the transport of water and sediment to restore the natural equilibrium.
- Variation in the downstream water level, which is often the downstream boundary of the river, influences the velocity around the outflow of the river in time and space. This also affects the sediment transport rate and is related to changing bed characteristics.
- Consolidation of the ground in the main channel of the river can vary spatially and that influences the bed slope and bed elevation spatially.
- Sediment supply depends on the amount and composition of available sediment and on the sediment transport capacity. If sediment supply differs from the transport capacity, the sediment balance is disturbed and this will be restored by sedimentation and erosion of the riverbed or -banks. Bank-erosion is uncommon in the Rhine since most parts of the river bank are stabilized with groynes. Consequence of the bed adaptation is a different bed elevation, bed composition and possibly bed slope when it occurs on large scale.
- Human interventions affect the flow conditions. This results to changes of the riverbed characteristics and controlling variables. Human interventions are taken to manage and improve the river functions according to the present policy. Political changes or changing

riverbed characteristics that affect the river functions are reasons for human intervention in the river.

An overview of the controlling variables is given in Table 2. Variation or changes in controlling variables affect the flow conditions and conveyance of water and sediment. It also causes adaptation of the riverbed characteristics towards a new (dynamic) equilibrium that corresponds with the present water and sediment conditions. The variation and adaptation varies per controlling over time and space.

Table 2 Overview of the controlling variables that cause adaptation of the bed characteristics

Controlling variables
Upstream discharge
Downstream water level
Consolidation
Sediment supply
Human interventions

2.3. Aspects related to hydraulic load

The assessment of a flood defence system depends on the strength of and hydraulic load on the flood defence. Flood safety is quantified by the risk of flooding during a high water event. Risk is the consequence of a flood event times the probability of a flood to happen as a combination of different failure mechanisms. Hydraulic load is based on the height, period and direction of the water level and wind wave parameters (Rijkswaterstaat, 2017c). When these parameters change over time, the hydraulic load and flood safety might be different than assumed.

Hydraulic load might be changed by the bed characteristics in the main channel. The wind wave parameter is supposed to be insufficiently influenced by changes of the riverbed characteristics. The water level parameter can be affected by changes of the bed elevation in the main channel in two ways: 1) bed forms affect the water level by inducing variation in bed roughness and 2) the long-term development of the average state affects the bed level of the main channel relative to the floodplain level and this induces a different water level. Bed slope development influences the water level as well. A milder or steeper bed slope results in a different water depth due to changes in flow velocities. The bed composition does not directly influence the water level. It was mentioned to be related to the bed roughness in paragraph 2.1. Higher roughness leads to more resistance and therefore a higher water level. In case of a plane bed, the roughness depends particular on the grain roughness. Coarser sediment induces higher roughness and therefor higher water levels.

Variation of the discharge directly relates to a different water level. The water levels that reach untill the levees are interesting for flood safety, so when the water level is higher than the summer dikes and floodplains are flooded. Hydraulic load is determined for discharge >6000 m^3/s (Chbab et al., 2017b), but the discharge for which water flows through the floodplains varies locally. The downstream water level influences the flow capacity downstream. An increased downstream water level increases the water level on the river in upstream direction with a back water curve.

The discharge upstream can also be dependent on the discharge distribution at a bifurcation. A different distribution than expected for an upstream discharge results in a different water level and different hydraulic load downstream of the bifurcation. This leads to a different flood risk as well (Brandsma, 2016).

Figure 5 gives an overview of the variables that control the water distribution at the bifurcation. The water distribution depends on the upstream discharge, downstream water level, downstream geometry and the morphology around the bifurcation, but also weirs and a regulation system influence the distribution. The distribution, and therefore the water level downstream, changes when one of these variables is changed.

The discharge distribution in the Rhine at bifurcation Pannerdense Kop is regulated with weirs in the Nederrijn-Lek. The regulation is described with the weir-program and depends on the water level at Lobith. The discharge distribution at Pannerdense Kop is controlled by the weirs for a water level of 8.65-10.00 m +NAP at Lobith, i.e. around 1.600-2.600 m^3/s (Rijkswaterstaat, 2015). Appendix I gives more information on the weir program. For extreme discharge conditions, a regulation system is available to regulate the discharge distribution at the political assigned fixed distribution, as mentioned in paragraph 1.1. The regulation system consists of two inlets: Pannerdensche Overlaat (around Pannerden) and Hondsbroekse Pleij (around IJsselkop). More information about the regulation system can be found in Appendix I as well.

Table 3 gives an overview of the riverbed characteristics and controlling variables related to hydraulic load. Hydraulic load can be determined as the water level and is affected by adaptation of riverbed characteristics and three controlling variables; the discharge upstream, the downstream water level and the discharge distribution upstream. The water level changes when the riverbed characteristics or controlling variables change. For the purpose of this research, the wind wave parameter in the upper part of the Dutch Rhine is supposed to be insufficiently influenced by changes of the riverbed characteristics and therefore assumed to be irrelevant in this research.

Table 3 Overview of relevant parameters for hydraulic load and their controlling variables

Hydraulic load	Controlling variables
Water level	Riverbed characteristics
(Wind waves)	Upstream discharge
	Downstream water level
	Discharge distribution at bifurcation

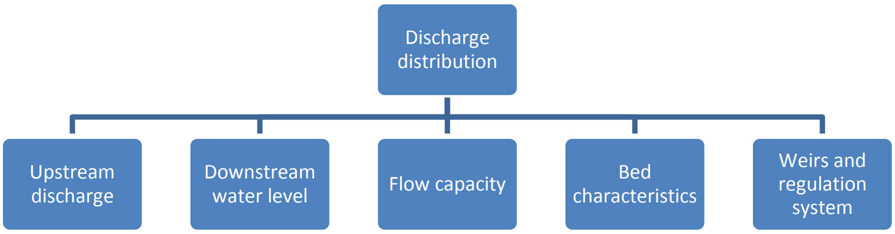

Figure 5 Variables that influence the discharge distribution at a bifurcation

2.4. Conclusion

Riverbed characteristics and controlling variables that are related to hydraulic load are of interest in this research. From the previous paragraphs is known that hydraulic load can be determined from the water level and is affected by adaptation of riverbed characteristics. The riverbed characteristics are on their turn controlled by various controlling variables. If the controlling variables change, the river adapts the riverbed characteristics towards a new (dynamic) equilibrium that corresponds with the present water and sediment conditions.

An overview of the relation between riverbed characteristics, their controlling variables and hydraulic load is given in Table 4. The discharge distribution at the bifurcation is not taken into consideration in this thesis due to time constrains, and the amount of variables indicate that this controlling variable has potential to be a research topic of its own. Human interventions is in the list of controlling variables, but it influences the other controlling variables as well.

Table 4 The most relevant controlling variables of the bed parameters and bed parameters for the most relevant parameter of hydraulic load

Controlling variables	Riverbed characteristics	Hydraulic load
Human interventions	Bed slope	Water level
Upstream discharge	Bed composition	(Wind waves)
Downstream water level	Bed elevation	
Consolidation	Bed roughness	
Sediment load		
(Discharge distribution at bifurcation)		

3. Analysis of past and present development of the controlling variables and riverbed characteristics in the river

This chapter is an analysis of the past and present development of the riverbed characteristics in the main channel of the river Rhine and their controlling variables. The purpose of this chapter is to determine if and how much influence the controlling variables have had on the bed characteristics and what the development of the bed characteristics itself has been in the past. This analysis is based on literature and data and focusses on the long-term development, because this gives information for riverbed scenarios over 50 and 100 years.

First, the past of human interventions in the Rhine are analysed, because this gives insight in the effect that intervention have or have had on the riverbed characteristics in the Dutch Rhine. Secondly, the past development of the controlling variables and the riverbed characteristics is analysed and possible trends are quantified.

3.1. Human interventions in the river Rhine

Human interventions in the river affect both the bed characteristics and controlling variables. Over centuries people have built constructions to protect against flooding and to manage of the river functions. A measure has an effect on the hydrodynamic and morphologic behaviour of the river. It changes the flow and sediment transport capacity of the river. The response of the bed characteristics differs in time and space, around an intervention (see Figure 2, p.4). Many types of measures are taken in the Rhines' history, like groynes, dams, weir structures, longitudinal dams, canalization of side rivers, (re)placement of summer- and winter-levees, lowering of the floodplain and dredging and suppletion of sediment.

Already in 1350, people build a levee system along the river against flooding. The levees decreased the flood conveyance capacity. In the 19th century, normalisations in the river were excecuted and this decreased the conveyance capacity even further. Groynes were built to control bend erosion, ice dams and navigation. The bed characteristics are probably still adapting towards the interventions in the Rhine in the 19th and 20th century (e.g. Frings et al. (2013); Kleinhans et al. (2013); Sieben (2016)). The reduced conayance capacity led to an increased sediment transport capacity and adaptation towards a milder bed slope on large-scale. Measures were taken to control the discharge distribution as well (Kleinhans, et al., 2013). The weirs in the Nederrijn-Lek control the discharge distribution at Pannerdense Kop for discharges of 1600-2600 m^3/s at Lobith and regulation structures around the bifurcations control the distribution for extreme discharge events, >16.000 m^3/s at Lobith on the fixed distribution over bifurcation Pannerdense Kop imposed by policy.

Many dredging activities in the river between 1970-1990 decreased the sediment availability in the river and led to an accelerated degradation of the riverbed. Also, dams in the German Rhine and in the tributaries affect the sediment (and water) transport in the downstream direction. In 1978, Germany started with sediment nourishment to compensate the bed degradation and sediment availibility (Frings, et al., 2013). Since 1990, the dredged material in the Netherlands upstream of Zaltbommel must be discharged into the river again near the dredging place. Nourishment of sediment influences the sediment load and transportation rate of the river (Kleinhans et al., 2013) and the influence depends also on the nourished composition. Too coarse nourishment increase the bed erosion downstream, because transport mobility and capacity of the riverbed material are affected (Blom, 2016).

Several artificial armoured layers are contructuded in the Dutch Rhine as well. These layers are non-erodible and applied to prevent erosion of the bed for instance in an outer bend. An armoured layer is present in the Waal around Nijmegen at river kilometre (kmr) 883.2-885.2 since 1988 and around St. Andries at 925.0-928.2 kmr since 1999. Upstream of Lobith at 858-861 kmr around Spijk is an armoured layer present since 2010. Another type of measure to prevent erosion is bed groynes and this is applied as well in the Waal around Erlecom between 873-876 kmr since 1996.

Latest interventions in the river were longitudinal dams and adjustment of groynes. Both are part of the RftR-measures. Since 2016, the longitudinal dams have replaced the groynes in the Waal between Wamel and Ophemert (±12 km). The longitudinal dams divide the river in a main and side-channel. This increases the water level in the main channel under low flow conditions and increases the flood conveyance capacity under high flow conditions. Lowering of the groynes is applied in other parts of the Waal, because the design height is 0.5 m below the average water level, but this has become approx. 0.7 m probably due to bed erosion (Sieben, 2009). Lowering of the groynes increases the flood conveyance capacity and probably decreases the bed roughness under moderate and high discharge conditions (Kleinhans et al., 2013). This results in lower water levels, lower sediment transport capacity and probably less erosion of the bed during high discharge events.

Other recent programs in the river are e.g. IRM, DBR[2]. These programs focus on the development of the bed characteristics and possibly introduce interventions in the river that contribute or control the riverbed developments to manage the river functions.

3.2. Controlling variables that encourage riverbed development

The development of the upstream discharge, downstream water level, subsidence of the ground and sediment supply over the past are analysed to determine the contribution to the development of the riverbed characteristics.

3.2.1. Upstream discharge

The water discharge depends on the climate associated with the geological location of the river and on human interventions affecting the conveyance upstream. It can also depends on a bifurcation point in the river that influences the upstream discharge of the downstream branches. The variation in the yearly discharge hydrograph is the result of seasonal variation in precipitation and run-off. Climate change is a slow process that affects the seasonal weather conditions on long-term and can lead to a change in statistical occurrence of discharges in the Rhine. That changes the yearly average discharge, resulting in a change in annual sediment transport capacity and different bed characteristics. Human interventions might control the discharge by dams or weirs in the river (par. 3.1).

The development of the upstream discharge over the past and present years is analysed to determine the contribution to the development of the riverbed characteristics. The equilibrium bed slope is related to the to the variable flow rate of the yearly discharge hydrograph (Blom et al., 2017). The river adapts the bed slope towards the natural equilibrium between the riverbed and transport of water and sediment. The variable flow rate is expressed as the standard deviation over the mean of the daily discharge (σ_w/μ_w). If the flow rate increases significantly, it indicates a change in hydrograph and statistical occurrence of the discharge and in sediment transport capacity. An increased flow rate results in a milder bed slope to restore the natural equilibrium.

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[2] IRM – Integraal riviermanagement, DBR – Duurzame Bodemligging Rijntakken.

The data of discharge measurements at Lobith is modified into the development of the monthly median discharge hydrograph for four periods of 30 years and this is given in Figure 6. A varying hydrograph over time is observed. The flow rate associated to each period is given in Table 5. The flow rate slightly increased in time by an increasing standard deviation and therefor it might could have had a (small) contribution to equilibrium bed slope in the Rhine.

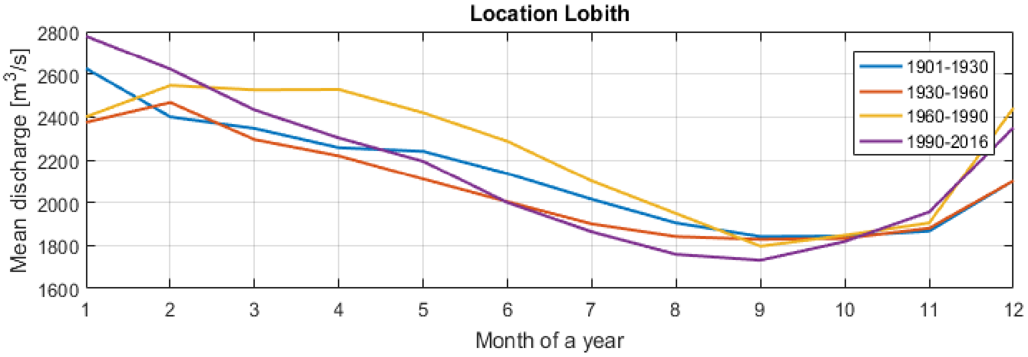

Figure 6 Monthly median discharge over time per time period of 30 years (data from Rijkswaterstaat)

Table 5 Mean, standard deviation and flow rate of the daily discharge per period of 30 years

Period	Mean (μ)	Standard deviation (σ)	Flow rate (σ/μ)
1901-1930	2205.8	1062.5	0.48
1930-1960	2168.8	1174.3	0.54
1960-1990	2296.6	1156.1	0.50
1990-2016	2226.5	1137.2	0.51

The change in statistical occurrence also affects the probability of occurrence of extreme discharges. This might be induced by climate change and might lead to more frequent high water levels in the Rhine and a higher probability on hydraulic load on the flood defences. Extreme discharge events can have various impacts on the bed characteristics like movement of coarse material, damage on or even flooding of the levees, (extreme) local erosion and scour holes. An impact like branch cut-off can influence the river on large-scale, but this process takes probably more than one extreme flood to develop and it is expected to be likely that people will restore the damage before such a large change can fully develop. The rarely occurrence of extreme discharges and the local and temporary impacts results in less contribution to the (large-scale) morphologic behaviour and equilibrium of the riverbed than the moderate, relative frequent discharges (Blom et al., 2017).

3.2.2. Downstream water level

The mean sea level (MSL) is the downstream boundary condition of the river Rhine and influences the river water level. The downstream water level changes on short-term due to tide and storm surges. On the long-term, climate change causes sea level rise and this influences the river water level upstream with a back water curve. If this effect reaches until the bifurcation point, it also affects the discharge distribution.

A higher downstream water level imposes different flow and morphologic conditions. The flow velocity at the downstream boundary is decreased and sedimentation occurs. This leads to aggradation of the riverbed and after a long period to a milder bed slope. That might cause a higher water level along the river during high water as well. However, climate change and morphologic development of the riverbed are both slow processes, but the time scale of morphologic development is longer than of hydraulic development (Liang, 2010).

The riverbed aggradation is induced by the sea level rise and will eventually become equally to the amount of sea level rise, but it develops under a different time scale than the sea level rise (Liang, 2010). This is also shown by Soci (2015) with Figure 7, where the adaptation rate of the riverbed is given under influence of sea level rise after simulation of 3 mm/y sea level rise over 25 years. From this figure can be observed that the aggradation rate is in order of mm/y and increases in time, but is not equal to the rate of sea level rise. The more upstream in the river, the less influence the sea level rise has on the bed aggradation. The increase of the aggradation rate over time is larger upstream than downstream. From Soci (2015) is also observed that the absolute riverbed adaptation after 25 years is in the order of cm and dependent on the location upstream of the sea.

The sea level rise effect of the North Sea on the downstream water level of the Rhine over the past and present years is known from Van den Hurk et al. (2014). From this source is known that the MSL of the North sea increased with 1.2 mm/y in the period 1951-1980 and with 2.0 mm/y in the period 1980-2010. Future expectations show that the rate of sea level rise can be between 1.0-10.5 mm/y for 2085, dependent on the climate scenario. It is expected that the rate increases over time. This means that the (slower) response of the riverbed also increases in time and space.

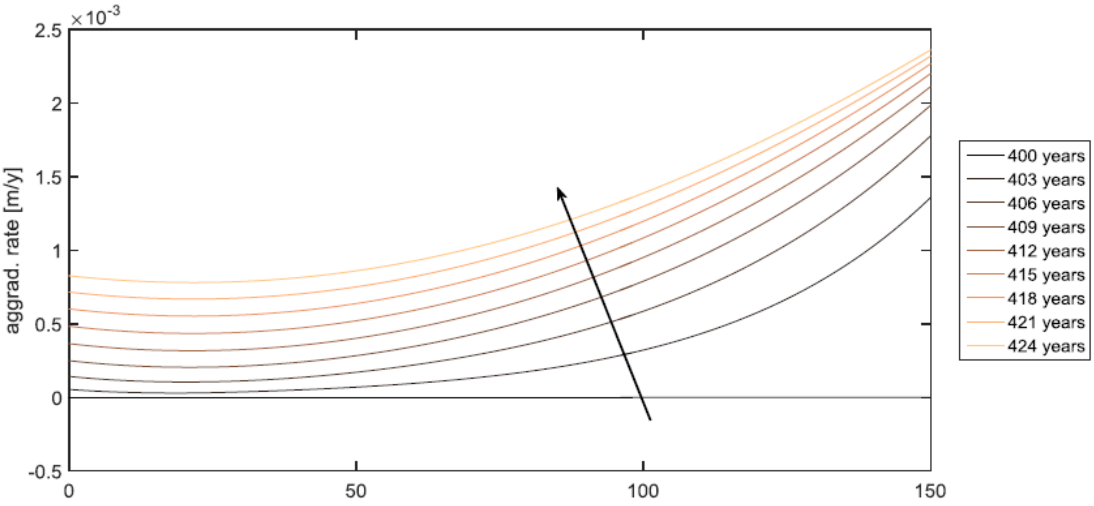

Figure 7 The riverbed aggradation rate under influence of sea level rise after 25 years of 3 mm/y sea level rise, at the x-as is 0 the upstream boundary of the applied model and 150 is located at sea (Soci, 2015)

3.2.3. Subsidence of the ground

The subsidence of the ground is divided into two developments: the tectonic movement and the consolidation of the soil. Both developments have consequences for the bed elevation relative to NAP and for the bed slope when development is unequal over the river system.

Tectonic movement is a slow natural development of plates of the Earth's crust. Tectonic movement is in vertical direction and the North Sea plate, on which the Netherlands is located, is moving downwards. This influences the level of the country, so also the riverbed level relative to the water level. Tectonic movement causes a bed degradation of approx. 3 cm per century, which is on average 0.3 mm/y (Cohen, 2003; Bolleboom et al., 2017).

Consolidation of the ground is the result of loading and human intervention, like drainage and land reclamation by poldering (Bolleboom et al., 2017). The largest developments occurs due to consolidation of clay and peat. Figure 8 shows the expected consolidation rate within 50 years, until 2050. The lower-reach of the Dutch Rhine consolidates faster (±20-40 cm in 50 years, e.g. 4-8 mm/y) than the upper-reach (±10 cm in 50 years, e.g. 2 mm/y). The Waal and Pannerdensch Kanaal are located in the upper-reach.

The ground under a river is expected to be unaffected by consolidation since the soil is saturated. Consolidation under the flood defences could change the flow profile of the river. Asselman et al. (2014) argues that the flood defences along the river are less affected by the consolidation than the surrounding area. This is based on the observation of gradually lowering of the area in the direction of the lower hinterland related to differences in consolidation rate. The consolidation is therefore assumed to be equal for the cross-sectional direction of the river, e.g. the main channel, floodplains and dikes, and does not induce a difference in flow profile.

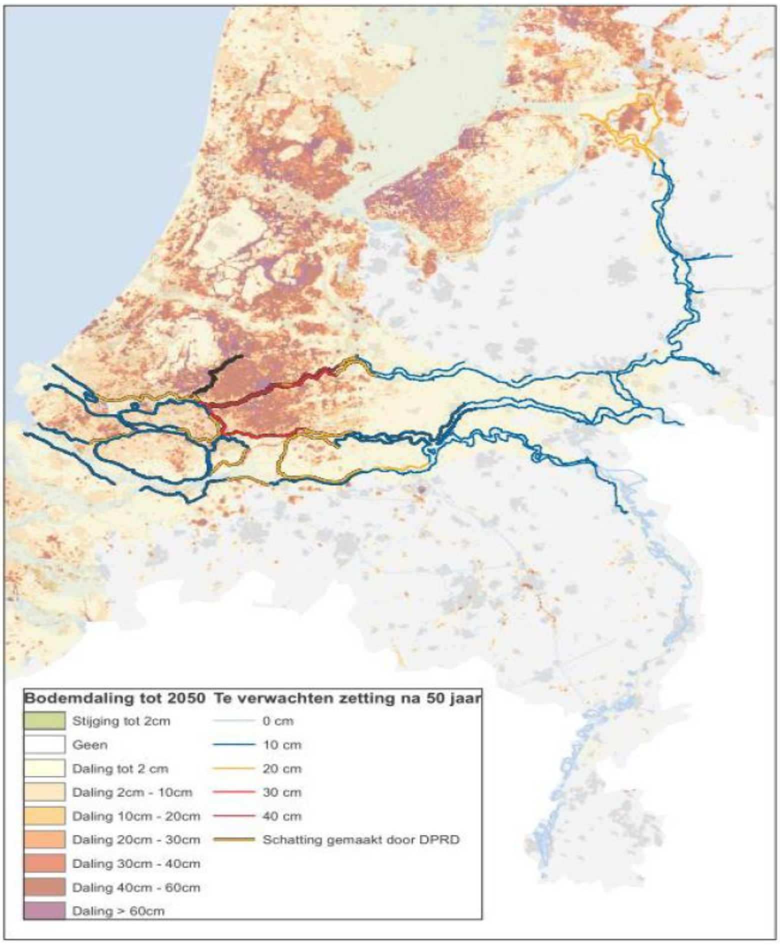

Figure 8 Expected consolidation rate of flood protection over a period of 50 years (Asselman et al., 2014)

3.2.4. Sediment supply

The sediment supply depends on the availability of sediment with variation in amount and composition, and on the sediment transport rate varying over time under natural variation of the water discharge. Sediment can be divided into silt, clay, sediment and gravel. Sand and gravel are morphologically most relevant (Frings et al., 2014).

The sediment supply in the river Rhine is uncertain due to uncertainty in or little to no measurements of sediment transport (Frings et al., 2014). However, there are reasons to assume that it has changed, such as the coarsening of bed material in the Rhine and the impact of human interventions on the sediment availability. The coarsening occurred due an combination of degradation of the bed into a coarser (Pleistocene) layer, nourishment of coarse sediment in the German Niederrhine and mainly transportation of fine sediment while coarse sediment remained (Frings et al., 2014; Blom, 2016). This final cause is accelerated by the increased sediment supply to compensate the increased sediment transport capacity induced by the normalisations. Human interventions like nourishment, distraction of sediment and trapping by dams are likely to have had a contribution to a lower sediment availability in the river. The influence of sediment supply is probably seen in the development of the riverbed characteristics.

A sediment balance for sediment and gravel in the Rhine is determined by Frings, et al. (2014) and shown in Figure 9. He argues that the source of sediment depends on bed degradation, supply from upstream, artificial supply by human for stabilization of the bed and bed-load supply. Sediment is transported in downstream direction or deposited outside of the main channel. Dredged sediment is discharged into the river again near the dredging site since 1990, but before this time it was extracted from the river. That affected the sediment supply downstream of the dredging site.

Variation in the sediment sources or sinks can encourage development of the riverbed characteristics. The variation on short time scale does not influence the equilibrium state, but on the long-term it can affect the average value of sediment supply (Blom et al., 2017). This influences the equilibrium between the riverbed and transport of water and sediment and induces adaptation of the riverbed characteristics to restore the equilibrium.

R.M. Frings et al. / Catena 122 (2014) 91–102

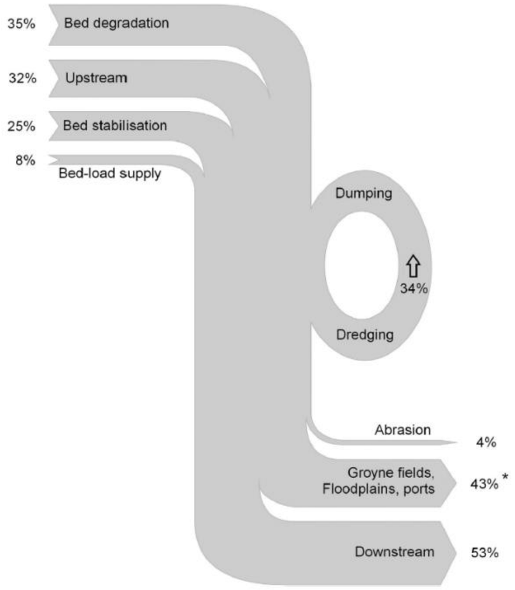

Fig. 11. Sediment budget for gravel and sand for the Rhine reach between km 640–865 (period 1991–2010). 100% = 1.26 Mt/a * estimated.

Figure 9 Sediment balance for sediment and gravel in the Rhine between kmr 640-865 for the period 1991-2010 with an estimated total transport of 1.26 Mt/y (Frings et al., 2014)

3.3. Bed characteristics of the main channel

The development of the controlling variables is related to the development of the riverbed characteristics, as seen in paragraph 2.2. The historic and present development of the riverbed characteristics in the main channel of the Rhine can be studied from data of riverbed measurement and previous analysis in literature. This is done for the riverbed characteristics bed elevation, bed slope, bed composition and bed roughness.

3.3.1. Bed elevation

The bed elevation of the main channel varies on short-term around the dynamic equilibrium for the variation in discharge by bed forms. Seasonal variation of the bed elevation influences the bed elevation level. From Sieben et al. (2012) it is known that this variation is around 0.2-0.4 m in the Waal and around 0.2-0.3 m in the Pannerdensch Kanaal. The (dynamic) equilibrium state of the riverbed elevation in the main channel can change on long-term by adaptation towards a new equilibrium, for instance due to an intervention that changes the flow conditions.

The development of the average bed elevation in the main channel of the Bovenrijn, Waal and Pannerdensch Kanaal is also analysed by processing the data of riverbed measurements for the period 1978-2015. This is visualized in respectively Figure 10, Figure 11 and Figure 12. Around 2000, a difference between data points is observed and indicated by different colours. This is induced by a change measurement technique in 1999.

The Bovenrijn is observed to be almost stable since 2000, but this might occurred earlier. Possibly since around 1990 in the upstream and since around 1995 in the downstream part of the Bovenrijn, but the difference in measurement technique gives some uncertainty to this observation. The branch average stabilization in the Bovenrijn is suggested by Blom (2016) to be associated with coarsening of the bed surface.

The development of the Waal and Pannerdensch Kanaal both show around 1980-1990 an acceleration in degradation. This is likely to be induced by the dredging activities around this time period. The observed stabilization in the Bovenrijn does not occur in the Waal and Pannerdensch Kanaal, except for the Lower-Waal (916-950 kmr); the bed elevation seems stable since 1990 (neglecting the bed elevation difference in 1999) and slightly increases between 2008-2010. However, this branch is not directly connected to the Bovenrijn. The stabilization possibly occurred by sedimentation, what could be the present benefit of discharging dredged material into the river again. It is uncertain whether this observed increase is a trend, a temporary development or stabilization is maintained. Analysis of smaller sections (Δ10 km) of the Lower-Waal showed that the stabilization and slightly increase of bed elevation occurred over the entire branch. Just upstream of the branch (<916 kmr, around Tiel), the bed elevation trend is degradation, as seen in the Upper- and Middle-Waal as well. The slightly increase of bed elevation at the Lower-Waal since 2010 is assumed to be a too small period to know whether the increased bed elevation is a trend or if stabilization continues. Also dredging might be applied to maintain stabilization, since an increase of bed elevation affects the water level under high and low discharge conditions, resp. flood safety and navigation.

From the figures can also be seen that the development rate of the bed elevation depends on the observation period. The development since 2000 is assumed to be the most recent and reliable development due to the different and more accurate riverbed measurement technique since 1999. The development rate in the Bovenrijn and the Waal is determined with a linear fit through the data since 2000 and in the Pannerdensch Kanaal since 2002. An overview of the determined degradation rates is given in Table 6. It was noticed from the development rates that the bed elevation in the Upper- and Lower Pannerdensch Kanaal developed almost with an equal rate since 2000. The decreasing degradation rate in the downstream direction of the Waal indicates a bed slope development towards a milder slope. The development rates in the Bovenrijn and Lower-Waal are small compared to the development rate in the Upper- and Lower-Waal and Pannerdendesch Kanaal.

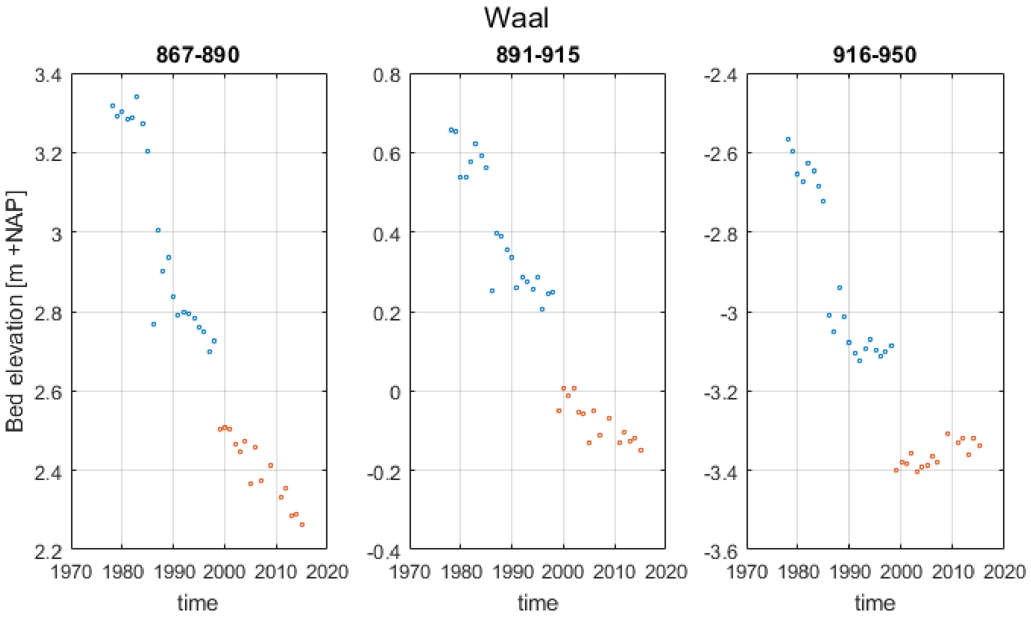

Figure 10 Average bed elevation of the main channel for the Upper- (867-890 kmr), Middle- (891-915 kmr) and Lower-Waal (916-950 kmr) over time, with a different measurement technique before (blue points) and since 1999 (orange points) (data from Rijkswaterstaat)

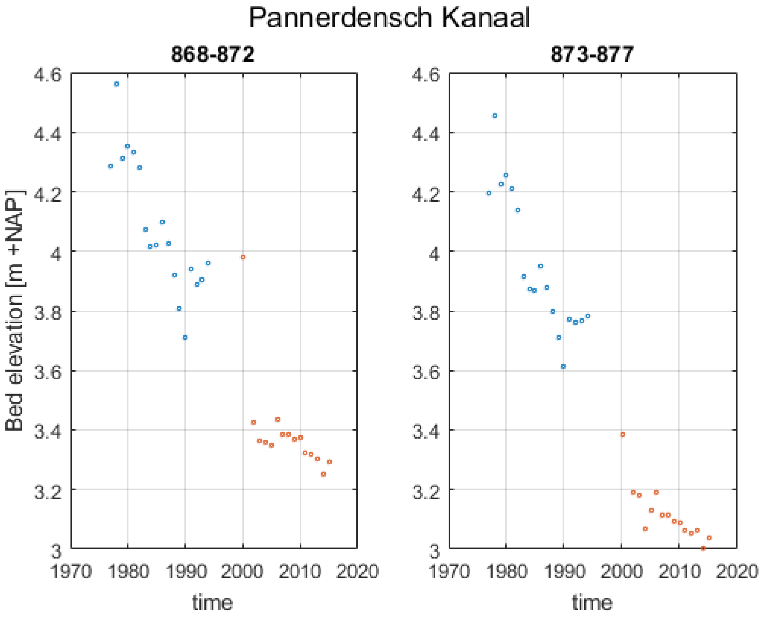

Figure 11 Average bed elevation of the main channel in the Upper- (868-872 kmr) and Lower-Pannerdensch Kanaal (873-877 kmr) over a time, with a different measurement technique before (blue points) and since 1999 (orange points) (data from Rijkswaterstaat)

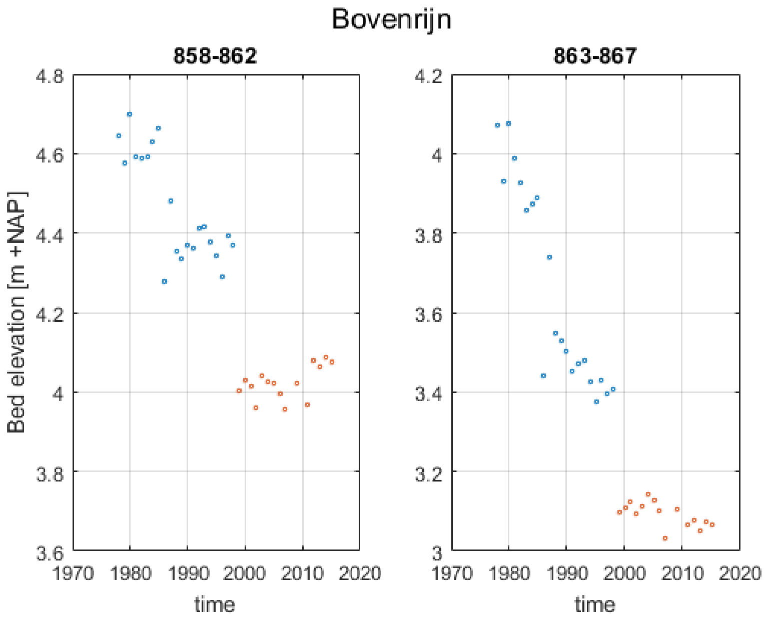

Figure 12 Average bed elevation of the main channel in the Upper- (858-862 kmr) and Lower-Bovenrijn (863-867 kmr) over a time, with a different measurement technique before (blue points) and since 1999 (orange points) (data from Rijkswaterstaat)

Table 6 Development rate of the branch average bed elevation in the main channel of the Bovenrijn, Waal and Pannerdensch Kanaal for the period 2000-2015, based on data analysis in this research

Branch	Development rate (2000-2015)
Upper-Waal (867-890)	~ –1.5 cm/y
Middle-Waal (891-915)	~ –0.9 cm/y
Lower-Waal (916-950)	~ +0.4 cm/y
Pannerdensch Kanaal (867-877)	~ –1.0 cm/y
Upper-Bovenrijn (858-862)	~ +0.4 cm/y
Lower-Bovenrijn (862-867)	~ –0.4 cm/y

A bed degradation of 1-4 cm/y in the main channel of the Dutch Rhine branches, varying per river branch and time period, is known from several literature (e.g., Sieben et al. (2012); Frings et al. (2013); Sieben (2016)). These values are branch averaged, it can vary locally between 1-6 cm/y. An overview of the branch averaged degradation rates from several literature is given in Table 7. The development rates found in literature are compared with the results of the data analysis in this research.

The development rates found in Sieben (2009) are higher for the Upper- and Lower-Waal, Bovenrijn and Pannerdensch Kanaal. This difference is induced by the difference in period of measurements used within the different analysis. Best comparable are the analysis of Sieben et al. (2012) for the period 2000-2007, Sieben (2015) for the period 2000-2012 and the data analysis of this research for the period 2000-2015, since these all use data since 2000.

Sieben et al. (2012) remarked a lowering trend of 0.1 cm/y in the Bovenrijn. From data analysis in this research, a trend of ±0.4 cm/y is observed. Sieben (2015) observed a trend of -1.0 cm/y in the lower reach of the Bovenrijn (865-867) and this research a trend of -0.4 cm/y over a somewhat larger reach (862-867). This indicates that trends can variate locally.

The development rate of the Upper-Waal is almost equal in all three analysis. The development rate of the Middle-Waal is observed to be larger in this study than in the other two. It increases with the increased time period for the different studies. The result of development rate in the Lower-Waal shows an equal rate of development of 0.4 cm/y in all three analysis. Sieben (2015) also observed larger aggradation. Although, in Figure 10 is also observed that the increasing trend observed in this research is likely to be induced by an increase of the bed elevation between 2008-2010. The aggradation rate could be induced by a temporary development instead of being a trend.

The observation in the Pannerdensch Kanaal varies between the different analysis. The analysis of Sieben et al. (2012) is larger. Perhaps due to inclusion of the measurement data in 2000, which is remarkably different (0.6 m) than measurement data in the successive years. The results of Sieben (2015) is remarkably small compared to the result from this research. He found although a standard deviation of 1.7 on this mean value. That is relatively large. This research applies to most recent data to derive the degradation rate and therefore it is assumed that the degradation rate of 1.0 cm/y is a sufficient estimate.

From Table 6 and Table 7 it is seen again that the development rate depends on the applied period of measurements. This data analysis in this research is executed for a period until 2015. This is the most recent analysis compared to the literature used in this research. Based on the comparison above it is assumed that the executed research is a sufficient data-analysis to the interpret the bed elevation development.

Table 7 Development rate of the branch average bed elevation in the main channel of the Bovenrijn, Waal and Pannerdensch Kanaal, based on literature analysis

Location	**Sieben, 2009**	**Sieben et al, 2012**			**Sieben, 2015**
Measurement period	**(1950-2000)** [cm/y]	**(1950-1973)/** **(1970-1999)/** **(2000-2007)** [cm/y]			**(2000-2012)** [cm/y]
Upper-Waal (868-886)	-3.0	-1.0	-3.0	-1.7	-1.5
Middle-Waal (887-915)	-1.0	-1.0	-1.0	-0.5	-0.7
Lower-Waal (916-951)	-2.6	+1.0	-2.0	+0.4	+0.4-1.0
Pannerdensch Kanaal (868-879)	-4.0	-2.0	-4.0	-1.5	-0.2
Bovenrijn (859-867)	-3.0	-3.0	-3.0	-0.1	
(865-867)					-1.0

3.3.2. Bed slope

Bed slope development is induced by changes of the dynamic equilibrium of the river. The adaptation of the bed slope is a very slow process and changes due to large-scale erosion/sedimentation or changes in the planform, sinuosity of the river, for instance due to human interventions (e.g., Buffington, 2012). The riverbed upstream of a reach can develop different from the riverbed downstream.

The bed slope development over the past is analysed with riverbed data from measurements in the main channel of the Waal, Pannerdensch Kanaal and Bovenrijn. The bed slope data is processed by a linear fit of the average elevation over a section of a branch per year. The bed elevation development of the main channel corresponding to the bed slope of the analysed branches can be found in Appendix II.

Figure 13 gives the average bed slope development of the main channel in the Waal over time. The bed slope shows a development towards a milder slope, with small fluctuations over time. This corresponds with Figure 14 from Blom (2016), where the bed elevation was analysed and the development of the slope towards a milder slope was observed as well, despite the different analysed time period. The observed bed slope development in the Waal towards a milder slope corresponds with the reduced degradation rate over time in the downstream direction of the Waal.

Figure 15 shows the average bed slope development of the main channel in the Pannerdensch Kanaal. It is unknown what causes the fluctuation around 2000, it might be a measurement error. A milder slope over time and more stabilization since around 2007 can be observed, but the fluctuations make this observation uncertain. The observed stabilization of the bed slope development in the Pannerdensch Kanaal corresponds with the almost equal degradation rate over time in the Upper- and Lower-reach of Pannerdensch Kanaal.

Figure 16 shows the average bed slope in the main channel of the Bovenrijn. A development of the bed slope towards a steeper bed slope is observed until 1990. After 1990 a trend is less clear, but stabilization could be observed until around 2010. From 2010 again a small development towards a steeper bed slope can be observed as well. The bed slope has become slightly steeper in the period 2000-2015 and this corresponds with the observed opposite development over time of bed elevation between the upper- and lower-reach of the Bovenrijn.

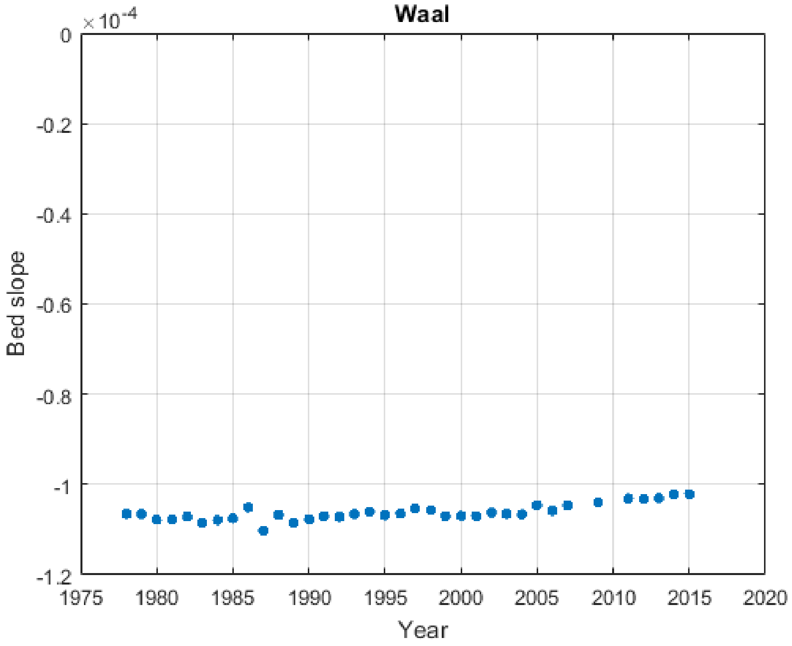

Figure 13 Development of the branch averaged bed slope of the Waal over time (867-950 kmr), for a linear fit of the yearly average bed elevation (data from Rijkswaterstaat)

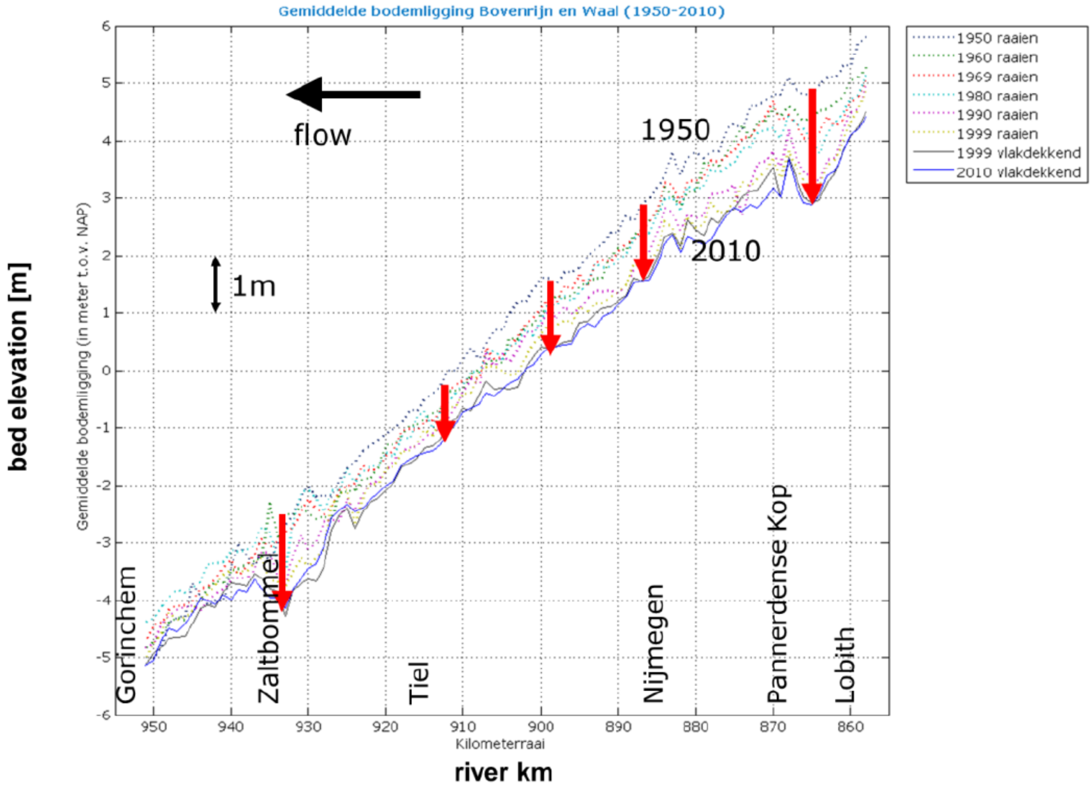

Figure 14 Mean bed level development of the Upper-Rhine and Waal (862-952 kmr) for the period 1950-2010 (Sieben et al., 2012)

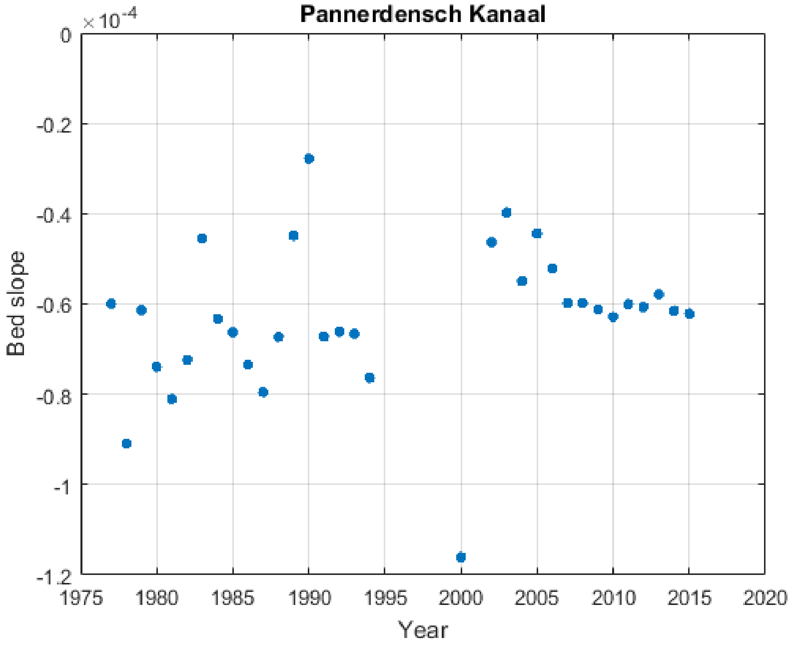

Figure 15 Development of the branch averaged bed slope of the Pannerdensch Kanaal over time (867-950 kmr), for a linear fit of the yearly average bed elevation (data from Rijkswaterstaat)

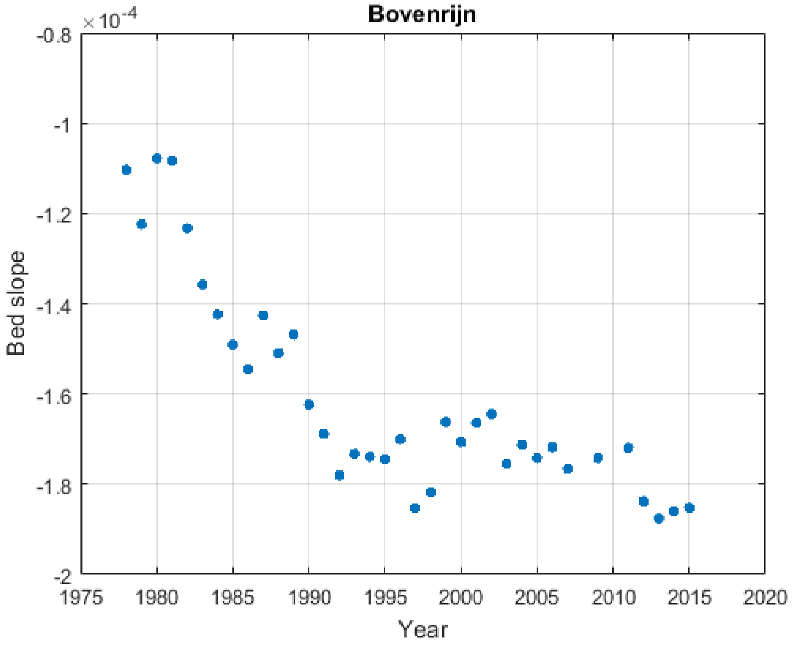

Figure 16 Development of the branch averaged bed slope of the Bovenrijn over time (867-950 kmr), for a linear fit of the yearly average bed elevation (data from Rijkswaterstaat)

3.3.3. Bed composition

The bed composition of the surface layer, in terms of the characteristic sediment grain size (D_{50}), is controlled by the amount and composition of the sediment supply. There is a difference between the surface and sub-surface layer, as shown in Figure 17. The riverbed surface is coarser than the subsurface. Frings & Kleinhans (2002) studied the measurements of 2000 of the sub-surface around the bifurcation and mentioned that below the surface layer at 90 cm depth, a sand layer is found with a median grain size of 0.7 mm. If the more coarse surface layer is eroded on long-term or transported under extreme discharge, the erosion rate is increased due to the increased transportation capacity of the finer and more mobile sediment.

Development of the bed composition at the surface layer in the main channel is related to the bed forms and bed roughness in the river. The development is analysed from literature and available data from measurements. Grab samples are taken in 1966, 1976, 1984, 1995 in the Waal and Pannerdensch Kanaal and in 2008 and 2016 around Pannerdense Kop. Deep coring's are performed in 2000 and 2002 around the bifurcations Pannerdense Kop and IJsselkop. The available data varies over time, space and type of measurement. There are indications that the measurement technique before 1984 differs from the other years and this makes data comparison uncertain (Frings & Kleinhans, 2002). The spatial resolution of the measurement campaign in 2008 and 2016 is higher than during earlier measurements (Emmanouil, 2017b).

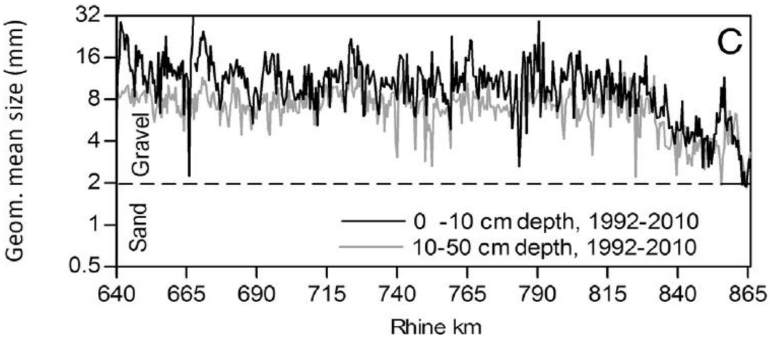

Figure 17 Grain size difference between surface (0-10 cm) and subsurface (10-50 cm) for the lower part of the German Rhine, between 640-865 km (Frings et al., 2014)

Figure 18 gives the development of the median grain size in the Waal for the period 1966-1995. It is difficult to observe a trend from these data, due to the large fluctuations over time and space. The median grain size is estimated to be around 0.7-2 mm. Figure 19 shows the development of the median grain size in Pannerdensch Kanaal for the period 1966-1995. Variation over the branch can be observed, but the variation is smaller upstream than downstream. Possibly there has been little to no development in the upstream part (868-875 kmr). The median grain size in the Pannerdensch Kanaal is estimated to be around 2-5 mm.

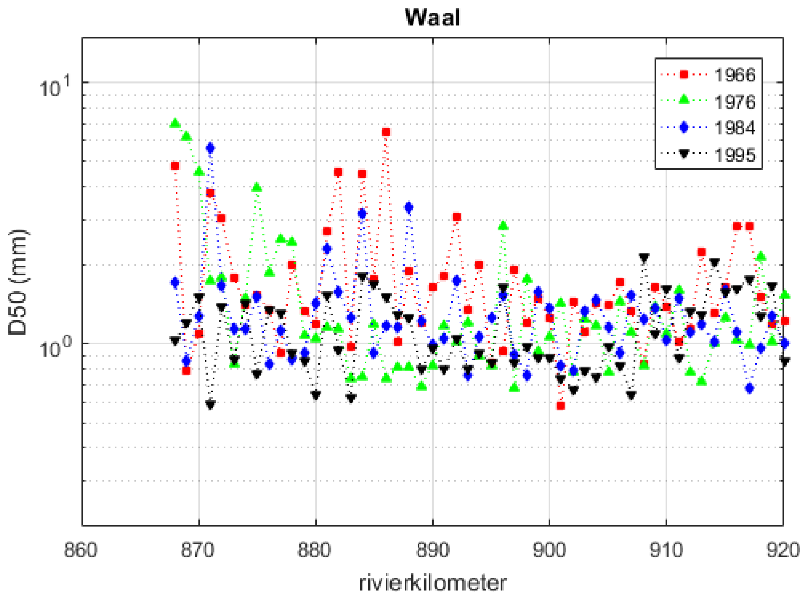

Figure 18 Data of grain size diameter for the Waal (867-920) for surface layer measurements of 1966, 1976, 1984 and 1995 (data from Rijkswaterstaat)

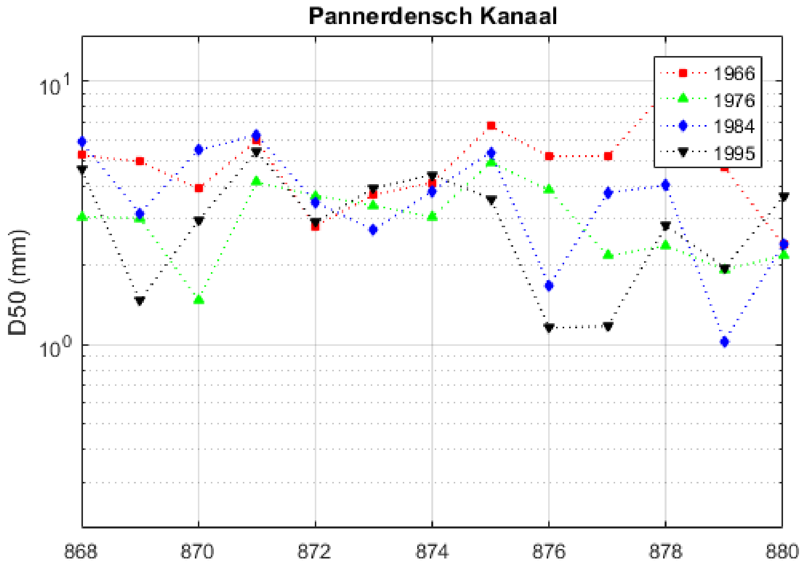

Figure 19 Data of grain size diameter for Pannerdense Kanaal (867-880) for top-layer measurements of 1966, 1976, 1984 and 1995 (data from Rijkswaterstaat)

Both the Waal and Pannerdensch Kanaal are located downstream of the bifurcation Pannerdense Kop. Development upstream of the bifurcation might occur downstream over time as well. The analysis of Frings, et. all. (2014) shows with Figure 20 that there is a gravel-sand transition (GST) in the Rhine upstream of Pannerdense Kop. Upstream of GST, the river consists of gravel and downstream in the Waal, it consists of sand. Figure 20 also gives the development of the median grain size for the period 1980-2010. Frings, et. al. (2014) argues with this figure that a coarsening of the riverbed is observed in the reach 740-865 kmr. The present median grain size in the Bovenrijn is estimated to be around 2-8 mm.

More recent analysis of the data from measurements in 1995, 2008 and 2016 is done by Emmanouil[3]. He observes a coarsening in the Bovenrijn as well (858-870 kmr) and in the upper part of the Upper-Waal (867-870 kmr) between 1995-2016. It is suggested by Emmanouil that the coarsening decreases linearly over the reach in the downstream direction for the data of 2016. At the most upstream part of the Bovenrijn (858-862 kmr), the median grain size was observed to be around 6-7 times coarser in 2016 than in 1995 and at the most downstream part (867-870 kmr), it was observed to be around 1.5-2 times coarser. For lower parts of the Waal it is unknown whether this coarsening occurred as well. The coarsening might expand downstream, but large grains move slowly through the system and the bifurcation often transports coarse material towards Pannerdensch Kanaal as the result of sediment sorting by bend flow, induced by a bend in front of the bifurcation (Frings, 2007), see also Figure 21.

Coarsening may have several reasons. Blom (2016) mentions several reasons. One reason is degradation of the riverbed into coarser fluvial deposits of the Pleistocene layer causing coarser sediment supply over time. Also coarse sediment nourishment in the German Rhine probably led to coarsening of the bed. Another cause might be that fine sediment was transported while coarse sediment remained. An advantage of a coarser bed is local stabilization of the riverbed, as analysed from the bed elevation development in the Bovenrijn (par. 3.3.1), but it also leads to less sediment mobility and erosion downstream (Sieben et al., 2011).

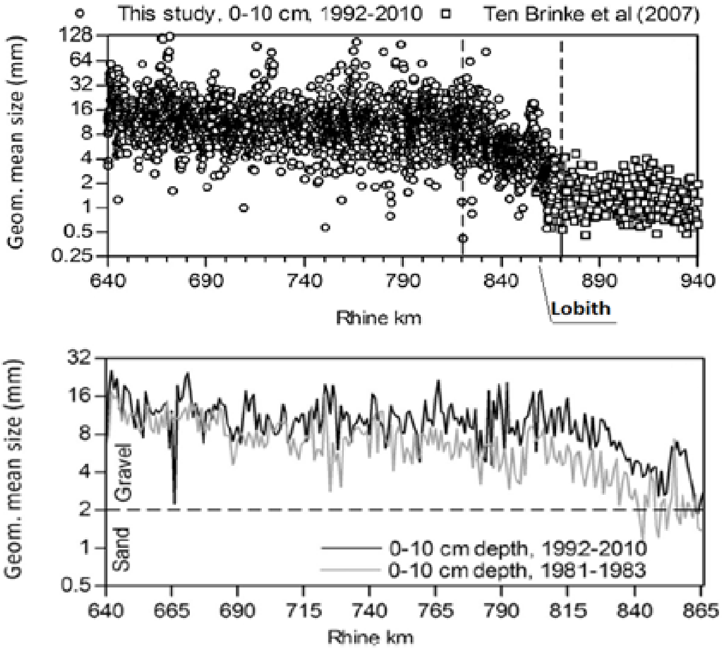

Figure 20 Spatial variation of grain size with the transition from gravel to sand reach between the dotted lines (upper graph) and grain size difference between the mean of grain size measurements taken between 1981-1983 and between 1992-2010 (lower graph) between 640-865 kmr (Frings et al., 2014)

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[3] Not published yet, information obtained by personal mail correspondence with A.Blom (April, 2018)

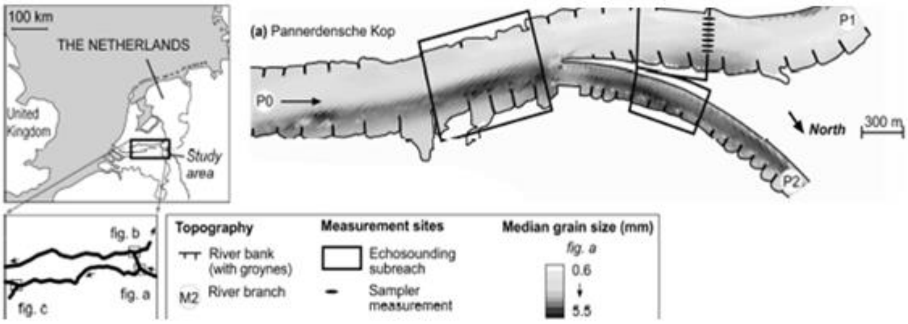

Figure 21 Bed composition of the bifurcation points Pannerdense Kop and IJsselkop with grain size information from measurements in 2000 and 2002 (Frings, 2007)

3.3.4. Bed roughness

The bed surface material is influencing the development of bed forms together with the shear stress induced by flow. Bed forms induce bed roughness, as explained in paragraph 2.2. Fine material has a higher mobility than coarse material under the same hydraulic conditions. Wilbers and Ten Brinke (2003) studied the relation between bed material and bed forms in the Dutch Rhine. It was found that dunes are always present in the Waal where the bed sediment is relatively fine (±0.7-2 mm), while upstream of Pannerdense Kop in the Bovenrijn the material is relatively coarse (±2-8 mm) and dunes were found to occur only under high discharge events. This also applies to the upstream reach of Pannerdensch Kanaal were relatively coarse and constant sediment is observed in time (±2-5 mm). Wilbers and Ten Brinke (2003) also observed that the dune length increases with the discharge in the coarse section during a flood and remained constant in the fine section. The dune height was observed to increase in all sections during a flood.

The different development in height and length affects the steepness of the dunes and influences the roughness. The relation between dune forms and bed roughness is uncertain and not well known. An empirical relation of Van Rijn (1993) between the dimensions of bed forms and roughness is given:

$$k_s'' = 1.1y\Delta(1 - \exp\left(-\frac{25\Delta}{\lambda}\right)) \qquad \text{3-1}$$

With k_s'' = bed form roughness, y = 0.7, Δ = dune height, λ = dune length. From this relation can be determined that bed roughness increases for an increasing dune height and also depends on the dune steepness (Δ/λ). The empirical character of the relation gives uncertainty to the result.

In paragraph 3.3.3 it has been observed that the bed composition has become coarser in the Bovenrijn and upper reach of the Upper-Waal. Coarsening of the bed surface leads to less mobility of the surface sediment and from the results of Wilbers and Ten Brinke (2003) it is observed that this leads to lower bed forms under low and moderate flow conditions and to longer and higher bed forms under high flow conditions. From the equation of Van Rijn (1993) can be determined that this possibly results in less roughness under low and moderate flow conditions and higher roughness under high flow conditions. However, this bed roughness development is derived in a slightly devious way. It is based on one study and without specific relation between the bed grains, bed forms and bed roughness. This makes the observations less sufficient.

In case of a plane bed, no dunes are present and roughness is dominated by the grain resistance (Van Rijn, 1982). A plane bed can occur under low force when no dunes are formed, and under extremely high force, i.e. Upper Stage Plane Bed (USPB), when dunes are flushed away. USPB is dependent on the Froude number and suspension number (Naqshband et al., 2014). Daggenvoorde (2016) studied the probability of Upper Stage Plane Bed (USPB) to occur in the Dutch Rhine for the present state of the riverbed characteristics. He found that the probability of USPB in the Dutch Rhine is very small and the most probable location would be in the IJssel near Kampen. However, when the bed sediment changes in the Dutch Rhine it affect the suspension number by a different fall velocity of the sediment. This results in a change of probability on USPB in the Dutch Rhine branches. Coarsening would decrease the probability of occurrence of USPB, like in the Bovenrijn and upstream of the Waal.

3.4. Conclusion

Based on the analysis in this chapter it is concluded if and how much influence the controlling variables have had on the bed characteristics and what the development of the bed characteristics itself has been in the past. An overview of the controlling parameters and their contribution to the riverbed characteristic development is given in Table 8. An overview of the development of the riverbed characteristics in the main channel of the Dutch Rhine is given in Table 9.

There are many types of interventions that have had an effect on the bed characteristics. Each intervention has (had) its own contribution to the development of the riverbed characteristics in the past, but it is unknown how much their contribution has been. Probably the normalisations and sediment supply changes in the 19th and 20th century have had the most significant influence and riverbed characteristics are still adapting to this.

Development of the controlling variables in the past is analysed for the upstream discharge, downstream water level, subsidence of the ground and sediment supply. From the analysis is concluded:

- The variable flow rate of the upstream discharge slightly increased over time in the past. An increase in flow rate induces a milder bed slope on large-scale. The increase was observed to be induced by an increasing standard deviation of the discharge over time. This indicates a change in statistical occurrence of the discharge and that is also of influence on the occurrence of hydraulic load on the flood defences.
- The contribution of the downstream water level to bed elevation development is small compared to the observed bed elevation development in the Pannerdensch Kanaal and Waal.
- Tectonic movement of the ground has a small contribution to the observed bed elevation change. The ground under a river is expected to be unaffected by consolidation as well since the soil is saturated. The consolidation rate is found to have less influence on the flood defence along the river than on the surrounding area. This indicates potential equal influence of the consolidation on the main channel, floodplains and dikes and negligible change in flow profile. Development of the subsidence of the ground is therefore concluded to have had no significant influence on the bed characteristics.
- The contribution of sediment supply is unknown, but the observed coarsening of bed material in the Rhine might indicate a change in sediment supply and a contribution to the bed characteristic development (Frings et al., 2014; Blom, 2016). It is also likely that the impact of human interventions in the river have had influence on the sediment supply in time.

Development in the past of the bed characteristics is analysed for the bed slope, bed elevation, bed composition and bed roughness. From the analysis is concluded:

- The bed elevation development rate in the Waal decreases in downstream direction. The present development in the Lower-Waal is different from the Upper- and Middle-Waal. Stabilization is observed since 1990 and an increase in bed elevation between 2008-2010. It is uncertain whether this observed increase is a trend, a temporary development or stabilization is maintained. Assumed is that the Lower-Waal remains stable at the present elevation level due to sediment extraction in this area. The bed elevation development is observed to be almost equal in the upper- and lower-reach of the Pannerdensch Kanaal and opposite for the upper- and lower-reach of the Bovenrijn.
- It is known from the observations that the bed slope develops and can be seen from the bed elevation development as well. The bed slope in the Waal is observed to develop towards a milder slope and that corresponds with the decrease in degradation rate of the branch-averaged bed elevation in downstream direction since 2000. The slope of the Pannerdensch Kanaal looks stable since 2007 and this corresponds with the observed equal degradation rate for both the up- and downstream reach of this branch. The bed slope in the Bovenrijn is

observed to have become steeper in time and that corresponds with the observed bed elevation development as well.

- Coarsening is observed in the Bovenrijn and possibly in the upstream part of the Upper-Waal as well (kmr 867-870). The downstream boundary of the measurement area is at 870 kmr and it is unknown whether lower parts of the Waal became coarser as well. The Pannerdensch Kanaal seems stable in the upstream reach.
- The bed roughness is determined from the relation with bed forms and development in bed composition. The uncertainty in the development of the bed composition reflects on the derived development of the bed roughness. The relation is derived in a slightly devious way. It is based on one study and without explicit relation between the bed grains, bed forms and bed roughness. This makes the observations less sufficient to conclude about the bed roughness development in the past and present and also to be able to determine potential future development.

Table 8 The contribution of the past and present development of the controlling variables to development of the riverbed characteristics

	Associated bed development	**Comments**	
Human interventions	Increased sediment transport capacity, milder bed slope	Normalisations and sediment changes in the 19th and 20th century	
Upstream discharge		(Small) Contribution to the development of the bed slope towards a milder slope	
Downstream water level	Aggradation rate in order of mm/y	For a sea level rise of in order of mm/y	
Subsidence of the ground	-0.3 mm/y	Tectonic movement	National average of the Netherlands
	-2.0 mm/y	Consolidation rate	In the upstream area, around the river
Sediment supply	-	Possibly less sediment availability in the river	

Table 9 Past and present development of the riverbed characteristics

	Development	Comments
Bed elevation	Present degradation rate of resp. ~–1.5 cm/y, ~-0.9 cm/y and ~+0.4 cm/y.	Upper- (867-890 kmr), Middle- (891-915 kmr) and Lower-Waal (916-950 kmr)
	Present degradation rate of ~–1.0 cm/y.	Pannerdensch Kanaal (867-878 kmr)
	Present degradation rate of resp. ~+0. 4 cm/y and ~–0.4 cm/y.	Upper- (858-862 kmr) and Lower-Bovenrijn (863-867 kmr)
Bed slope	A development towards a milder slope is observed.	Waal (867-950 kmr)
	A milder slope development is observed over time before 2007, but there are large fluctuations making this conclusion uncertain. The slope is observed to be more stable since around 2007.	Pannerdensch Kanaal (867-878 kmr)
	A development towards a steeper slope is observed, with small fluctuations over time.	Bovenrijn (858-867 kmr)
Bed composition	Coarsening is observed in the upstream reach of the Upper-Waal (kmr 867-870), but it is unknown whether lower parts of the Waal became coarser over time as well. The present median grain size is estimated to be around 0.7-2.0 mm.	Waal (867-950 kmr)
	Hardly any development is observed in the upstream reach between 1966-1995. The present median grain size is estimated to be around 2.0-5.0 mm.	Pannerdensch Kanaal (867-878 kmr)
	The median grain size in the Bovenrijn is observed to have become coarser over time. The present median grain size is estimated to be around 2.0-8.0 mm.	Bovenrijn (858-867 kmr)
Bed roughness	Coarsening possibly resulted in less roughness under low and moderate flow conditions and higher roughness under high flow conditions. However, the derivation was considered to be insufficient substantiated to draw this conclusion.	Waal (867-950 kmr) and Bovenrijn (858-867 kmr)
	The stable condition of the surface sediment in the upstream reach resulted in a constant bed roughness over time.	Pannerdensch Kanaal (867-878 kmr)

4. Potential future riverbed development

This chapter is about generation of scenarios for bed elevation development in the main channel in the Dutch Rhine over 50 and 100 years. Several methods to generate scenarios are reviewed and compared to each other in Appendix V. The analysis is based on information from conversations with several river engineering experts in the Netherlands, a literature and trend analysis towards the development of the bed characteristics and controlling variables that might occur or continue in the future. A summary of the results from conversations with experts is given in the first paragraph and the results of the analysis of literature and trends are given in the second paragraph. The final paragraph describes the procedure of scenario generation and gives the riverbed scenarios itself.

The analysed controlling variables are human interventions in the river and the upstream discharge. The downstream water level is not included, because it needs more investigation to the effect on the downstream boundary of the Lower-Waal and the time of this thesis was limited. The other controlling variables are concluded to have a small contribution compared to the development of the bed characteristics. The analysed bed characteristics are bed elevation and bed composition. The bed slope is related to the bed elevation and the bed roughness development was not substantiated enough to determine potential future development.

4.1. Summary of the information resulting from conversations with Dutch river experts

Conversations have taken place with several river experts in the Netherlands as part of the analysis. It is used to provide information and opinions on the development of riverbed characteristics and human interventions. This paragraph is a summary of the information gathered from the conversations, without quotes of the river experts, but with (partially) shared opinions. The most relevant information obtained from the conversations is given below in a summary. A more detailed summary of the conversations is given in Appendix III.

Short summary of the information from conversations with river experts

The present development of the riverbed characteristics was submitted to the experts. They mentioned that the limited sediment supply from upstream and the normalisations that changed the sediment transport capacity are the most important causes of bed erosion and coarsening developments in the river. The system is probably still adapting towards the normalization, but meanwhile, people are already changing the river again in response to the adaptations.

It was mentioned that if people do not intervene in the present development of the riverbed characteristics, it would probably continue until the natural equilibrium of the riverbed is achieved. Continuation of present development means a stabilizing bed elevation in the Bovenrijn and continuation of erosion in the Waal and Pannerdensch Kanaal. This erosion might even increase due to the coarsening upstream. If coarsening expands towards the Waal, the riverbed dynamics would become more like the Bovenrijn.

It was mentioned that it is important that the various involved parties, managing the various river functions, work together towards new solutions and not separately. Experts think that we will do something to stop bed erosion and mention that various programs are already focussing on this, e.g. IRM, DBR[4], but it is also mentioned that it possibly could take more than around 10 to 30 years until a solution is found, and only if we do want to find a solution. It is questionable to which price a solution like riverbed stabilization is wanted. Is it necessary to intervene in the river in advantage of the river functions or should people start to work together with the river rather than against it? However, until we find a decent solution, trends in bed elevation erosion are plausible to continue.

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[4] IRM – Integraal Riviermanagement, DBR – Duurzame Bodemligging Rijntakken.

The experts were asked what type of measures would be likely to occur in the future. Sediment management was often mentioned and is one of the present pilot projects in the river. Sediment management in the river is relatively new. Some experts mentioned that it is less sustainable in the river than at the coast, since periodic nourishment is required, but someone also mentioned that it might turn out to be the only thing we have to do for maintenance of and to control the present riverbed. It is expected to be the most effective when applied over the whole river or locally around a problem area. However, it does not remove the cause of the problems. It was also mentioned that it is important to find and understand the source of the problems when searching for a solution. It is probably the most effective if we find a solution to lower the sediment transport capacity instead of allowing natural adaptation of the river towards a milder gradient. It was opposed that it probably would be desirable to apply a combination of measures, like the sediment management together with a solution that lowers the sediment transport capacity.

A final aspect that was mentioned by the river experts was the problem of bed erosion and the armoured layers in the Waal. The armoured layers in the river become more of a problem over time, because those are non-erodible. Artificial lowering of the armoured layers would solve this problem, but it is only a short-term solution when bed erosion continues (until natural equilibrium is reached). It would also have negative effects, because the armoured layer currently induces a higher water level upstream and this is assumed to delay the erosion upstream and stop backward erosion from downstream.

4.2. Analysis of potential developments of the controlling variables in the Rhine

The development of the controlling variables in the future is analysed and determined for two controlling variables: human interventions and the upstream discharge. Other controlling variables have had a small contribution to the bed characteristics in the past or information was inadequate and a method to determine the contribution was not found yet, as concluded in paragraph 0. This paragraph is based on literature, the analysis to the past and present development that might continue in the future and information from the conversations with experts.

4.2.1. Interventions in the river

Recently and in the near future, people try to mitigate, slow down or stop the on-going negative developments in the river. It is uncertain what types of interventions will be applied in the future, because it particularly depends on the future riverbed development and its’ impact on the river functions, like changes in flood risk or influences on navigation.

Recent measures in the Rhine are measures of the program Room for the River (RftR). The RftR-measures are more or less finished. The contribution of these measures to bed aggradation on long-term is locally significant (Dankers, 2016), but this contribution possibly increases the dredging activity as well to maintain the navigation function of the river. This might slow down or cancel out the long-term effect on large-scale.

A few interventions in the Rhine that may have potential in the near future are expansion of the longitudinal dams, adjustment of groynes and sediment management. The longitudinal dams in the Waal are applied as a pilot study and might be expanded when the pilot study shows a positive effect on the bed characteristics (*according to expert information*). First findings indicate no significant contribution to the bed degradation trend in the main channel of the Rhine (Huthoff et al., 2015), but optimization around the dams like dimensions and height of the inlet and the width of the side-channel, might reduce the effect.

The adjustment of groynes in branches of the Rhine might be extended as well, but not when longitudinal dams are applied. Adjustment of groynes increases the flood conveyance and sediment transport capacity. This might lead to a less erosive situation, but on the long-term it probably does not lead to a reduction of the bed erosion trend (Kleinhans et al., 2013), since it does not remove the cause of the problems. Lowering of the groynes is planned in the Pannerdensch Kanaal (Rijkswaterstaat, 2018).

Sediment management in its present way, by local suppletion of sediment in the river is a periodic measure. It could contribute to the bed-load supply and bed stabilization in the main channel of the Rhine, but therefore continuity is required and probably expansion of the suppletion area towards more locations in the Dutch Rhine as well (*according to expert information*). The composition of the supplied sediment should be well considered when the goal is to limit or stop the bed degradation downstream of the nourishment area (Blom, 2016; Emmanouil, 2017b).

Extreme interventions are highly interesting for future development of riverbed characteristics when applied. An extreme intervention might be total stabilization of the riverbed. This intends to stop the ongoing bed erosion, but how to construct this intervention is unknown and it seems ecologically undesirable. It seems unlikely to happen in the near future. Besides stabilisation due to human intervention, it might also occur naturally by achievement of the dynamic equilibrium riverbed state.

4.2.2. Upstream discharge

Future climate change probably affects the weather conditions in terms of more rain and less snow precipitation in the winter due to heating of the earth. The result will be increased water discharge in winter and reduced melt water in spring. It is expected that the extreme discharges of the river, low and high, will become more extreme and occur more frequent (Van den Hurk et al., 2014). The consequence of more frequent extreme discharges is more frequent high water levels and load on the flood defences, and perhaps a change in mean annual sediment transport capacity, what affects the bed characteristics.

Four climate scenarios are determined by KNMI (KNMI'14 scenarios). These scenarios consist of various temperature developments (mean (G) or high (W)) and air circulation patterns (low (L) or high (H)). A conceptual overview of the four scenarios (GH, GL, WH, and WL) is given in Figure 22. A larger change in climate change has a smaller probability of occurrence, but the consequences are likely to be larger. Weiland, et al. (2015) translated the climate changes into potential future extreme discharges for specific return period for each scenario in 2050 and 2085, by using the GRADE-instrument[5]. The effect of the different climate scenarios on the discharge regime is shown in Figure 23. The mean annual discharge becomes slightly higher for most scenarios, but adaptation of the riverbed is a slow process.

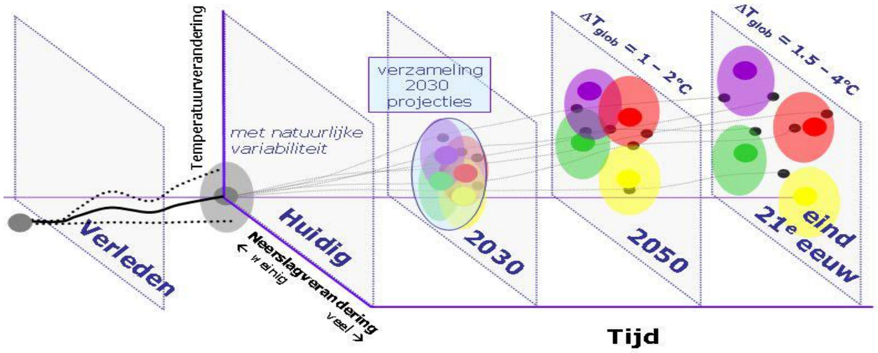

Figure 22 Conceptual overview of the construction of the KNMI'14 scenarios with the dots representing the scenarios: GH is yellow, GL is green, WH is red and WL is purple(Van den Hurk et al., 2014)

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[5] GRADE is a method to derive the extreme discharge changes in the future based on climate changes. It gives a statistical discharge based on the W+ scenario and is generated from measured data(Weiland et al., 2015).

A changing discharge regime affects the probability of occurrence of a discharge and therefor the hydraulic load on flood defences. The expected change of the discharge at Lobith for various climate scenarios is shown in Figure 24. Policy prescribes that the W+ scenario is the most plausible in the future and can be used for design and assessment of flood defences (Rijkswaterstaat, 2017b). Figure 24 shows that the reference discharge, i.e. present conditions for a return frequency of 1/1250 is around 16.000 m^3/s. In 2050 resp. 2085, this might be around 19.000 m^3/s resp. 22.000 m^3/s for the W+ scenario. This is without the correction for flooding upstream of Lobith. During extreme discharge events it might occur that the peak flow is reduced by floodings upstream of Lobith. Figure 25 shows that the expectation for this scenario results in a maximum discharge of around 17.500 m^3/s at Lobith. Policy prescribes to assume a (maximum) potential discharge of 18.000 m^3/s in future scenarios, which includes the correction for flooding upstream (Rijksoverheid, 2014).

The upstream discharge of the Waal and Pannerdensch Kanaal depends on the discharge distribution at the bifurcation Pannerdense Kop. The distribution of extreme discharges that never occurred before is based on models and extrapolation of high water measurements for the present layout of the river (ten Brinke, 2013). This distribution is uncertain, mostly due to uncertainty in morphodynamics and hydraulic roughness of the main channel and floodplains under these conditions. Ten Brinke (2013) analysed the uncertainty in discharge distribution for 16.000 m^3/s at Lobith and compared it with several studies (e.g. Paarlberg, et al., 2010). He concluded that the 90%-confidence interval of the uncertainty in discharge distribution at Pannerdense Kop for 16.000 m^3/s at Lobith is around 500 m^3/s (±250 m^3/s).

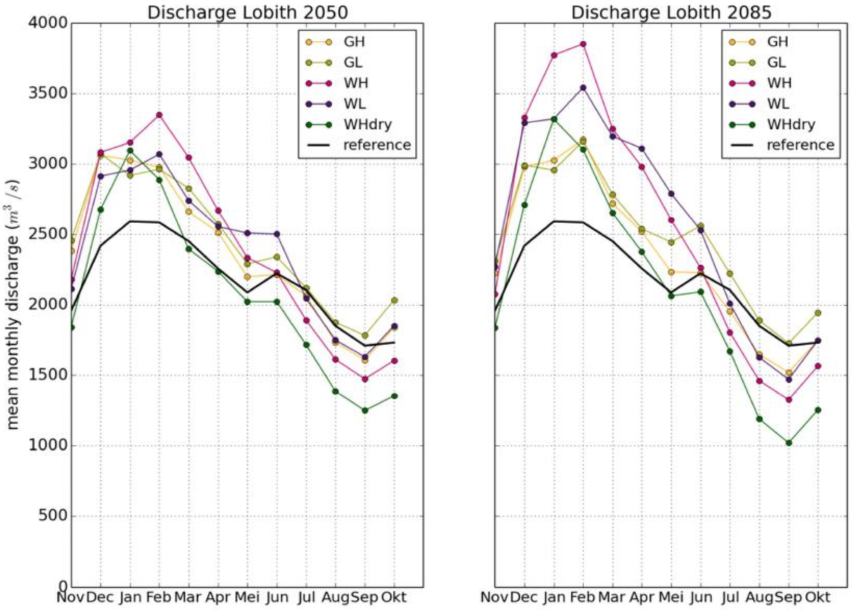

Figure 23 Average monthly discharge regime at Lobith for the recent climate situation and the four KNMI'14 scenarios, combined from the temperature development (mean(G)/high(W)) and change of air circulation pattern (low(L)/high(H)) (Weiland et al., 2015)

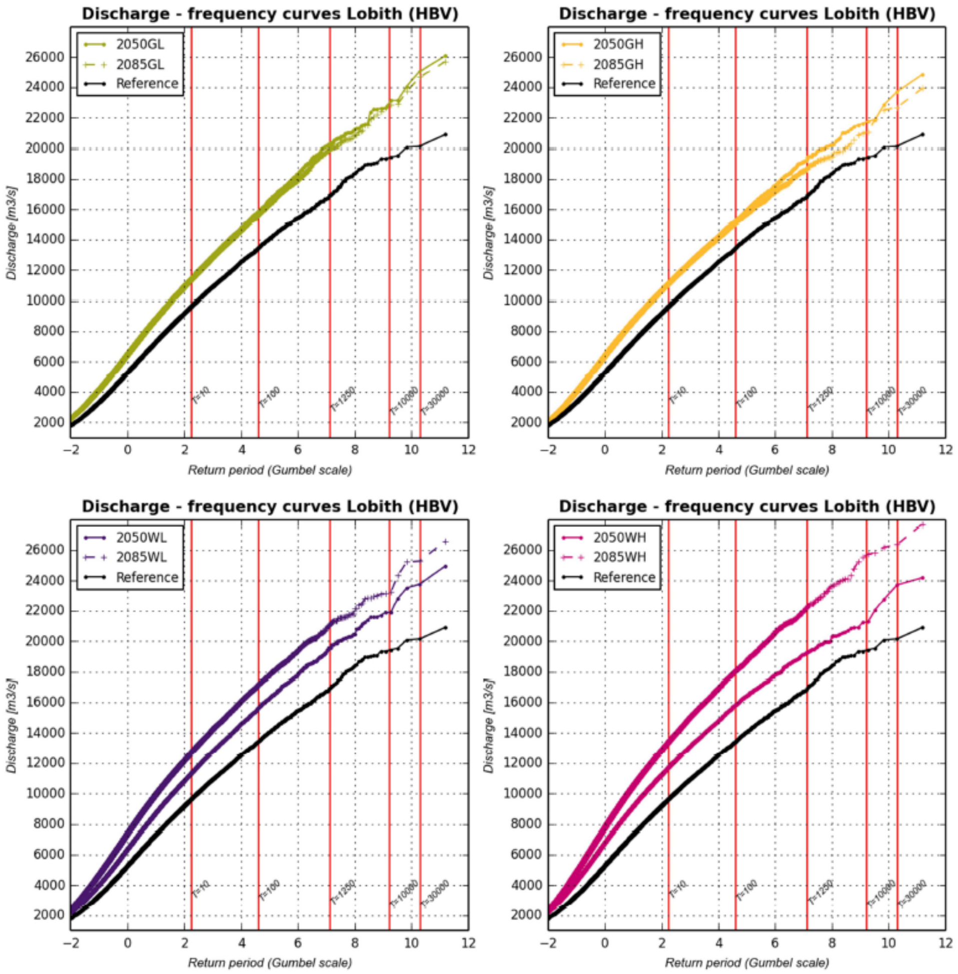

Figure 24 Frequency curve of the discharge in the Rhine at Lobith for different KNMI'14 scenarios and the years 2050 and 2085, around +35 resp. +70 years from now[6] (Weiland et al., 2015)

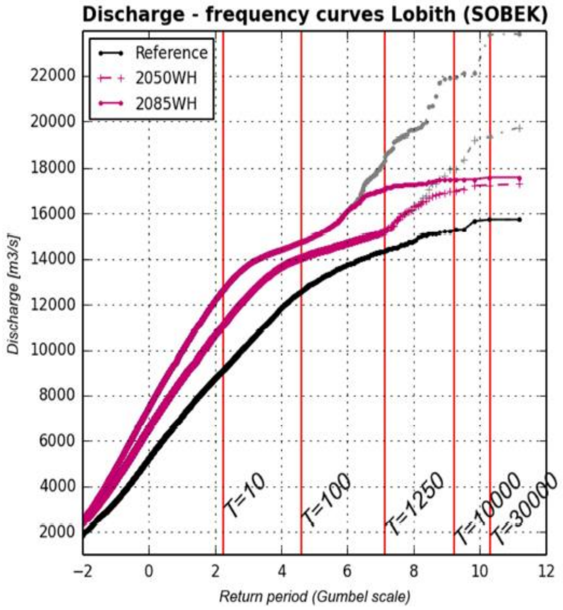

Figure 25 Frequency curve of the discharge in the Rhine at Lobith for the W+ scenarios and the years 2050 and 2085, with the effect of flooding upstream of Lobith (Weiland et al., 2015)

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[6] HBV (Hydrological rainfall-runoff models) is the name of the applied model in Weiland et al. (2015)

4.3. Analysis of potential developments of the riverbed characteristics in the Rhine

Potential development of the riverbed characteristics in the future is analysed for bed elevation and bed composition in the main channel of the river. This analysis is based on literature and the analyses of past and present development, which might continue in the future. The bed slope trend could be observed from the bed elevation trend as well, so the bed slope development is not treated separately in this chapter. For each bed characteristic development, it should be kept in mind that the results of this research are analysed on (relatively large sections of the) branch-scale. The development might vary locally.

4.3.1. Bed elevation

Trends in the bed elevation development in the main channel of the Waal and Pannerdensch Kanaal were observed in paragraph 3.3.1. The observed trends are probably mainly caused by large changes in the river inducing erosion of the bed. The trends might continue, increase, slow down or become constant in the future by new developments in the river system, human intervention or achievement of the natural equilibrium.

It is expected that the eroding trends in the main channel of the Waal and Pannerdensch Kanaal are not stopped in the near future (±10-30 years) (*according to expert information*), but perhaps a solution is found on long-term. Some human interventions might contribute to a (temporary) change in degradation rate. The contribution of the longitudinal dams and lowering of groynes was already mentioned to have little effect on the degradation rate on the long-term (par. 4.2.1). Sediment management affects the sediment supply and can be intended to increase the sediment load and decrease the erosion rate of the riverbed.

The degradation trend in the Bovenrijn in the past is likely to be reduced by the coarsening of the surface sediment. Blom (2016) mentions that coarsening leads to an increase in degradation downstream due to the reduced mobility of the sediment and therefore reduced sediment supply downstream of the coarse layer. This might result in continuous erosion or even an increased rate due to the lowered sediment supply. If the coarse material of the Bovenrijn is transported into the Waal, the degradation of the Waal might be reduced or stopped as well. It might also lead to an increase in erosion downstream. Sieben et al. (2012) remarked that continuous decrease in sediment supply can cause a degradation of 5 meter in the sandy riverbed in the Waal between Lobith and Tiel, when the sediment transport capacity remains unchanged. The bed upstream of Pannerdensch Kanaal is coarse as well and erosion probably occurs in the downstream reach of this branch.

Table 10 Potential future developments of the bed elevation in the Rhine around Pannerdense Kop

Development	Effect on the bed degradation trend	Location
Continuation of the bed erosion The trend continues (until natural equilibrium is reached)	(Provisional) Continuation	In both branches
Sediment management e.g. sediment nourishment	Decrease	On the location of nourishment
Coarsening of the riverbed Degradation into Pleistocene layer or nourishments	Decreases/Stops Increases	Locally at the coarsening Downstream of the coarsening

4.3.2. Bed composition

The bed composition in the Bovenrijn was observed to have become coarser in time, but no clear trend was observed in the Waal. There is literature that shows coarsening in the upper part of the Upper-Waal (until kmr 870) as well in the period 1995-2016 (Emmanouil[7]). It is uncertain whether this occurred downstream as well since kmr 870 is located at the downstream boundary of the measurement area.

A cause of coarsening in the river might be the nourishments upstream in the German Niederrhine as an intervention against erosion (Blom, 2016). The coarsening of the Bovenrijn might be the result of transportation of coarse sediment from upstream. If the Bovenrijn affects the Waal, it depends on the transportation rate, sediment load and sediment distribution at Pannerdense Kop if and how much coarser the median grain size in the upper reach of the Waal might become in the future. It is also possible that it might expand further downstream into the Waal in the future, but how much and how far is uncertain.

The upstream reach of Pannerdensch Kanaal was concluded to consists of a stable coarse surface sediment. This coarse layer might come in suspension under an extreme discharge event. A hypotheses of Sieben (2012) is that erosion of the armoured top-layer might lead to exposure of this fine sediment. If the coarse surface layer (2.0-5.0 mm) is transported under extreme discharge, this exposes the subsurface layer of finer sediment material below (±0.7 mm). The larger mobility of fine sediment leads to a local increase of erosion and to erosion pit. This can also occur with the coarse layer in the Bovenrijn. High water events are likely to occur more frequently in the future due to climate change and therefore the probability of fine material exposure becomes higher.

Table 11 Potential future developments of the bed elevation in the Rhine around Pannerdense Kop

Development	Location
Sediment management	Downstream of the nourishment site
Continuation of coarsening of the riverbed Transportation of coarse sediment from upstream	Upper-reach Boven-Waal and Bovenrijn
Expansion of coarsening in the downstream direction Transportation of coarse sediment	Waal/Pannerdensch Kanaal, dependent on the sediment distribution
Exposure of fine sediment Under extreme discharge events	Bovenrijn and Upper-reach Pannerdensch Kanaal

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[7] Not published yet, information obtained by personal mail correspondence with A.Blom (April, 2018)

4.4. Scenarios of the riverbed in the upper part of the Dutch Rhine over 50 and 100 years

Potential riverbed scenarios are generated in this paragraph based on the analysis of potential development of the controlling variables and riverbed characteristics. First, the procedure of scenario generation is described and subsequently, the analytical bed elevation scenarios of the main channel in the river Rhine over 50 and 100 years are generated. Finally, the scenarios applied in a numerical simulation model to determine the effect of the scenarios on the water level are specified as well.

4.4.1. Procedure

Duinker and Greig (2006) developed some useful guidelines for scenario development. These guidelines are used to generate the riverbed scenarios after long-term development:

- Describe and label the scenarios clearly by following the situation under which it occurs.
- Consistency between the scenarios is required to be able to compare the scenarios, but significant difference as well.
- Scenarios should be possible and probable, not impossible.
- Between 2 and 5 scenarios is considered to be appropriate.

The scenarios are generated with information from and decisions made in the previous chapters and paragraphs. It is decided to generate only bed elevation scenarios, because it is not possible to change the bed composition in the used model. The scenarios are developed for the downstream branches of the bifurcation Pannerdense Kop; the Waal and Pannerdensch Kanaal. Some variation to the bed elevation scenarios is applied for the approach of the armoured layers in the Waal and variation on the boundary conditions.

The analytical riverbed elevation scenarios consist of a description of the establishment of a scenario, for instance due to human intervention or continuous development of the riverbed characteristic. The scenarios are given for two periods of development; 50 and 100 years from now. This would be roughly around the year 2070 resp. 2120.

4.4.2. Analytical riverbed elevation scenarios of the main channel in the river

The scenarios of the main channel in the Waal and Pannerdensch Kanaal over 50 and 100 years, are given below and based on large-scale degradation. The bed elevation of the Lower-Waal is assumed to remain stable, because of the uncertain present development and possibly dredging of sedimentation. An overview of the scenarios is given in Table 12.

Reference scenario – present situation (**S0**)

The bed elevation scenarios are compared with the reference scenario. This is the present available bed in the base model. The available bed conditions are different for the main channel and flood plains. The main channel riverbed available in the models is the riverbed of the Rhine in 2013 (Berends, 2014) and the conditions of the floodplains are dependent on measurement in 2017.

Bed elevation scenario 1– Continuous bed elevation development (**S1**)

In the most extreme case there is no solution established for the eroding trend of the bed elevation and no natural equilibrium is reached in the previous 50 to 100 years. The bed elevation remains lowering with the present speed. This is 1.5 cm/y in the Upper-Waal (867-890 kmr), 0.9 cm/y in the Middle-Waal (891-915 kmr) and 1.0 cm/y in Pannerdensch Kanaal.

This development leads to the following scenarios of bed elevation in the previous 50 to 100 years:

> *Continuous bed elevation* development *– 50y: lowering of 75 cm in the Upper-Waal, 45 cm in the Middle-Waal and 50 cm in Pannerdensch Kanaal.*

> *Continuous bed elevation* development *– 100y: lowering of 150 cm in the Upper-Waal, 90 cm in the Middle-Waal and 100 cm in Pannerdensch Kanaal.*

Bed elevation scenario 2 – Solution bed elevation development (**S2**)

From analysis and experts information is concluded that it is possible that a solution will be found for the bed degradation in the future and that the bed elevation becomes stable for instance due to sediment management, large-scale human intervention or a natural equilibrium is reached. Until that time, the riverbed remains eroding with the current speed. Several time periods before finding a solution are assumed. Two solution periods are applied:

A solution is found after 25 years:

> *Solution bed elevation – 50y: lowering of 37.5 cm in the Upper-Waal, 22.5 cm in the Middle-Waal and 25 cm in Pannerdensch Kanaal.*

A solution is found after 75 years:

> *Solution bed elevation – 100y: lowering of 112.5 cm in the Waal, 67.5 cm in the Middle-Waal and 75 cm in Pannerdensch Kanaal.*

Bed elevation scenario 3 – Increase bed erosion due to coarsening of bed material (**S3**)

Coarsening of the Bovenrijn and perhaps the upstream part of the Waal might lead to a decrease in sediment supply and an increased erosion rate downstream of the coarsening. The coarsening is assumed to have no influence on the bed elevation trend in the Pannerdensch Kanaal, because this is already coarse in the upstream reach. The eroding trend is assumed to be increased from 1.5 cm/y to 2 cm/y for the Upper-Waal and from 0.9 cm/y to 1.5 cm/y for the Middle-Waal.

This development leads to the following scenarios of bed elevation in the previous 50 to 100 years:

> *Bed elevation* development *below coarsening – 50y: lowering of 100 cm in the Upper-Waal and 75 cm in the Middle-Waal.*

> *Bed elevation* development *below coarsening – 100y: lowering of 200 cm in the Upper-Waal and 150 cm in the Middle-Waal.*

Table 12 Quantitative scenarios for bed elevation development in the next 50 and 100 years

	Time period [year]	$\Delta z_{\text{Upper-Waal}}$ [cm]	$\Delta z_{\text{Middle-Waal}}$ [cm]	$\Delta z_{\text{Pannerdensch Kanaal}}$ [cm]
Reference scenario (S0)		0	0	0
Continuous bed elevation development (S1)	50	-75	-45	-50
	100	-150	-90	-100
Solution bed elevation development (S2)	50	-37.5	-22.5	-25
	100	-112.5	-67.5	-75
Bed elevation development below coarsening (S3)	50	-100	-75	-
	100	-200	-150	-

4.4.3. Riverbed elevation scenarios for modelling

The scenarios for modelling follow from the analytical scenarios for long-term riverbed development in paragraph 0. Only the scenarios for the Waal will be modelled, due to uncertainty by roughness sections around the bifurcation in the Rhine-branch-model for SOBEK-3 (see also paragraph 5.1 and Appendix VI), and only for 50 years of development, due to the available time for this research. The reference scenario (S0) is the riverbed as applied in the base model. Figure 26 gives the bed elevation of this scenario over the branch.

The bed elevation scenarios are divided into the amount of bed elevation change at the upstream boundary of the Waal. These scenarios are modelled by lowering the bed elevation over a gradient with a maximum value at the upstream boundary and zero in the Lower-Waal (916-950 kmr), because the Lower-Waal is assumed to remain stable in the analytical scenarios for future riverbed development due to a combination of sedimentation and dredging. Table 13 gives an overview of the bed elevation scenarios that are modelled and the corresponding labels used for indication in the results. Three scenarios of lowering are applied: 0.750, 0.375 and 1.000 m at the upstream boundary.

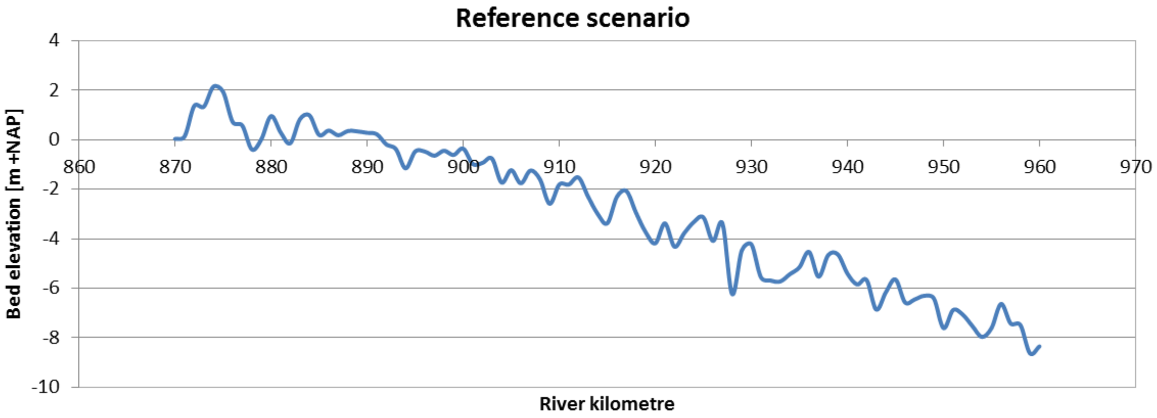

Figure 26 Schematization of the bed elevation of the reference scenario between 870-960 kmr, based on the riverbed from the base model

Table 13 Bed elevation scenarios for modelling varying in amount of erosion at the upstream boundary and with associated labels

$\Delta z_{Upper\text{-}Waal}$	Label
ref	S0
-0.750 m	S1
-1.000 m	S2
-0.375 m	S3

Variation in the bed elevation scenarios

From the conservation with experts is known that it might be possible that the armoured layers are artificially lowered in the future. The bed elevation scenarios are modelled with variation on the application of the armoured layers in the Waal. Two variations are applied to the scenarios:

I) Without lowering of the bed at the location of the armoured layers. The armoured layers in the Waal are considered to be non-erodible and assumed to remain on the present bed level for the scenario without lowering. This is shown in Figure 27.

II) With lowering of the bed at the location of the armoured layer. The lowering of the armoured layer is applied as part of the applied lowering of the bed elevation over a gradient. A schematization of the bed for these scenarios is given in Figure 28.

Only variation at the location of the armoured layer at Nijmegen (883.1-885.1 kmr) is applied to the scenarios, because the armoured layer at St. Andries is located in the Lower-Waal (925.0-928.2 kmr) and therefore assumed remain unaffected for these the bed elevation scenarios. The associated labels of the bed elevation scenarios with the variation in application of the armoured layers are given in Table 14. more information is given below. Figure 29 gives a schematization of the applied riverbed adaptation over the entire Waal branch in the model.

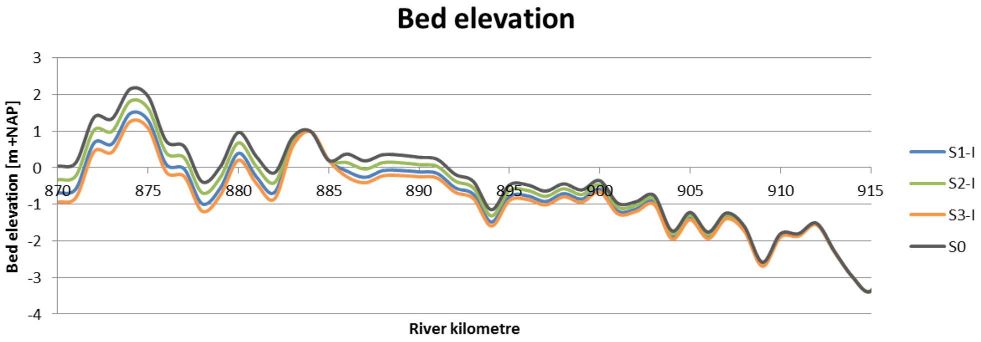

Figure 27 Schematization of the bed elevation scenarios between 870-915 kmr for variation without lowering of the armoured layer at Nijmegen (883.1-885.1 kmr)

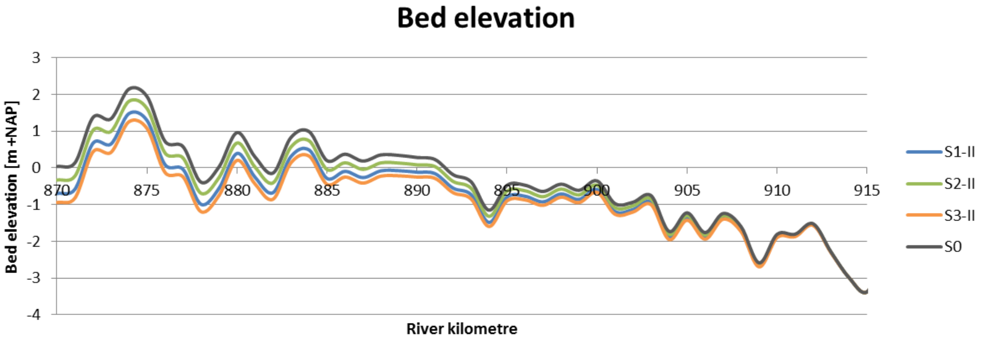

Figure 28 Schematization of the bed elevation scenarios between 870-915 kmr for variation with lowering of the armoured layer at Nijmegen (883.1-885.1 kmr)

Table 14 Variation in bed elevation scenarios in lowering of the armoured layer in the Waal at Nijmegen

Without armoured layer lowering	With armoured layer lowering
S0	
S1-I	S1-II
S2-I	S2-II
S3-I	S3-II

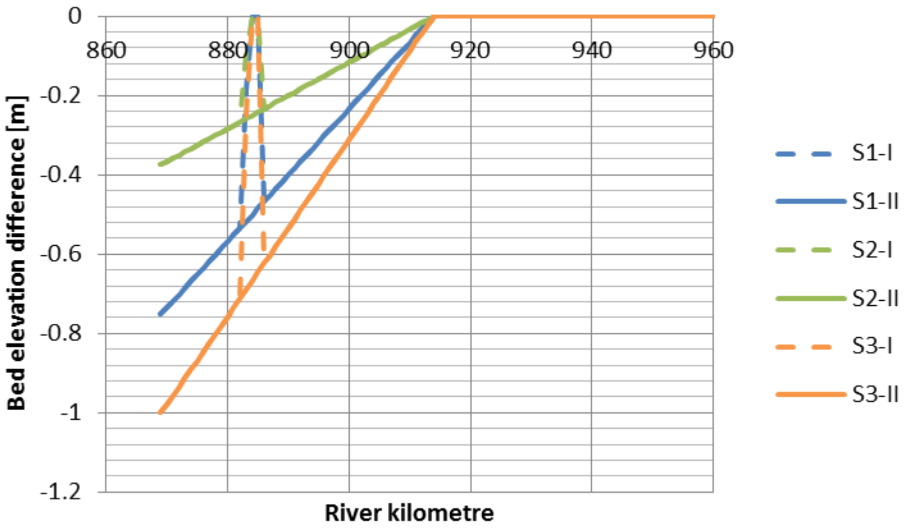

Figure 29 Bed elevation difference per bed elevation scenario with and without lowering of the armoured layer at Nijmegen compared to the reference scenario

Variation in the upstream boundary

A variation in the upstream discharge is applied as well. From the analyses to potential future development of the controlling variables is known that the discharge distribution at Pannerdense Kop has an uncertainty of 500 m^3/s (±250 m^3/s) in terms of a 90%-confidence interval for the extreme discharge of 16.000 m^3/s at Lobith. This uncertainty is applied to study the effect of the bed elevations on this uncertainty. The variation of the upstream discharge is only applied to bed elevation scenario with lowering of the armoured layer at Nijmegen, to separate the influence of the armoured layer from the influence of the uncertainty in discharge distribution. The associated labels of the bed elevation scenarios with the variation in the upstream boundary conditions are given in Table 14.

Table 15 Variation in bed elevation scenarios with lowering of the armoured layer for the upstream discharge (±250 m^3/s) for the extreme discharge of 16.000 m^3/s at Lobith, which is 10.173 m^3/s at the Waal

Variation in discharge
S0-a
S1-IIa
S2-IIa
S3-IIa

5. Modelling the effect of long-term riverbed scenarios

This chapter gives the details of simulation of the impact of the riverbed scenarios of long-term riverbed development in the main channel on the water level in the river Waal. The results of the simulation are used to determine the effect of the bed elevation scenarios on the water level. The details of the model set-up are given in the first paragraph. In the second paragraph the model results are given and analysed.

5.1. Model choice and set-up

The purpose of numerical modelling in this research is to model the effect of the bed elevation scenarios in main channel on the water level and to indicate the differences between the scenarios. The 1D-model SOBEK-3 with the version ‘rijn-j17_5-v1’ for the Rhine-branch-model is used to model of the hydraulic effect. A 1D-model allows simple and fast adaptation of the main channel riverbed in a schematization and has less computation time than a 2D- or (quasi-)3D-model. The government uses the hydraulic 2D-model WAQUA for flood safety assessments. Ideally, the WAQUA model would be used as well for hydraulic studies like this one, but adaptation of the riverbed is more complicated within a 2D-model, the calculation time is larger and a 1D-model is sufficient for the purpose of this research. If this study reveals that the effect is relevant, more research can be done with a 2D-numerical model (WAQUA), but that is outside the scope of this thesis.

Only the schematization of the Waal is used for simulation, because of large uncertainty in the settings of the model for discharge distribution. The model is calibrated on the discharge distribution with artificial roughness sections (see Appendix VI) and this gives uncertainty to the results when the riverbed is changed to implement the scenarios. By modelling only the Waal branch is modelled to exclude this uncertainty. Appendix VI gives more information about the calibration of the model.

The schematization of the Waal in the numerical model is part of and modified from the Dutch Rijn schematization, version ‘rijn-j17_5-v1’. The applied schematization of the Waal is shown in Figure 30. The base model consists of 5 calculation sections divided by LMW-station locations. The upstream boundary is located at river kilometre 869.06, just below the roughness section at Pannerdense Kop (867 kmr), and the downstream boundary is located at river kilometre 961, around Hardinxveld. The upstream boundary is given as a stationary discharge dependent on the discharge distribution of the base model. The distribution is based on measurements in the Dutch Rhine and extrapolation for extreme discharges, so independent of the added roughness sections. The discharge at Lobith starts at 4.000 m^3/s, because the higher discharges induce flooding of the floodplains, resulting on hydraulic load on the levees and that is of interest. Table 16 gives the upstream boundary at the Waal as a function of the discharge at Lobith. The downstream boundary is a water level at Hardinxveld based on the Qh-relation determined from measurements (Berends, 2014; Van der Wijk, 2016). This is given in Table 16 as well for the base scenarios.

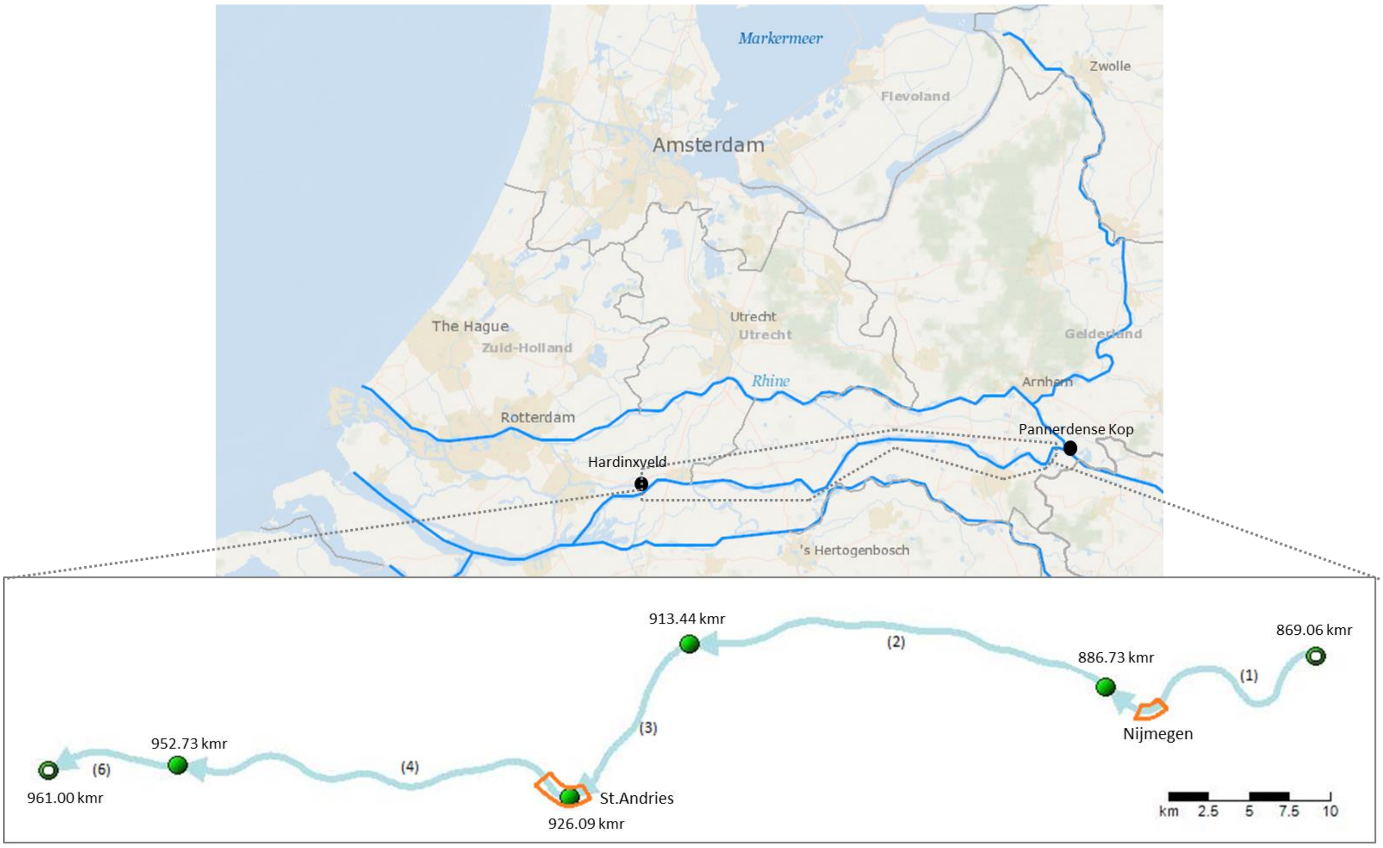

Figure 30 Schematization of the Waal, divided into 5 calculation sections in the base model, with marked armoured layers (orange) and an indication of various river kilometres

Table 16 Upstream boundary of the Waal as function of the discharge at Lobith, and downstream boundary at Hardinxveld based on the Qh-relation for the discharge at Lobith (data from Van der Wijk (2016))

Discharge Lobith $[m^3/s]$	Discharge Waal $[m^3/s]$	Water level Hardinxveld [m]
4.000	2.759	1.345
6.000	4.086	1.876
8.000	5.413	2.389
10.000	6.486	2.696
13.000	7.722	3.085
16.000	10.173	3.761
18.000	11.924	4.172

5.2. Model results and analysis of the results

5.2.1. Reference scenario

The reference scenario of the bed elevation in the Waal results in various Qh-relations for various locations and this is shown in Figure 31. The schematization of the Waal in Figure 30 can be used for indication of the locations. The locations are upstream of the branch (872 kmr), just above and below the armoured layer at Nijmegen (resp. 883, 886 kmr) and one more downstream (904 kmr).

The variation between the locations in the Qh-relation is related to variation in the cross-sectional profiles, e.g. variation in the level and pattern of the exchange between the main channel and floodplains. An example is given in Figure 32. The water level for the various discharge levels is drawn to indicate the flow area. More graphs of the cross-sectional profiles in the model can be found in Appendix VII. The floodplains are flooded when the water level is higher than the summer dike level. The floodplain at 883 kmr is flooded for a lower discharge than at kmr 872. This corresponds with the variation in Qh-relation between these locations. The Qh-relation for location 883 kmr shows a temporary milder increase in water level above 4.086 m^3/s and that corresponds with flooding of the floodplains. The small variation in increase above 6.486 m^3/s is related to the small widening of the flow area. The (small) variation above 4.086 m^3/s at location 872 kmr is related to the increase in the flow area. The floodplains are flooded for a discharge larger than 6.486 m^3/s.

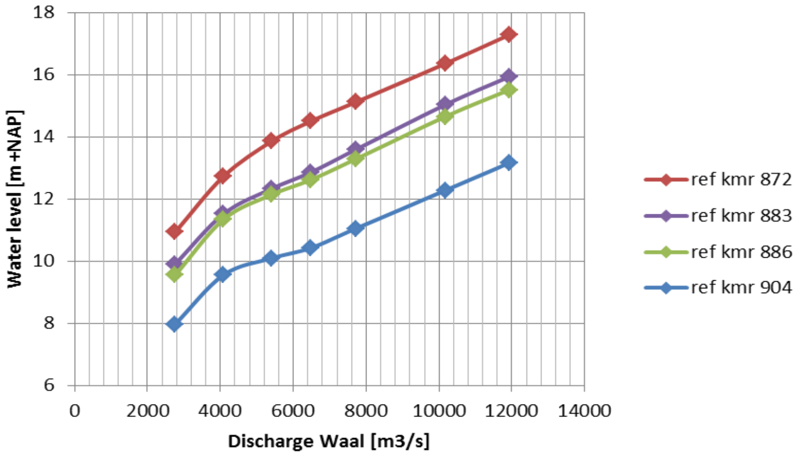

Figure 31 Qh-relation of the reference scenarios for the locations 872, 883, 886 and 904 kmr of the Waal branch

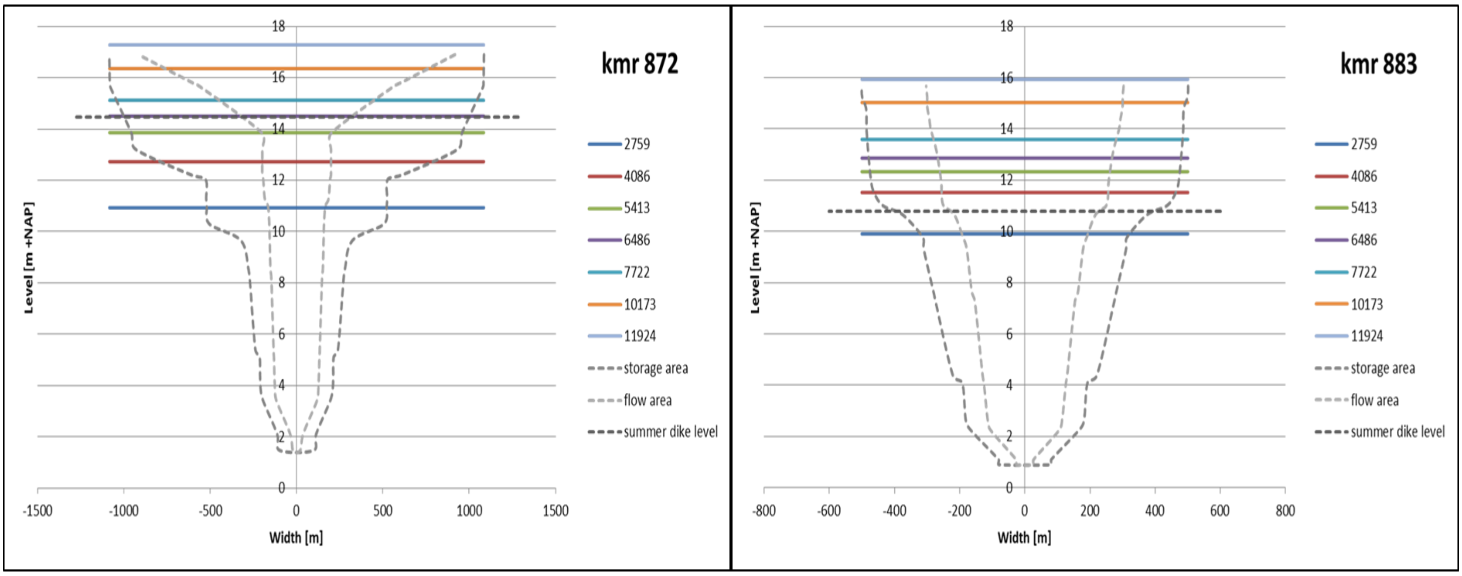

Figure 32 Cross-sectional profile of the locations 872 and 883 kmr for the reference scenario, dashed line indicates the level of the summer dike, flow higher than this dike flows through the storage area ('floodplains')

5.2.2. Effect of various bed elevation scenarios

The effect on the water level by the various bed elevation scenarios with (-II) and without (-I) lowering of the armoured layer is graphed in Figure 33 for the four different locations along the Waal. The zero bed elevation lowering below location 914 kmr induces zero water level effect, so only locations upstream of this point are analysed. The larger the bed elevation lowering in the main channel, the larger the effect on the water level. The largest effect is found upstream of the Waal, where the bed elevation lowering was applied to be the largest, as shown in Figure 29. The water level effect decreases in downstream direction of the branch related to the decrease in bed elevation lowering.

The lower the discharge, the larger the influence on the water level. This is the result of particular flow through the main channel for low discharge levels and flow through the floodplain as well for higher discharge levels. The increasing effect of even lower discharges is irrelevant for flood safety, but it might be interesting for other river functions like navigation and the discharge distribution control with the weirs in the Nederrijn-Lek. The lowering of the bed elevation is larger at 872 kmr than at 883 kmr, but also the flow profile is different, as known from paragraph 5.2.1. The water level effect is observed to be approximately equal for the discharges >6.486 m^3/s at location 872 kmr, for >4.086 m^3/s at locations 883 and 886 kmr and for >5.413 m^3/s at location 904 kmr. This corresponds with the level for floodplain flooding, so there can be concluded that the effect of the bed elevation scenarios relevant for hydraulic load is equal for floodplain discharges.

The bandwidth of the effect is given in Table 17 for the four highest discharges at the various locations. The effect of bed elevation lowering with a bandwidth of 35.1 – 93.5 cm upstream in the Waal (872 kmr) is a lowering of the water level with a bandwidth of 6.9 – 21.1 cm. At the extreme discharge level of 16.000 m^3/s at Lobith, the water level is reduced with around 19.2 cm for the most extreme bed elevation scenario (S1).

The effect of reducing the bed level of the armoured layer at Nijmegen, located between 883-885 kmr, is shown in Figure 33 as well. Downstream of the armoured layer (>886 kmr), no difference is observed between the riverbed scenarios with and without lowering of the armoured layer. Table 18 gives the extra effect on the water level by including the lowered armoured layer in the bed elevation scenarios. The influence on the water level effect decreases in upstream direction. It is lower at location 872 kmr than at 883 kmr. The difference in water level between the scenarios with and without lowering of the armoured layer seems almost constant over the discharges at 883 kmr, except for the lowest discharge, what is the result of the variation in flow profile. At 872 kmr, the effect varies more and it reduces almost to zero for the scenario with the least bed lowering (S3) at the discharges 6.486 and 7.722 m^3/s. These discharge levels were observed to be around the height of the summer dikes in paragraph 5.2.1 and lowering of the bed elevation affects the level of floodplain flooding and flow area. This reduces the influence of the armoured layer lowering on the water level effect.

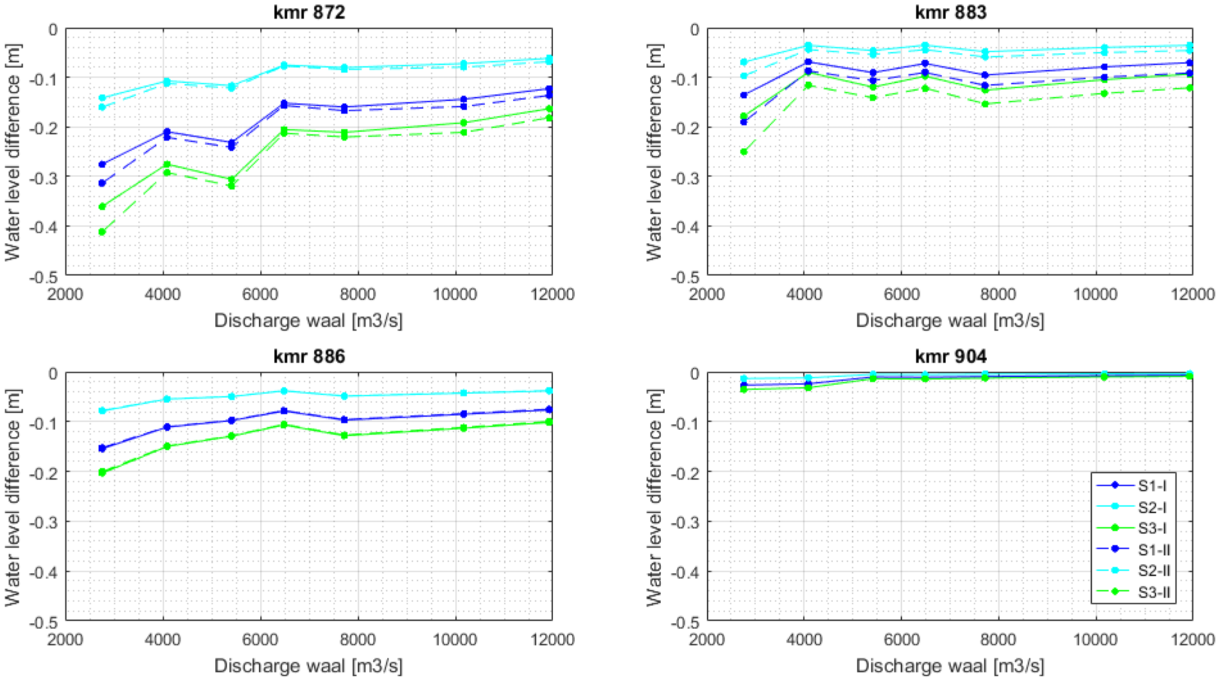

Figure 33 Water level difference with the reference scenario per upstream discharge for the influence of the bed elevation scenarios with and without lowering of the armoured layer on the locations 872, 883, 886 and 904 kmr

Table 17 Bandwidth of the water level effect for the bandwidth of bed elevation lowering without lowering of the armoured layers for various locations

Variation	Discharge Lobith	Discharge Waal	872 kmr	883 kmr	886 kmr	904 kmr
Bed level change			-35.1 -93.5 cm	-25.9 -68.9 cm	-23.4 -62.3 cm	-8.3 -22.2 cm
Water level effect	10.000 m^3/s	6.486 m^3/s	-7.0 -20.5 cm	-3.5 -9.8 cm	-3.8 -10.7 cm	-0.5 -1.5 cm
	13.000 m^3/s	7.722 m^3/s	-8.0 -21.1 cm	-4.8 -12.6 cm	-4.8 -12.8 cm	-0.5 -1.3 cm
	16.000 m^3/s	10.173 m^3/s	-7.2 -19.2 cm	-4.0 -10.4 cm	-4.3 -11.3 cm	-0.4 -1.0 cm
	18.000 m^3/s	11.924 m^3/s	-6.2 -16.3 cm	-3.5 -9.4 cm	-3.8 -10.2 cm	-0.3 -0.9 cm

Table 18 Bandwidth of the extra water level effect of the bed elevation scenarios by lowering of the armoured layer at Nijmegen for locations above the layer

Variation	Discharge Lobith	Discharge Waal	872 kmr	883 kmr
Bed level change			-35.1 -93.5 cm	-25.9 -68.9 cm
Water level effect	10.000 m^3/s	6.486 m^3/s	-0.2 -0.7 cm	-0.9 -2.4 cm
	13.000 m^3/s	7.722 m^3/s	-0.4 -0.9 cm	-1.1 -2.8 cm
	16.000 m^3/s	10.173 m^3/s	-0.7 -1.9 cm	-1.0 -2.8 cm
	18.000 m^3/s	11.924 m^3/s	-0.6 -1.8 cm	-1.0 -2.8 cm

5.2.3. Various boundary conditions

The variation in the upstream boundary was assumed to be an uncertainty in discharge distribution at Pannerdense Kop of 500 m^3/s in order of a 90%-confidence interval for an extreme discharge of 16.000 m^3/s at Lobith. This results a discharge of 10.173 m^3/s ±250 m^3/s towards the Waal.

Figure 34 graphs the uncertainty in water level due to the uncertainty in the discharge distribution for the reference bed elevation scenario. The difference in water level due to the uncertainty is given in Figure 35. The decreased effect in the downstream reach is due to an unchanged Qh-relation in the model. From the figures is observed that this discharge uncertainty gives a water level uncertainty of around 12-15 cm for the reference scenario.

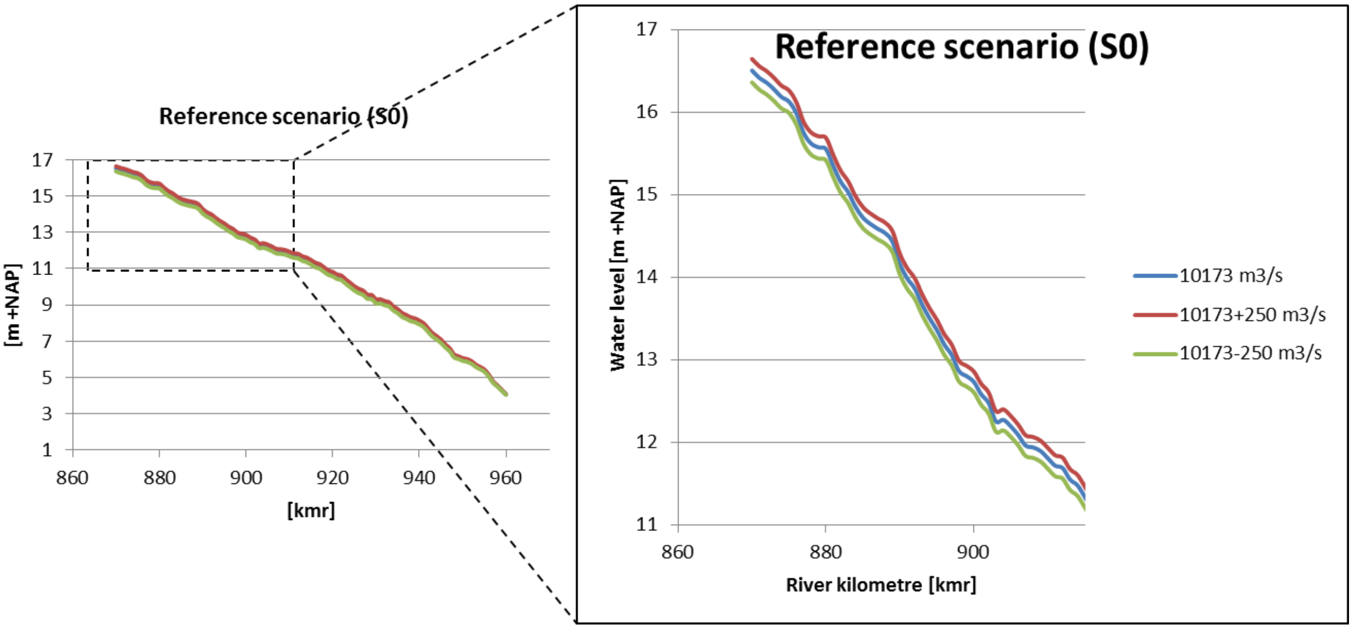

Figure 34 Water level for the uncertain discharge distribution at Pannerdense Kop under an extreme discharge of 16.000 m^3/s at Lobith with a discharge of 10.174 ±250 m^3/s towards the Waal, for the reference scenario

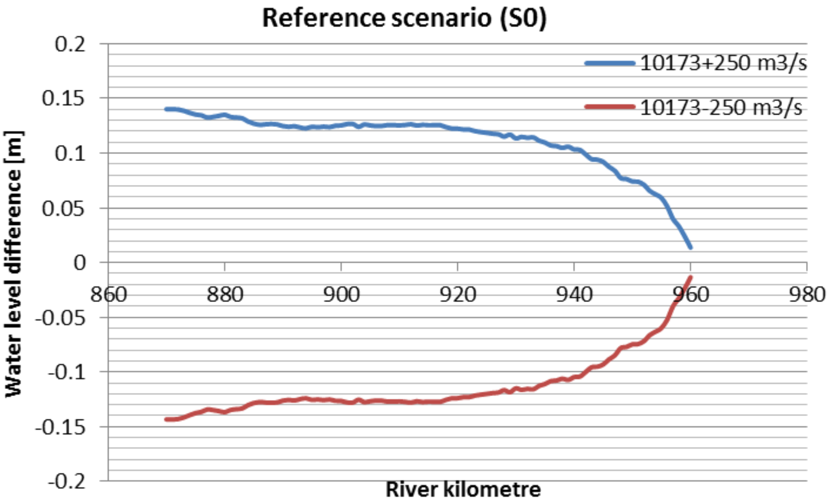

Figure 35 Water level difference between the water level of a Waal discharge of 10.174 m^3/s and of the discharge uncertainty (±250 m^3/s), for the reference scenario without changed Qh-relation

The uncertainty around the water level for the various bed elevation scenarios with lowering of the armoured layer is graphed in Figure 36. Table 19 gives the corresponding bandwidth of the effect at the various locations. The change in water level uncertainty is observed to be within order of millimetres. The effect is different between the increased and decreased discharge. From the increased discharge effect can be concluded that the water level uncertainty increases with an increased bed elevation lowering. The decreased discharge has had less effect on the water level at the upstream boundary and a slightly increased effect around the armoured layer.

The influence of the bed elevation scenarios on the discharge distribution is not included in the model, but it is plausible that the water level effect influences the discharge distribution. This leads to different water levels downstream than observed in this thesis. The reduced water level would theoretically lead to an increased discharge towards the Waal. The consequence is a different water level at the Waal and a different discharge and water level in the Pannerdensch Kanaal as well. However, this response of the discharge distribution depends on other factors in the river as well like the bed elevation development in the Pannerdensch Kanaal and development of the other bed characteristics in the Waal and Pannerdensch Kanaal. Other aspects that control the discharge distribution at a bifurcation mentioned in paragraph 2.3 can have influence as well.

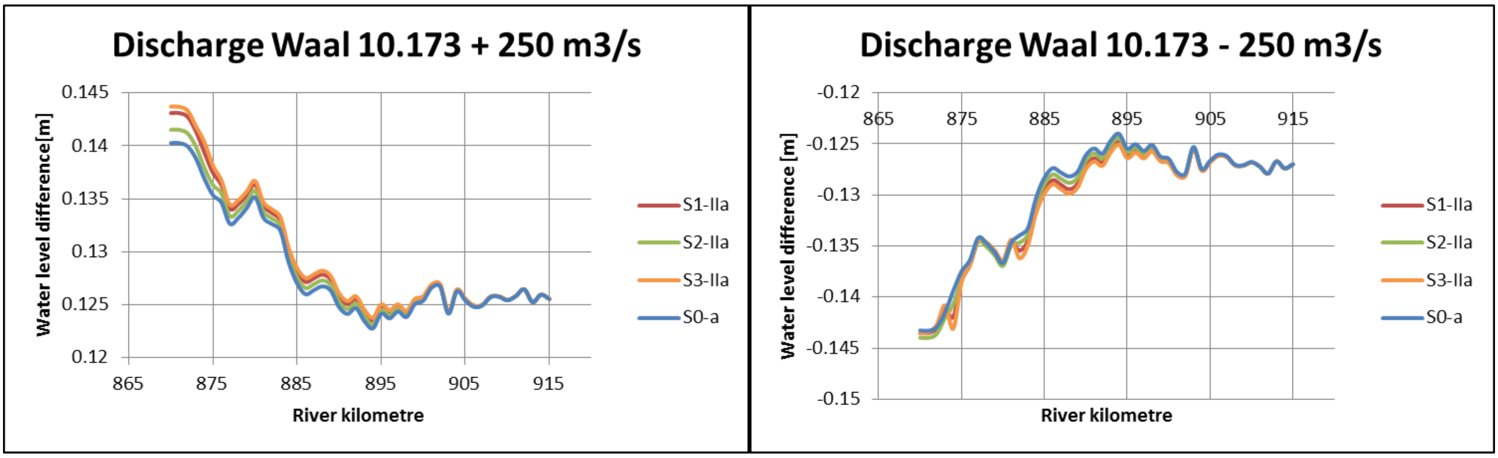

Figure 36 Water level difference between the water level of the reference discharge (10.174 m^3/s towards the Waal) and the discharge uncertainty (±250 m^3/s) per riverbed elevation scenario with lowering of the armoured layer at Nijmegen (-II)

Table 19 Bandwidth of the influence on the reference water level uncertainty for all bed elevation scenarios with lowering of the armoured layer (-II)

Discharge Waal	**872 kmr**	**883 kmr**	**893 kmr**	**904 kmr**
10.173 + 250 m^3/s	+0.12-0.33 cm	+0.04-0.12 cm	+0.05-0.15 cm	+0.00-0.02 cm
10.173 – 250 m^3/s	-0.02-0.06 cm	-0.06-0.16 cm	-0.06-0.16 cm	-0.00-0.01 cm

6. Relevance of long-term riverbed development on hydraulic load

The aim of this thesis is to determine whether the effect of potential long-term riverbed development is relevant for hydraulic load and to include in the guideline for the design of flood protections. The results and analysis of chapter 5 are used to determine the relevance of the bed elevation scenarios.

The results of this study show that the bed elevation scenarios reduce the water level. However, the results do not include the effect on the discharge distribution. The discharge levels relevant for hydraulic load are the levels that induce a water level above the summer dikes and flooding of the floodplains. It depends on the location which discharge levels induces this.

To ascertain the relevance, the effect of the various bed elevation scenarios and variations on the scenarios are compared together. The effect is also compared with an uncertainty factor of 0.3 m. This factor is prescribed by the design rules to be assigned to the hydraulic condition for design of flood defences in the Dutch river. It covers the model and statistical uncertainties (Rijkswaterstaat, 2017b). The influence of the bed elevation scenarios are assumed to be relevant when the effect is in the same order as the bed elevation scenarios. It is assumed to be relevant to for hydraulic load when it approaches the uncertainty factor, so when it has the same order of magnitude.

Bed elevation scenarios: The effect strongly depends on the amount of bed elevation erosion (lowering). More erosion is expected in the upstream than in the downstream reach of the Waal. The water level effect is observed to be equal for the discharge levels related to hydraulic load. The effect of bed elevation lowering with a bandwidth of 35.1 – 93.5 cm upstream in the Waal (872 kmr) is a lowering of the water level with a bandwidth of 6.9 – 21.1 cm. The bandwidth depends on the amount of lowering and therefore on the location in the Waal as well. This is quite a large bandwidth and in the same order of magnitude as the uncertainty factor. It is concluded to be relevant for hydraulic load.

With lowering of the armoured layer at Nijmegen: The armoured layer in the bed elevation scenarios influence the water level upstream. The influence of the layer decreases in upstream direction. The armoured layer induces a water level difference between the bed elevation scenarios with and without lowering. The difference is within a bandwidth of 0.9-2.8 cm near the armoured layer (883 kmr) for the relevant discharge levels. This is for a bed lowering with a bandwidth of 25.9 -68.9 cm. More upstream of the armoured layer, near the bifurcation (872 kmr) the difference is lower, within a bandwidth of 0.2-1.9 cm. This effect is an order of magnitude smaller than he effect of the bed elevation scenarios and the uncertainty factor. It is concluded to be irrelevant for hydraulic load.

Uncertainty in the upstream boundary: The uncertainty of ±250 m^3/s for a discharge of 16.000 m^3/s at Lobith results in an water level uncertainty of ±12-15 cm for the reference scenario. This is in the same order of magnitude as the effect of bed elevation scenarios on the water level. So, the effect of bed elevation scenarios is in the same order of magnitude as the uncertainty in discharge distribution. This demonstrates that the bed elevation scenarios are relevant as well. It is also in the same order of magnitude as the uncertainty factor and therefore concluded to be relevant.

The effect of the bed elevation scenarios on the water level uncertainty by discharge distribution is in order of millimetres. This is small compared to the effect of the bed elevation scenarios on the water level for a discharge of 16.000 m^3/s, which is in order of centimetres. It is also small compared to the uncertainty factor, so concluded to be irrelevant.

An overview of the various effects is given in Table 20. The observations of the results are only based on the influence of the riverbed characteristics on the water level. The effects and conclusion are likely to be different when the effect on discharge distribution is included as well. When the type of effect is determined to be relevant, it is recommended to do more research to the influence on the discharge distribution and related water level effect, and to the potential application in the design instrument for flood defences.

Table 20 Type of effect on hydraulic load and the associated order of effect on the water level

Type of effect on hydraulic load	Effect in order of magnitude
Uncertainty factor	dm
Bed elevation scenario	cm – dm
Armoured layer	mm – cm
Uncertain discharge	mm

7. Discussion and Conclusion

7.1. Discussion

The main objective of this thesis is to investigate what the effect is of potential long-term riverbed development on the water level in the Waal and to determine the relevance of the effect for hydraulic load. The potential long-term riverbed development of the past, present and potential future development is analysed with literature, data, extrapolation of trends and information from experts. The results are used to generate scenarios of bed elevation development over 50 years. Subsequently, the bed elevation scenarios are modelled and used to determine the impact on hydraulic conditions. In the end, the results of the impact are used to determine the relevance of the impact, i.e. of the riverbed development.

The discussion on this thesis is subdivided into a discussion on the generation of scenarios for the long-term riverbed development in the main channel of the Dutch Rhine system and a discussion on the determination of the effect of the riverbed scenarios on hydraulic load.

Scenarios of long-term riverbed development:

- The analyses of the past development of the controlling variables and bed characteristics is mainly limited to the branch-scale development. Local and more detailed analyses would probably give more information on the local influences and developments, like the contribution of local interventions. The bed elevation development might vary locally by erosion pits, local sedimentation or over the cross-section, for instance in a bend.
- The contribution of the downstream water level increase by sea level rise to the bed elevation of the river is in this study suggested to be small compared to the observed trend in bed elevation of the branches. The scenarios of bed elevation could be expanded with scenarios for the downstream water level. Therefore the effect of sea level rise on the bed elevation should probably be included since climate change is expected to increase the rate of sea level rise in the future. If this sea level rise and associated bed level aggradation are included, it results in different water level effect along the river. It possibly compensates for the water level effect on the bed elevation scenarios.
- The influence of the upstream discharge is applied as variation on the scenarios of bed elevation. The upstream discharge was variated in the scenarios by uncertainty in extreme discharge distribution resulting in an uncertain discharge entering the Waal. Uncertainty in discharge distribution can occur as well for other discharge levels that also never occurred before. This would probably lead to the same conclusion that the influence on the water level uncertainty is small compared to the water level effect by the bed elevation scenarios for the applied discharge.
- The influence of subsidence was assumed to be negligible compared to bed elevation development. The sediment supply development over time was uncertain and no method was found to be able to determine future development in a substantiated way. More research and information is necessary to clarify and decrease the uncertainty around the contribution of both controlling variables to the developments of bed characteristics.
- The bed roughness development is derived in a slightly devious way. It is required to to do more research to the development of (future) bed composition and bed roughness in the river. Investigation in a method to related these bed parameters with more certainty is also necessary. It would result in more sufficient information to conclude about the development in the past and present and also to be able to determine potential future development. If the development can be determined in a substantiated way, the bed scenarios can be expanded

with scenarios for the bed composition and bed roughness and the effect on hydraulic conditions can be compared with the scenarios of bed elevation.

- An advantage of this methodology compared to using a morphodynamic model to analyse potential development of the bed characteristics is that it is independent of the determination of a hydrograph. It is also clear how the riverbed development is generated. The advantage of a morphodynamics model is that it is possible to include and analyse the influence of variation in discharge hydrograph over time. The resulting bed elevation over 50 years is then also related to this variation by morphologic adaptation of the riverbed.
- The floodplains were assumed to remain at the present level, because the main channel was mainly of interest in this research. The floodplains increase due to depositing of silt when flooded. An increase of the floodplain level would change the results, because the discharge level for flooding increases. The bed elevation scenarios have the most effect on flow particular in the main channel. The higher floodplain level induces more discharge levels to flow particular through the main channel and larger water level effects for these discharges.
- Political guidance and research are the driver behind measures in the river to manage the river functions. The assumption of lowering the armoured layers in the river will depend on policy in the future and is therefore applied as a variation on the scenarios. Policy also determines whether to dredge the riverbed and that can give different bed conditions in the future. For instance, politics might decide to stop or to remain dredging of the Lower-Waal. In the future, politics might also decide to increase the Waal in the future as compensation of bed erosion in the past.

Effect on hydraulic load:

- The effect of the riverbed elevation scenarios are only determined for the water level in the Waal. The water level change also affect the discharge distribution at the bifurcation Pannerdense Kop and this effect is not included in the results. The observed lower water level at the upstream boundary of the Waal will induce more discharge towards the Waal. This changes the effect and conclusions of this thesis. The larger discharge will reduce the lowered water level effect and even increase the water level at the locations where the bed did not degrade, like at the downstream reach Lower-Waal. Development of the bed elevation in the Pannerdensch Kanaal and the morphodynamics and hydraulic roughness around the bifurcation can influence the water level and the discharge distribution as well.
- The model choice of a 1D-model gives a first interpretation of the effect on the hydraulic conditions in the Waal. This approach also can be applied to other branches of the Rhine and other bed characteristics as well like the bed roughness. A limitation of the base model in SOBEK-3 is the calibration on the discharge distribution with the artificial roughness sections just below the bifurcation.
- Hydraulic load is related to the water level in the river and influenced by variation in the riverbed characteristics. It is used to determine the risk of flooding and to assess flood safety, but the water level variation can also be used to determine the effect on other river functions like navigation, ecology or safety of cables and pipelines under the riverbed. Changes lead to maintenance of the functions by river management.
- The applied upstream boundary in the Waal for numerical modelling is based on the measured distribution for discharge levels measured in the past. With the chosen range of levels, a good insight is given on the impact on hydraulic load. Even higher discharge are applied in the design instrument (20.000-24.000). Application of these discharge is not likely to give more information to this study, because the effect on the water level is more or less equal for the high discharges. The observed effect on main channel discharges is probably interesting for navigation, especially due to the observed increasing effect for lower discharges.

- The effect of the bed elevation scenarios on the water level is in order of cm. The morphodynamics of the seasonal variation is also in order of cm. The morphodynamics already affecting the water level. However, bed forms are fluctuating over the bed and the effect is likely to be on small-scale. The induced long-term bed elevation development is expected to be on large-scale.
- The scenarios do not include the effect of exposure of erodible layers under extreme discharges. An extreme discharge occurs in the next 50 years and the armoured layers are transported. This might expose sub-layers of finer sediment. The finer, more mobile sediment is transported under lower discharge levels and that induces increased bed erosion. This influences the bed characteristics and results to different hydraulic conditions after the flood as well. The bed elevation will be lowered locally and the bed surface sediment will be finer.
- The bed elevation scenarios are applied as lowering over a gradient until the Lower-Waal (>915 kmr, around Tiel) corresponding with the observed trends in bed elevation and bed slope. Different scenarios can be applied as well. The Lower-Waal might be eroded as well when the erosion upstream influences the downstream reach as well. This would result in lower water levels downstream as well. The armoured layer at St. Andries in the Lower-Waal would induce more or less the same effect as the armoured layer at Nijmegen. A different scenario could also be aggradation of the Lower-Waal induces by sea level rise. This leads to higher water level upstream along the river by a backwater-curve.
- In this thesis only scenarios of bed elevation erosion are generated. The effect of an increased bed elevation would be different. This does not corresponds with the observed trend, but future political decisions might oppose a method to counterbalance the erosion effects by an increased bed elevation. An increased bed elevation would increase the water levels in the Waal, but the amount of effect is smaller than the amount of the bed lowering. The water level will flow through the floodplains for lower discharge.

7.2. Conclusion

The main question of this research was ‘What are scenarios of long-term riverbed development in the main channel of the Rhine system and what is the impact on hydraulic load?’. Answering this question is guided by five sub-questions.

Q1) How are riverbed characteristics and hydraulic load related?

Variation in the riverbed characteristics causes changes to the hydraulic load. Riverbed characteristics in the main channel that are related to hydraulic load are bed slope, bed elevation, bed composition and bed roughness. The variation of the riverbed characteristics is induced by the controlling variables in the river. Control variables are the human interventions, upstream discharge, downstream water level, subsidence of the ground and sediment supply.

Q2) What long-term riverbed developments, for the riverbed characteristics related to hydraulic load, are observed from historical and recent measurements in the river Rhine?

Development of human interventions is concluded to have had signification contribution to the development of the bed characteristics. The adaptation towards the normalisations and changes in sediment availability is still continuing. Development of the upstream discharge and downstream water level are concluded to have had no significant influence on the bed characteristics compared to the observed trends of the bed characteristics. A changed probability of occurrence of the discharge level upstream is observed as well and this affects the hydraulic load. Development of the subsidence of the ground is concluded to have had no significant influence on the bed characteristics. The sediment supply was mentioned in literature as probably changed in the past due to the observed coarsening upstream of Pannerdense Kop, but information was inadequate to determine the development and the contribution of sediment supply.

Development of the bed elevation was observed in the Bovenrijn, Waal and Pannerdensch Kanaal. The present bed elevation in the Bovenrijn is opposite in the upper- and lower-reach of the Bovenrijn. The upper-reach aggrades and the lower-reach degrades. In the Waal, an eroding trend is present. This trend is smaller in the downstream than in the upstream reach of the Waal. An erosion trend is present in the Pannerdensch Kanaal. This trend is equal for the down- and upstream reach. The bed elevation in the lowest reach of the Waal (915-950 kmr) was concluded to have been stable over the past 25 years. The bed elevation development of the branches corresponds with the present bed slope. The Bovenrijn becomes slightly steeper over time, the Waal develops towards a milder slope and the Pannerdensch Kanaal is stable since around 2007.

The bed composition development is concluded to have become coarser over time in the Bovenrijn, but uncertain in the Waal. The bed composition in the upstream reach of the Pannerdensch Kanaal is concluded have been stable in the past. The information and data of the bed roughness in the past are concluded to be inadequate to determine the development in a substantiated way within the available time for this thesis.

Q3) Which scenarios of long-term riverbed developments in the main channel might occur in the Dutch Rhine?

Scenarios of long-term riverbed development in the main channel of the Dutch Rhine are determined for the Waal and Pannerdensch Kanaal over 50 and 100 years for the bed elevation. It is determined that the eroding trend is likely to be reduced or stopped in the future by human interventions or in a natural way, but until that time, the eroding trend is assumed to continue with the same speed. It is also expected that no new interventions are applied that can accelerate the erosion again, but the observed coarsening might expand and this phenomena accelerates erosion downstream. The derived potential developments in this research have led to three scenarios of the bed elevation in the Waal and Pannerdensch Kanaal:

1. The bed elevation continues to erode with the present rate.
2. A solution is possibly found within 50 or 100 years and erosion is stopped.
3. Erosion might even be increased due to coarsening upstream and associated decrease of sediment supply downstream.

The bed elevation scenarios are varied by the integration of the armoured layers in the river and by uncertainty in the upstream boundary condition. The armoured layers in the river are non-erodible and remain at the same level while the surrounding bed erodes, except when human intervene and artificially lower the layer(s).

Q4) What is the effect of scenarios of long-term riverbed development in the main channel on hydraulic load in Waal?

The bed elevation scenarios for the main channel are used to investigate the effect on the water level in the Waal by using a numerical simulation model. The influence on the discharge distribution is not included, but it is likely it has an influence and this will change the water level downstream.

The effect of bed elevation lowering in the main channel with a bandwidth of 35.1 – 93.5 cm upstream in the Waal (872 kmr) is a lowering of the water level with a bandwidth of 6.9 – 21.1 cm. The water level effect is equal for flow through the floodplains at each location.

In combination with lowering of the armoured layer, the water level effect of the bed elevation scenarios is increased upstream of the layer. In other words, the armoured layer in its present condition reduces the influence of the bed degradation on the water level. The difference has a bandwidth of 0.9-2.8 cm near the armoured layer (883 kmr) for the relevant discharge levels. This is for a bed lowering with a bandwidth of 25.9 -68.9 cm. More upstream of the armoured layer, near the bifurcation (872 kmr) the difference is lower, within a bandwidth of 0.2-1.9 cm.

Variation in the upstream boundary due to uncertainty in discharge distribution over the bifurcation Pannerdense Kop of ±250 m^3/s for 16.000 m^3/s at Lobith induces a water level uncertainty of around 12.0-15.0 cm for the reference bed scenario in the Waal. The water level uncertainty increase with millimetres for a larger bed lowering.

Q5) How relevant is the effect of long-term riverbed development in the main channel on hydraulic load in the design of flood defences along the Dutch Rhine?

The water levels relevant for hydraulic load are the levels that induce a water level above the summer dikes and flooding of the floodplains. The bed elevation scenarios are relevant to include in the guideline for the design of flood protections when the effect on the water level approaches the uncertainty factor of 0.3 m for hydraulic load. The effect of the bed elevation development on the water level is concluded to be relevant. The effect of the armoured layer in the bed elevation scenarios and the effect of the bed elevation scenarios on water level uncertainty, by uncertainty in discharge distribution, are irrelevant compared to effect the bed elevations scenarios. However, this is without consideration of the response of the discharge distribution on the changed water level.

Final conclusion

The final conclusion of this research answers the main research question. The answer is divided into two parts. The first part is the potential scenarios of long-term riverbed development that can be determined for the main channel of the Rhine system. The conclusion can be drawn after answering sub-question 3. It was concluded that scenarios only can be generated for the bed elevation, because the information on these bed characteristics was adequate. It is concluded that 3 bed elevation scenarios are potential:

1. The bed elevation continues to erode with the present rate.
2. A solution is possibly found within 50 or 100 years and erosion is stopped.
3. Erosion might even be increased due to coarsening upstream and associated decrease of sediment supply downstream.

The second part of the conclusion is about the impact on hydraulic load. The relation between hydraulic load and bed elevation follows from sub-question 1. The impact of the long-term riverbed development on hydraulic load is concluded to be is equal for the discharge levels related to hydraulic load. It has a lowering effect on the water level relative to NAP for each bed elevation scenario. The impact is the largest for the largest bed erosion in the Waal. The bed erosion (trend) is concluded to be the largest in the Boven-Waal (867-890 kmr).

7.2.1. Recommendations

Scenarios of bed development:

- The results of this research are only based on the influence of the riverbed characteristics on the water level in the Waal. The influence of water level effect on the discharge distribution is not included. It is likely that the distribution changes by the effect of the bed elevation scenarios and that changes the results of this thesis. It is recommended to do more research to the impact of the water level effects on the discharge distribution upstream.
- The results of this research might be interesting for other river functions than flood safety as well like navigation and ecology. The reduced water level influences the navigation depth over time, the ground water level, might induce different inflow levels of or loading on hydraulic structures. It is recommended to investigate the consequences of bed elevation scenarios on the water level for other river functions as well, with consideration of the influence on the discharge distribution.
- It is recommended to do more frequent measurements of the bed composition of the (Dutch) Rhine system can reduce the uncertainty in the development.
- It is recommended to do more research to the development of (future) bed composition and bed roughness in the river, and to investigate a method to related these bed parameters with in a more certain way. This would result in a more substantiated way to conclude about the development in the past and present and to be able to determine potential future development.
- Scenarios of other bed characteristic developments can be compared with the bed elevation scenarios to indicate the different effects on the hydraulic condition in the river.
- It is also recommended to develop the scenarios of the bed elevation by using a morphodynamic model.
- The variation on bed elevation scenarios can be expanded with variation of the downstream boundary to investigate the effect on hydraulic conditions. The effect of sea level rise and the response of the riverbed by aggradation are likely to have influence on the downstream water level of the Waal. More research is necessary to the effect over time.
- Potential scenarios of local development could be applied by following the same procedure used in this research. A local and more detailed analyses would give more information on the local developments and effects.
- Final recommendation is to do more research to the development of the bed elevation in the Dutch Rhine. This might give more insight in the processes and future development. This type of research is also interesting to apply in the Lower-Waal, since it is important to get insight in the present observed development. It is assumed to remain stable, but this might be different in future. The observed (small) increase of bed elevation might be a trend or a temporal development, and it is also uncertain what caused this development. The different development probably results in different hydraulic conditions than obtained in this research.

Appendix I – Regulation of the discharge distribution in the Dutch Rhine

The discharge distribution at Pannerdense Kop is for some discharges regulated with weirs in the Nederrijn-Lek. The regulation is included in the weir-program and dependent on the water level at Lobith, as shown in Table 21 (Reeze et al., 2017). For a water level <8.65 m +NAP (<±1.600 m^3/s) at Lobith, the weirs are fully closed and regulation is not possible. For the water level between 8.65-10.00 m +NAP (±1.600-2.600 m^3/s) at Lobith, the weirs are used to affect the discharge distribution at Pannerdense Kop for regulation of a minimum water level in the Waal for navigation. For a water level between 10.00-11.40 m +NAP at Lobith, regulation of the weirs only influence the water level at IJsselkop. A water level >11.40 m +NAP (>±3.600 m^3/s) at Lobith, the weirs are fully opened and it is not possible to regulate the discharge distribution with the weirs in the Nederrijn-Lek. Potential bed degradation at Lobith results in lowering of the water level for a discharge level. The weirs will become to regulate at higher discharges with an increase degradation of the bed level.

Table 21 Weir-program of the weirs in the Nederrijn-Lek for water level and discharge value at Lobith (Rijkswaterstaat, 2015; Reeze et al., 2017)

Weirs	H_{Lobith} [m +NAP]	Q_{Lobith} [m^3/s]
All weirs fully closed, stowing	< 8.65	< 1.600
Opening weir Driel partly	8.65-10.00	1.600-2.600
Weir Driel fully opened, other weirs partly opened	10.00-11.40	2.600-3.600
All weirs fully opened, high water, free flow	> 11.40	> 3.600

The expected discharge distribution for various high discharges at Lobith is given in Table 22 (Rijkswaterstaat, 2017a). The distribution of extreme discharges that never occurred before is based on models and extrapolation of high water measurements to the extreme discharge level for the present layout of the river(ten Brinke, 2013).

The extreme discharges are supposed to be regulated with a regulation system in the Dutch Rhine. The regulation system consists of two inlets: Pannerdensche Overlaat (around Pannerden) and Hondsbroekse Pleij (around IJsselkop). Table 23 highlights some characteristics of the regulation system, like the inlet height and the control range. Every summer, both structures are adapted with partitions to the normative hydraulic load, determined from recent summer- and winter-bed level and present vegetation roughness (ten Brinke, 2013). The Hondsbroekse Pleij is often assumed to be adaptable periodically in modelling. However, experts question whether is it possible to adapt this system periodically, during extreme discharge, when necessary[8].

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[8] For discharges between 10.000 and 16.000 m^3/s, all partitions of the Hondsbroekse Pleij are closed. For lower discharges, only one partition is opened. For higher discharges, the partitions are opened.

Table 22 Discharge distribution at the Pannerdense Kop (over the Waal and Pannerdensch Kanaal) and the IJsselkop (over the Nederrijn and IJssel)

Lobith	**Waal**	**Pan.Kan.**	**Nederrijn**	**IJssel**
10.000 m^3/s	6.473 m^3/s	3.527 m^3/s	2.077 m^3/s	1.450 m^3/s
16.000 m^3/s	10.465 m^3/s	5.835 m^3/s	3.380 m^3/s	2.461 m^3/s
17.000 m^3/s	10.970 m^3/s	6.030 m^3/s	3.380 m^3/s	2.656 m^3/s

Table 23 Characteristics of the regulation system in the Dutch Rhine, source: (ten Brinke, 2013)

Regulation system	**Pannerdensche Overlaat**	**Hondsbroekse Pleij**
Height of inlet	12.0 – 17.0 [m + NAP]	11.0 – 15.2 [m + NAP]
90%-confidence interval for 16.000 m^3/s	500 m^3/s (±250 m^3/s and ±1,6% of Q_{waal})	300 m^3/s (±150 m^3/s and ±2,5% of Q_{ijssel})
Control range for 17.500 m^3/s(9)	500 m^3/s *Fully opened: +400* m^3/s *towards PK*(10) *Fully closed: -110* m^3/s *towards PK*	200m3/s *Fully opened: +50* m^3/s *towards IJK*[10] *Fully closed: -160* m^3/s *towards IJK*
Control range(11) for 18.000 m^3/s	- 50 m^3/s towards the Waal	

---

[9] The control rang of Pannerdensche Overlaat with 500 m^3/s is not comparable with the confidence interval of 500 m^3/s at the bifurcation. The confidence interval shows that the discharge towards Pannerdensch Kanaal can be 250 m^3/s more (or less) than expected. The control range shows that the Pannerdensche Overlaat distributes up to 110 m^3/s towards the Waal.

[10] PK = Pannerdensch Kanaal; IJK = IJsselkop.

[11] Without the Rijnstrangen area, where 500 m^3/s can be withdrawn. When this area is included, the situation is equal to the control range for 17.500 m^3/s.

Appendix II – Bed elevation development on branch-scale

Figure 37 shows the bed elevation development over time of the main channel in the Waal from data analyses. Figure 38 shows the bed elevation in the Pannerdensch Kanaal and Figure 39 of the Bovenrijn. These figures are used to determination of the bed slope development in the past.

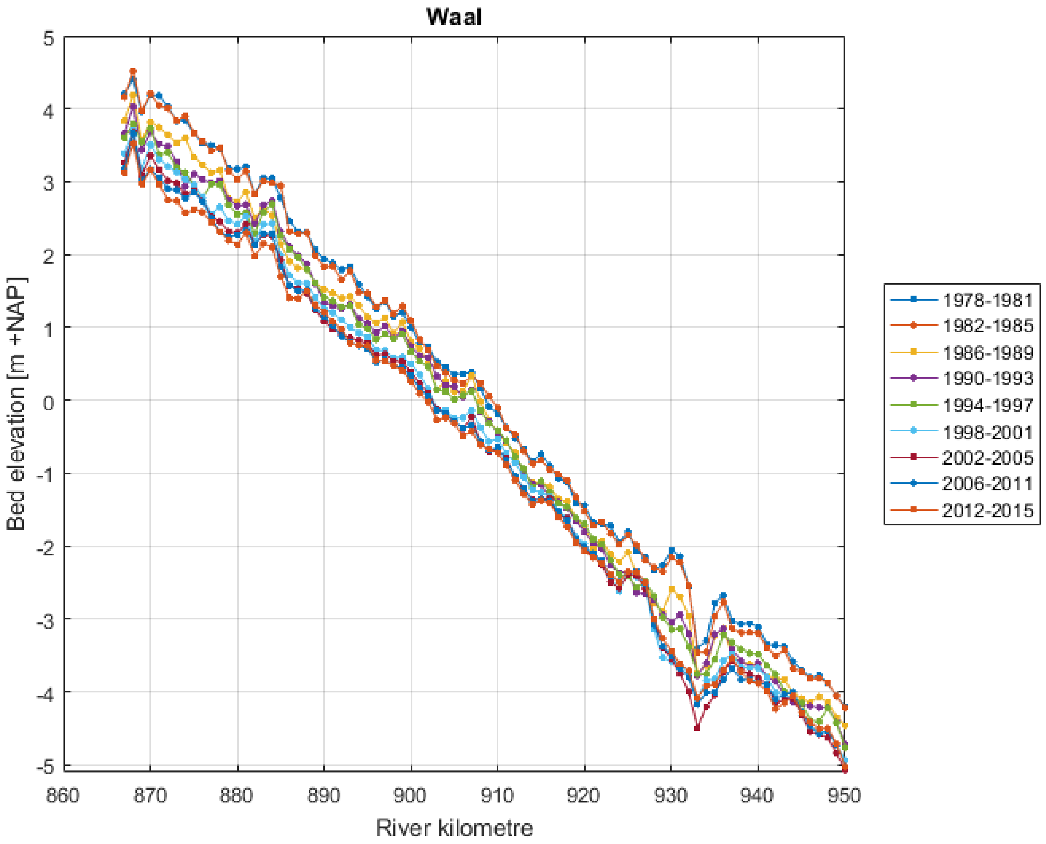

Figure 37 Average bed elevation of the Waal (868-950 kmr) over a time period of 4 years for the period 1978-2016 (data of 2008 and 2010 were not available) (data from Rijkswaterstaat)

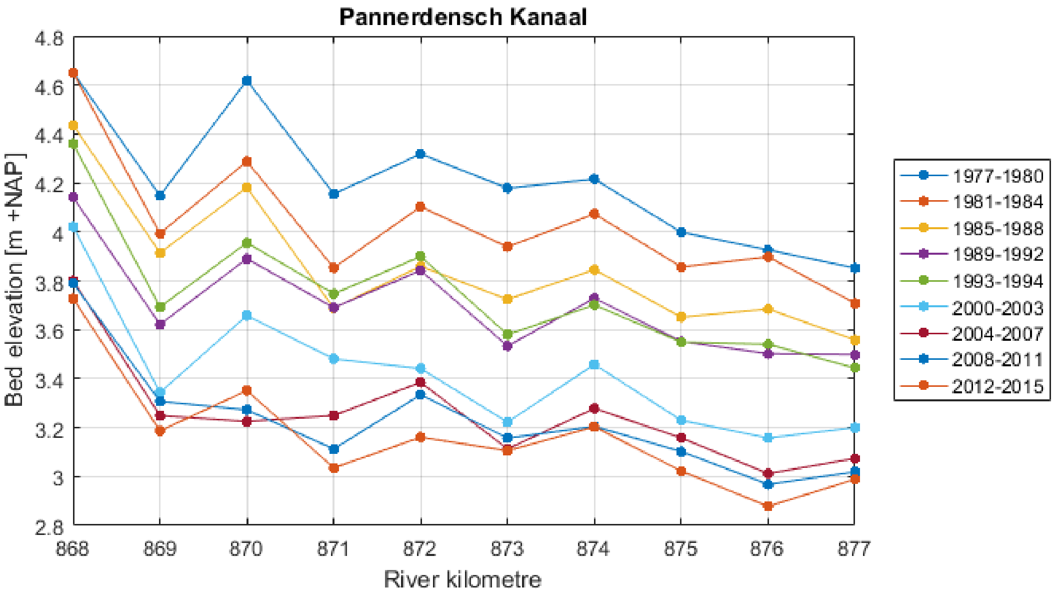

Figure 38 Bed elevation of Pannerdensch Kanaal (868-877 kmr), the average over time period of 4 years for the period 1978-2016 (data of 1995-1999, 2001, 2008 and 2010 were not available) (data from Rijkswaterstaat)

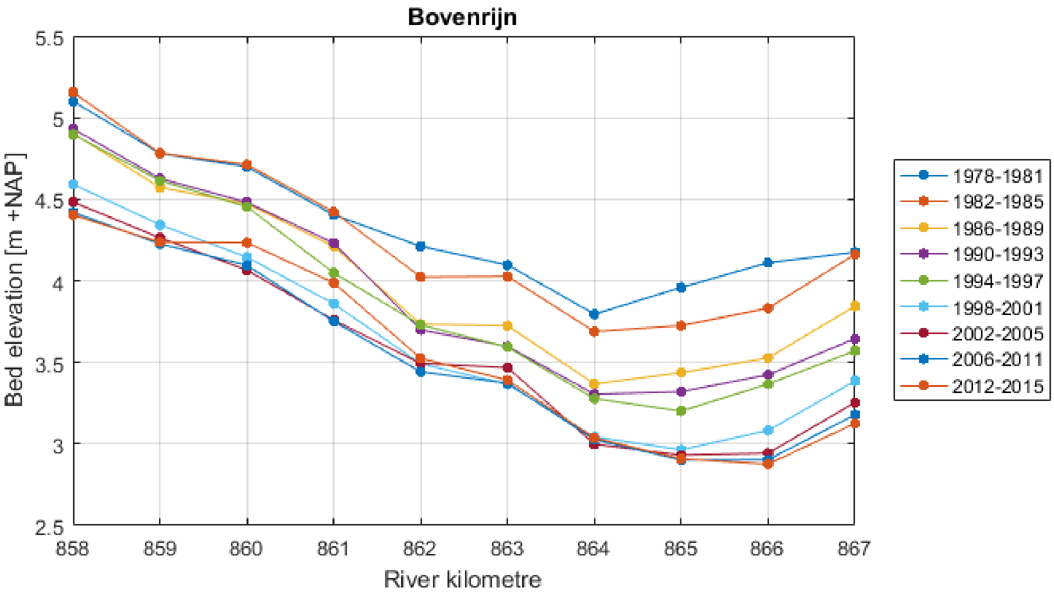

Figure 39 Average bed elevation of the Bovenrijn (858-867 kmr) over a time period of 4 years for the period 1978-2016 (data of 2008 and 2010 were not available) (data from Rijkswaterstaat)

Appendix III – Extended summary of the information from conversations with river experts

As part of the analyses, conversations have taken place with 10 river experts in the Netherlands to provide information and opinions on the development of riverbed characteristics and human interventions. This is the extended summary of the information gathers from the conversations, without quotes of the river experts, but with (partially) shared opinions. Various subjects were discussed with various experts. The most relevant information from the conversations is given below, with also subjects that were less relevant for continuation of this research, but also interesting for river engineering.

Long summary of the information from conversations with river experts

Human interventions in the river resulted in adaptation of depth, gradient and grain size diameter. Almost each expert names the large normalization in the river Rhine in the 19^{th} and 20^{th} century as the cause of the bed strongly eroded bed elevation in the past. Dredging accelerated this process, but the excessive dredging was stopped in 1992 and nowadays dredged sediment must be returned into the river near the dredging site. Only sediment downstream Zaltbommel may still be extracted from the river, but it might be possible that policy changes this in the future, because it induces backward erosion in the river. When sedimentation is allowed, this might counterbalance the erosion upstream.

The system is probably still adapting towards the normalization, but meanwhile, people are already changing the river again in response to the adaptations. The RftR-measures returned some space to the river, but it is still way smaller than what is used to be. The effect of sedimentation and erosion is a large difficult pattern. The longitudinal dams are recent measures in the river. This does not stop the development towards a milder gradient, but it might cause a certain aggradation layer. Feasibility of the longitudinal dams is currently studied and when this is positive, some expert mention that it might be a good solution to be applied in more sections of the river. Applying longitudinal dams in the whole river would give uniform pattern and reduces the sedimentation/erosion wave through the system, it is however probably costly. It should be researched whether price and profits are balanced.

Sediment management in the river is relative new, not long ago it wasn't a subject at all. Suppletion of sediment is a pilot project. Some experts mention that is might be not very sustainable, but it also might be the only thing we have to do to control the river system. It possibly works best over the whole river, but it doesn't remove the cause of developments. Best is if we find a solution to lower the sediment transport capacity to provide the river to be more in equilibrium, for instance due to more space and dynamic floodplain, to lower the velocity. Perhaps a combination of this and suppletion. Suppletion do is flexible and easy to adapt when necessary, compared to permanent measures, like armouring. It is not regret measure. It has potential to be applied over the whole river, because that might be the most effective. The material of the suppletion comes from sand-mining pits. The downstream sediment downstream Zaltbommel is too fine to be used. The location of nourishment affects the sediment distribution over the river. Eventually a hard solution is more of an option or a combination of suppletion (short) and hard measures. This probably depends on the urgent, time and money.

The armoured layer at Nijmegen is often named as a problem in the Waal. It is a problem for navigation, because the bed around the layer erodes and this leads to local reduction of the water depth above the layer. The armoured layers in the river become more of a problem, because it is non-erodible and lowering the layers would solve this problem. However, it seems a short-term solution when the erosion continues. If the armoured layer is lowered, some experts mention that this affects the erosion rate, because an advantage of the armoured layer is that the induces higher water level upstream is likely to delay the erosion upstream and stop the backward erosion from downstream.

A complete armoured riverbed might be an extreme solution. Disadvantage is the increasing water level due to increasing roughness, but it is also unfavourable to ecology and very expensive. The question would also be: where do we stop, because over there erosion starts again… The experts with whom this subject was discussed find this solution unlikely to happen. Maybe the increasing floodplains, which is also marked as a problem in the Rhine, can be used to stop erosion. WNF currently looks into the possibility to create more sediment transport between the river and the floodplains (mentioned by an expert).

The regulations system in the Dutch Rhine, consisting of structures at Pannerden and Hondsbroekse Pleij, was also discussed with a few experts. They mentioned that during high water regulation would be favourable, but it is questionable whether this is feasible. It is never tested if the regulation system works as expected. Automatization might solve this uncertainty, but this was mentioned to be uncertain as well and probably expensive. The electronics might be vulnerable during floods and the system should be maintained and tested often, because the deployment is very low. During high water, the distribution point at Pannerdense Kop might get damaged, but afterwards people will fix it and stabilize it again. So real large changes at this point are not likely to occur on long-term.

The present development of the riverbed characteristics was submitted to the experts. The limited sediment supply from upstream and normalisation changing the sediment transport capacity were mentioned as the cause of coarsening and erosion developments in the river. Mentioned was that if the people do not intervene in the present development of the bed characteristics, it would probably continue, until the natural equilibrium of the riverbed is achieved. Continuation means that the Bovenrijn stabilizes, but lowering of the bed elevation in the Waal and Pannerdensch Kanaal continues or might even increase due to coarsening upstream and a part of the riverbed gradient might become steeper. Unequal bed elevation development between Pannerdensch Kanaal and the Waal influences the discharge distribution at Pannerdense Kop and this is a disadvantage for the river functions downstream, so there must be somethings done against it.

Mentioned was that the development of bed composition and bed gradient is important as well. If the median grain size becomes larger in the Waal, the riverbed dynamics would become more like the Bovenrijn. Over there, bed forms are larger than bed forms in the Waal for high discharges and smaller for low discharges. This has probably to do with the flow velocity. Some experts mention that the coarse layers in the river might come in suspension under extreme discharge conditions.

It was mentioned that is it important that the various stakeholders as users of the river work integral towards solutions, and not sectoral, and that it is important to search for the source of the problems in order to solve them. For instance, in the side-channel of the Rhine are many measures taken and this will have influence on the Rhine in the future. Measures in the side rivers of the Rhine also influence the main river and our Dutch Rhine. System development is very difficult and uncertain. A change in supply material by upstream changes like retreating glaciers was mentioned to be small. The released material is transported slowly and probably gets stuck in the Bodensee.

Present policy is not directly to stop the bed erosion, it is to maintain the present riverbed to maintain the river function, like navigation and flood safety. However, if stabilization might be the goal in Germany, we should do it here as well, otherwise the differences remain increasing. Until we find a decent solution, which might still can take 10 to 30 years and only if we do want to find a solution, the trends in bed elevation erosion are plausible to continue. Experts think that we will do something to stop bed erosion. However, policy is opposing that ‘if measure increase the bed, this is negative for flood protection, and mitigation is required, for instance in the floodplains. It is also questionable to which price is stabilization wanted. Do we need to want to stop the erosion? More measures means an even more difficult pattern of adaptations of bed characteristics in the river. Should the river always adapt in advantage of the human or should human start to move towards the river, so work with the river instead of against it. Shouldn’t navigation adjust to the river instead of the other way around.

Appendix IV – Additional figures for bed characteristics development

The two figures of Emmanouil (2017a) below give more information of the bed-load transport. The first figures graphs the amount of measurement points and results of bed-load transport for various locations points and the second figure gives more detailed information per period.

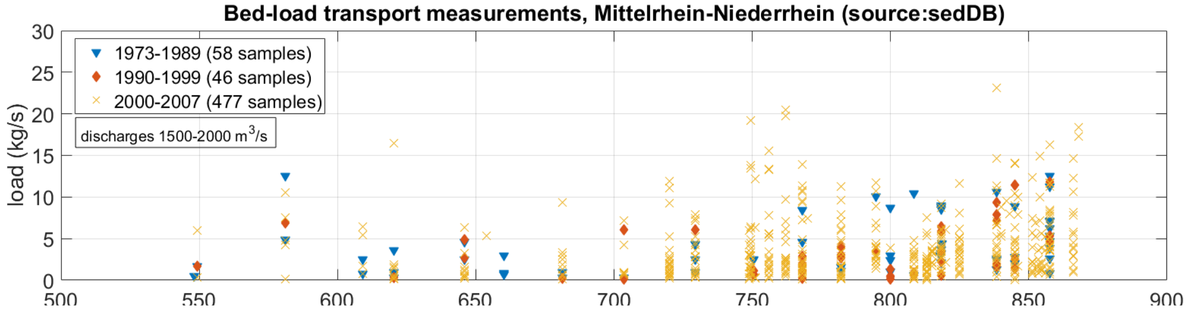

Figure 40 Measurement points of bed load transport for the Mittelrhein-Niederrhein (Emmanouil, 2017a)

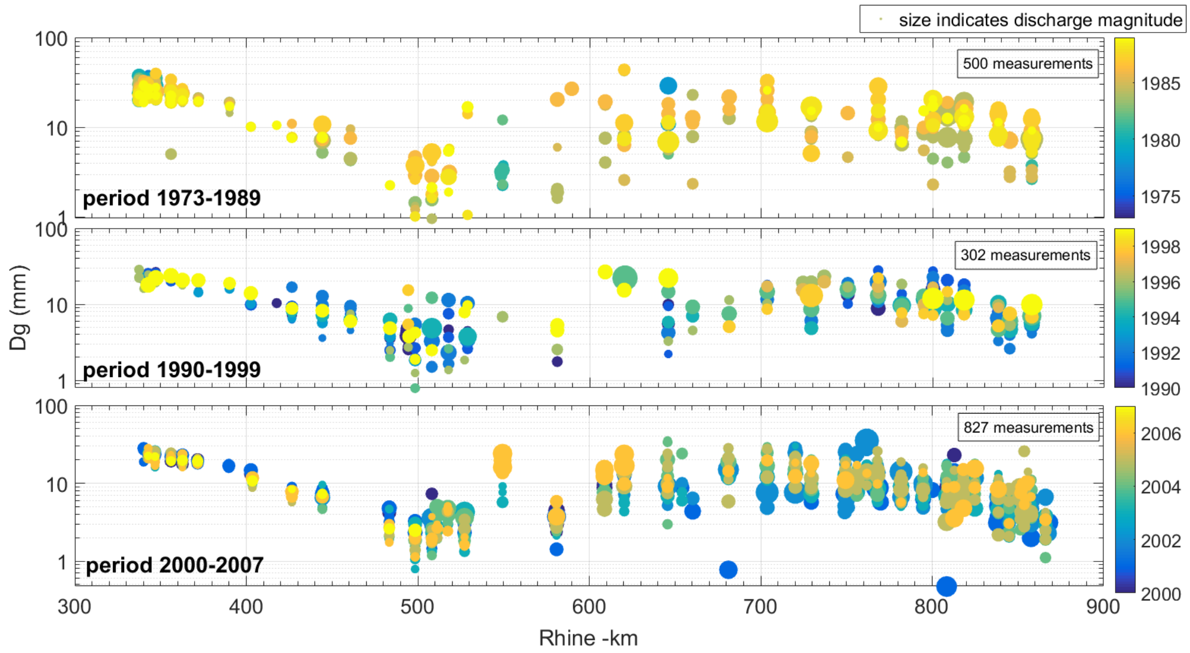

Figure 41 Composition of the bedload for three measurement periods (Emmanouil, 2017a)

Appendix V – Methods for scenario generation

Different possible riverbed developments are able to occur on the long-term. Future perspectives can be reviewed with a scenario analysis. Scenarios are not predictions, but hypotheses of potential future developments with a focus on uncertainties. From the analysis can be seen what situations perhaps occur and if interventions are necessary to change, mitigate or stop the development.

Scenario generations consists of two aspects: determination of the scenario aspects and application of a method. The aspects are already determined in the previous paragraphs. The applicable methods to generate scenarios of long-term morphologic development, like equations, trend analysis, modelling, essay writing, event tree and expert judgement, are discussed in this chapter. This report, and thus each technique, is based on forecasting, which uses a time line of development from the past and present towards the future.

Equations

Equations can be used to derive an impression of potential long-term development of the riverbed based on various driving forces. Relations described in De Vriend, et al. (2011) and derived from the Jansen (1979) formulas are given in Table 24. These relations are describing the morphologic effect on the equilibrium state of the riverbed. A too large change of ratio in water level (h) or bed gradient (i) imposes to do more research to the morphologic effects.

Table 24 Effects of water and sediment interventions on the equilibrium state of the riverbed, for a constant or variable discharge (De Vriend, et al., 2011)

Problem	Characteristic discharge	Variable discharge
Withdrawal of sediment $\Delta S \text{ and } \Delta V$	$\frac{i_1}{i_0} = \left[1 - \frac{\Delta S}{S_0}\right]^{3/n}$ $\frac{h_1}{h_0} = \left[1 - \frac{\Delta S}{S_0}\right]^{-1/n}$	$\frac{i_1}{i_0} = \left[1 - \frac{\Delta V}{V_0}\right]^{3/n}$ $V = \int_0^\infty S(Q)p(Q)dQ$
Withdrawal of water $\Delta Q \text{ or } p_0(Q) \rightarrow p_1(Q)$	$\frac{i_1}{i_0} = \frac{Q_0}{Q_0 - \Delta Q}$ $\frac{h_1}{h_0} = 1 - \frac{\Delta \mathrm{Q}}{\mathrm{Q}_0}$	$\frac{i_1}{i_0} = \left[\frac{\int_0^\infty Q^{n/3}p_0(Q)dQ}{\int_0^\infty Q^{n/3}p_1(Q)dQ}\right]^{3/n}$
Long constriction	$\frac{i_1}{i_0} = \left[\frac{B_1}{B_0}\right]^{\frac{n-3}{n}}$ $\frac{h_1}{h_0} = \left[\frac{B_0}{B_1}\right]^{\frac{n-1}{n}}$	$B^{1-\frac{n}{3}} i^{\frac{n}{3}} \int_0^\infty Q^{\frac{n}{3}} p(Q)dQ = constant$ So $\frac{i_1}{i_0} = \left[\frac{B_1}{B_0}\right]^{\frac{n-3}{n}}$

Trend analysis

Trend analysis is an analytical method to develop scenarios from empirical data. The data is gathered by measurements and progressed afterwards. The progressed data is analysed on development and trends. The result is used to assess potential future perspectives by extrapolation or reasoning based on previous developments.

Execution of a trend analysis depends on the amount of available data. More data makes assessment of future perspectives more reliable. The longer the time period of the future, the more difficult the assessment becomes, due to increasing uncertainty in time(De Bruijn et al., 2008). From Duinker & Greig (2006) is known that the historical time period should consist of a least twice the length of the prediction time period to assess future developments. In case of 50 years prediction ahead, 100 years historical data is necessary with a certain frequency and accuracy.

Data availability differs per riverbed property. Some properties are rarely measured, which makes trend analysis and future assessment difficult. If trend analysis is used in this research, it should be known what data is available exactly, on which time scale and frequency and for which locations.

The advantage of trend analysis is that it is a quantitative method and more data increases the accuracy of extrapolation. An advantage is as well that statistical developments can be considered. Disadvantage is that extrapolation does not consider uncertainties and the relation with other processes is difficult to analyse (De Bruijn et al., 2008). So, application of trend analysis for long-term development is difficult and uncertain.

Modelling

Modelling is a common tool for assessment of long-term development. A representation of reality is given based on schematisation, boundaries and equations. The input of a model are variables corresponding to this. The output is usually the absolute or relative value of variables after a time period. In the paragraph 0 is discussed how uncertain long period modelling is.

Model calculations can be done with 1-D, 2-D and (quasi-)3-D modelling. A completer model requires more parameters to be known, for which assumptions and empirical numbers are required due to lack of knowledge about the physical processes and parameters. It is more time consuming, but less simplification of the situation is necessary. A full 3-D model is often not used, because running the model takes too much time, is too expensive and is only interesting when the local details of a situation are necessary (De Vries, 1993). It is important to keep in mind that model results are not an exact representation, but an approach of reality (De Vries, 1993; Sloff et al., 2014).

Difference can be made between an analytical and numerical model. Rijkswaterstaat (2017a) advises to perform quantitative equations first for changes in the winter-bed. If this results in a significant morphologic effect in the summer-bed, an analytical method must be performed. When this gives a significant effect as well, optimization of the design is necessary. When significant effects remain after optimisation, an numerical model is required. An analytical model gives a quick and easy insight in the morphologic development after a long period and has limited effect on the hydraulic input parameters. A numerical model gives a more specific calculation of long-term morphologic development. This includes local and system changes, so outside the direct place of influence as well. Disadvantage is the longer calculation time and higher costs.

To apply models for scenario development, different input parameters and assumptions are necessary. For this research, at least morphologic variables as input parameters and 2-D processes for development of the bifurcation points are important.

Advantage of modelling is that it is a quantitative, consistent and specific method to create future perspectives of the riverbed properties (Dammers et al., 2013). It can also easily be applied in the next step of this research, assessment of the scenarios on hydraulic load, since modelling is used for this step as well and quantification is required. Dammers, et al. (2013) mentioned that a disadvantage of quantitative models is that new developments and unquantified aspects, like policy, are difficult to apply, since data and knowledge are restricted. Disadvantage of models is also the preparation and calculation time, increasing with dimension. More dimensions increases insight and reality, because more processes are considered, but it also requires more assumptions and empirical numbers due to lack of knowledge, which causes uncertainty. Final disadvantage is the difficult validation of models for long-term scenarios, because historical data does not include extreme value by statistical development.

Essay / Literature analysis

Dammers, et al. (2013) discussed essay as a technique for genaration of scenarios. An essay describes qualitative a logical coherence between developments and their cause and effect. It explains developments by words and helps to demonstrate the relevance of different scenarios.

Execution of writing an essay is based on literature, logical reasoning and writers expertise. The story of each scenario should connect to past and present developments and it is important that the story strengthens the imagination of readers and users. Each scenario has a certain potential to occur and the ability to compare with other scenarios on various elements. Dammers, et al. (2013) points that enough relevant literature and information about the subject must be available to execute the essay technique.

Advantage of generating scenarios with an essay is that it is qualitative and the reasoning, cause and effect are very clear. Also, various elements and uncertainties can be considered and the communication with this method is relative easy and clear. However, the disadvantage is that the approach often lead to global scenarios without quantification and perhaps the personal opinion of the writer influences the scenarios. Besides, the quantification of change is difficult to assess, because information and literature about this is probably limited.

Event tree

Bishop, et al. (2007) discussed the technique of an event tree. An event tree is telling a story of a series of events in a graphic way. The tree consists of different events and paths between the events to occur as sequence to an event. The paths are representing potential scenarios to occur in the future. Different paths are possible and the three ends at different potential conditions dependent of the followed path. In general, cause and effect are outlined with the method.

In this research, the events are covered by different potential developments of the riverbed properties. The properties that corresponds to each other become more clear and if the probability of each event is known, the final probability for a certain scenarios to develop, can be calculated. The paths are constructed by the responding of properties to an event. The end of the tree shows the resulting development.

The advantage of this method is that is gives a qualitative result due to the overview of cause and effect. Also quantitative results are possible when probabilities are known. A disadvantage of this method is that it is abstract and might become unclear when many paths can occur. Then decisions must be made, for which argumentation is necessary.

Expert judgement

Judgement is a technique that implements the knowledge of people who are expert in the field of research to create potential future perspectives. This method is used when less data is available. An expert is asked to think, share and give their ideas about certain developments of driving forces. The answers of several experts are compared and together they give insight and diversities in potential scenarios.

Several techniques of involving the experts are possible:

- Workshop, a meeting with experts where ideas and scenarios can be generated
- Delphi-technique, an iterative process were several times questions are answered and feedback on conclusions of earlier sessions can be given. This technique can be executed though computer.
- Interview, one on one technique, requires personal attendance and provides substantiated argumentation on the possibilities and wherefore personal attendance is required.

Execution of this method requires good reporting of the results and some expertise of the people involved. The group of experts consists preferably of diverse expertise within the field of research, but the experts individually must be related to the field of research and should be able think creative and after a long period (Dammers et al., 2013). The qualification of the experts can be examined by first asking a set of reference questions about the topic. The answer of this question is available and compared to the answer of the expert to verify the knowledge and accuracy of the experts.

Also important for the execution is asking the right questions in a good way to get the preferred type of results, qualified or quantified. A set of questions of interest is asked to provide an answer for different potential scenarios. Programs are available to assess and analyse the quantified answers.

The advantage of the judgement technique is that it provides insight and creativity beyond the researcher knowledge, it can examine scenarios and increases acceptation of the scenarios due to involvement of experts. It is both a quantitative as qualitative method. The disadvantage is that personal opinions instead of technical knowledge or lack of knowledge of an expert influence the results. Also selective participation of experts and group influence affect the results.

Decisions for scenario generation

The conclusion of this chapter and decisions for the next part of this research are given in this paragraph. In this research, long-term riverbed development is researched by scenario generation. A choice is made on the method to generate scenarios about long-term riverbed development is chosen. Table 25 gives an overview of the decisions.

Several methods are reviewed in paragraph 0, but the available time for this research is too short to perform all methods. However, Dammers, et al. (2013) mentions the “A good scenario is based on several methods”. This research executes two methods, trend analysis and expert judgement is used to provide potential future perspectives and to create quantitative values for it. Expert judgement is preferred over modelling, since this technique has no model uncertainties, it achieves a quantitative and qualitative result and less studies on long-term riverbed development are executed with this technique.

Table 25 Overview of the decisions made regarding scenario generation of long-term riverbed development

Methods	**Trend analysis**
	Literature analysis
	Expert judgement

Appendix VI – SOBEK-3 information

This appendix gives background information on the SOBEK-3 model used to determine the effect of riverbed scenarios after long-term riverbed development on the water level. The preconditions of the model are explained.

Background base model

In SOBEK-3, the version 'rijn-j17_5-v1' of the Rhine branch models is used. The riverbed is based on the bed elevation measurement in 2013 (Berends, 2014).The model is calibrated on results of the WAQUA-models. This is based on the discharge between 1.200-12.000 m^3/s at Lobith. Higher discharges never occurred in reality and are determined by extrapolation. This main channel is calibrated on measurements from 2014. The floodplain and cross-sections are yearly calibrated and the present calibration is based on measurements from 2017. First, the Rhine branches (Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn-Lek and IJssel) are calibrated separately on the water levels and then, it is calibrated on the measured and, for discharges at Lobith >12.000 m^3/s, calculated discharge distributions at the bifurcation points.

The calibration on the discharge distribution is done by 'roughness sections'[12] just downstream of the bifurcation, see also Figure 42. In reality, under extreme discharges, the regulation system is affecting the discharge distribution, but this 'widening' of the bed profile cannot be modelled in the SOBEK-model. The roughness sections are used to induce the presumed discharge distribution under extreme discharges. This adjustment can be based on various roughness combinations of the sections the two downstream branches (Berends, 2014). This means uncertainty in the roughness and the results of the model when adaptation are done to the riverbed in the model, which probably influence the discharge distribution.

Roughness in the SOBEK-3 model is given in the main channel as a manning coefficient and in the floodplain as a Chézy coefficient. SOBEK-3 computes the roughness of the flow profile as a Chézy-value and it is a function of both the main channel and floodplain roughness. The model converts the Manning coefficient to a Chézy-coefficient with the equation: $C = R^{1/6}/n_m$, with C = Chézy coefficient; R = hydraulic radius; n_m = Manning coefficient. The roughness of the main channel is largely determined by the bed forms, hydraulic structures (groynes), bed material (grain diameter, armoured layers) and possible vegetation (Berends, 2014).

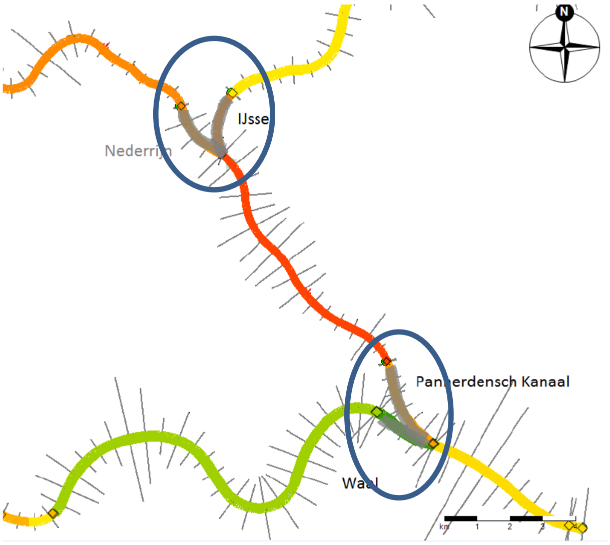

Figure 42 Position of the roughness sections in the SOBEK-3 model for the Dutch Rhine branches, located downstream of the bifurcation points and highlighted with the blue circles (Berends, 2014)

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[12] In Dutch: ruwheidstrajecten

Appendix VII – Flow profiles of several locations along the Waal

Figure 43 gives the global schematization of a bed profile in SOBEK-3. The profiles of the schematized Waal in SOBEK-3 are graphed in the figures below for various locations. For each profile, the water level per discharge, the flow profile of the main channel, the level of the summer dike and the flow area of the floodplain is indicated. Until the level of the summer dike is reached, water is only transported through the flow area. Above the summer dike level, water will be transported through the storage area, i.e. the floodplains, as well.

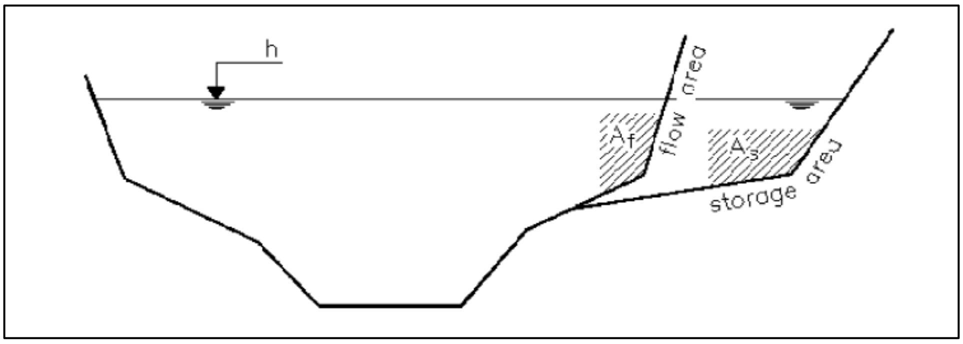

Figure 43 The schematization of flow (A_f) and storage area (A_s) in SOBEK-3 (Deltares, 2017a)

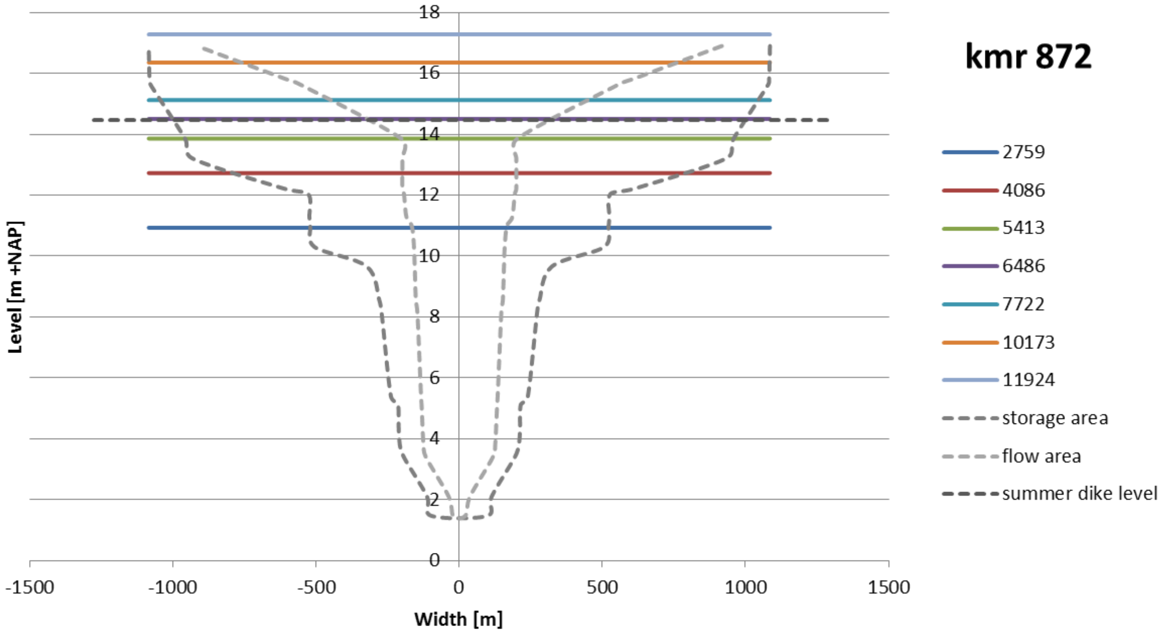

Figure 44 Bed profile and water level at various discharge levels at the location 872 kmr in the reference scenario

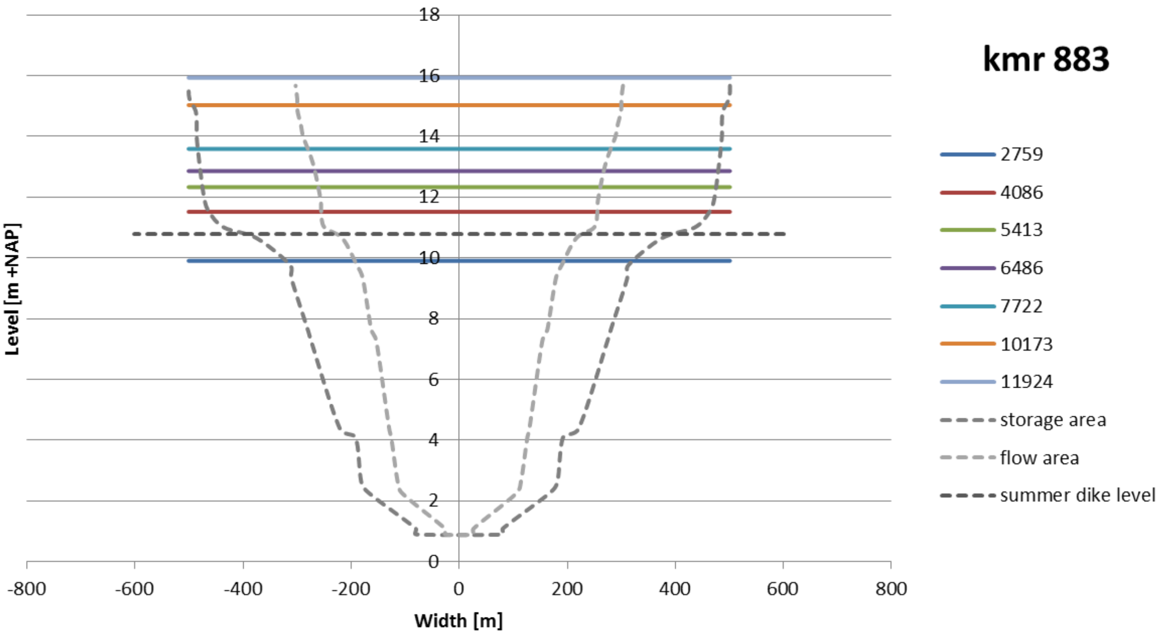

Figure 45 Bed profile and water level at various discharge levels at the location 883 kmr in the reference scenario

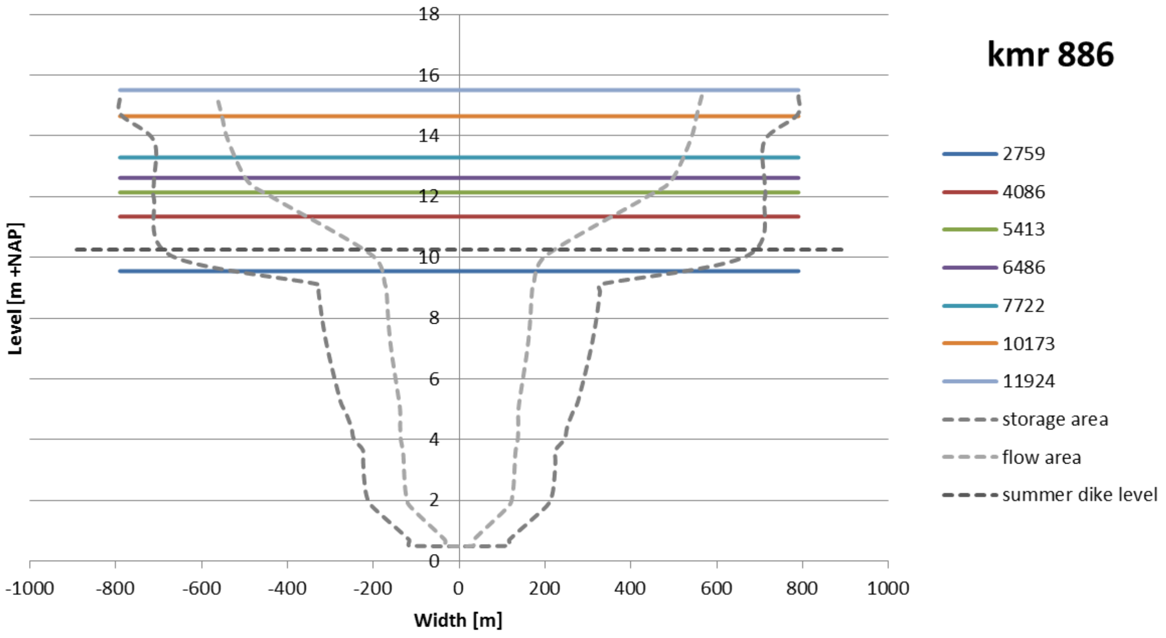

Figure 46 Bed profile and water level at various discharge levels at the location 886 kmr in the reference scenario

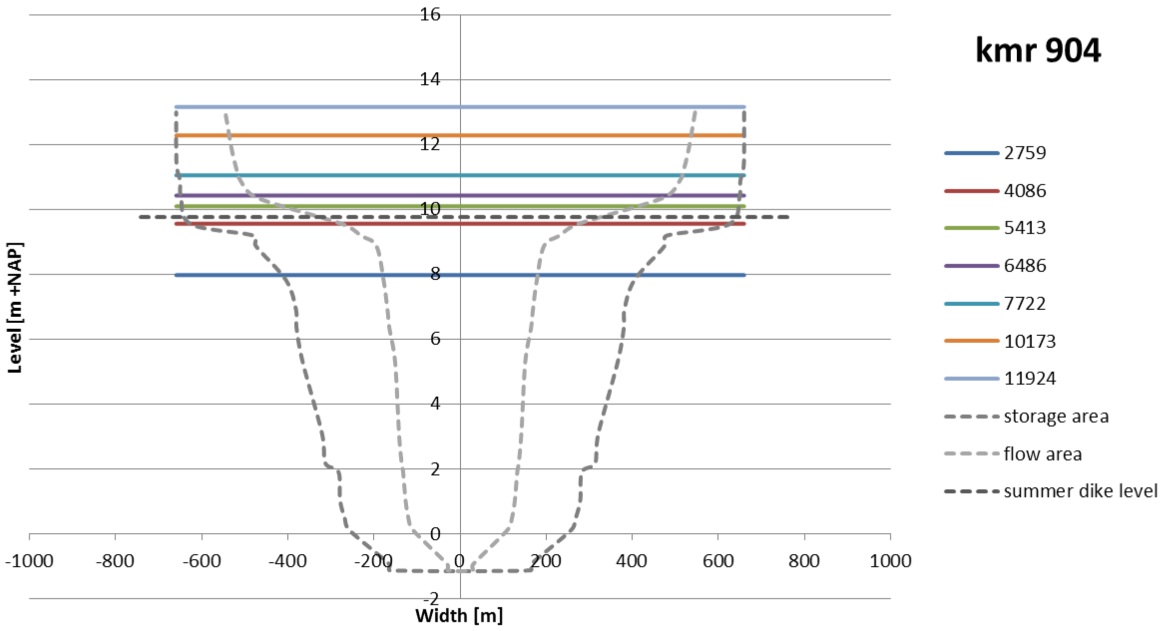

Figure 47 Bed profile and water level at various discharge levels at the location 904 kmr in the reference scenario

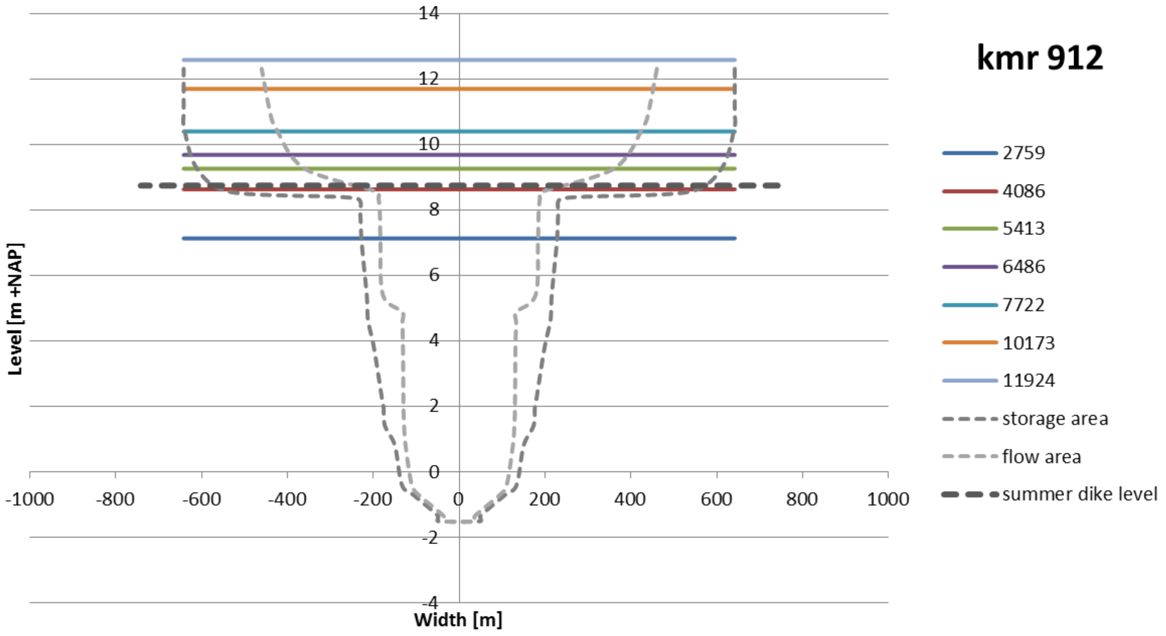

Figure 48 Bed profile and water level at various discharge levels at the location 912 kmr in the reference scenario

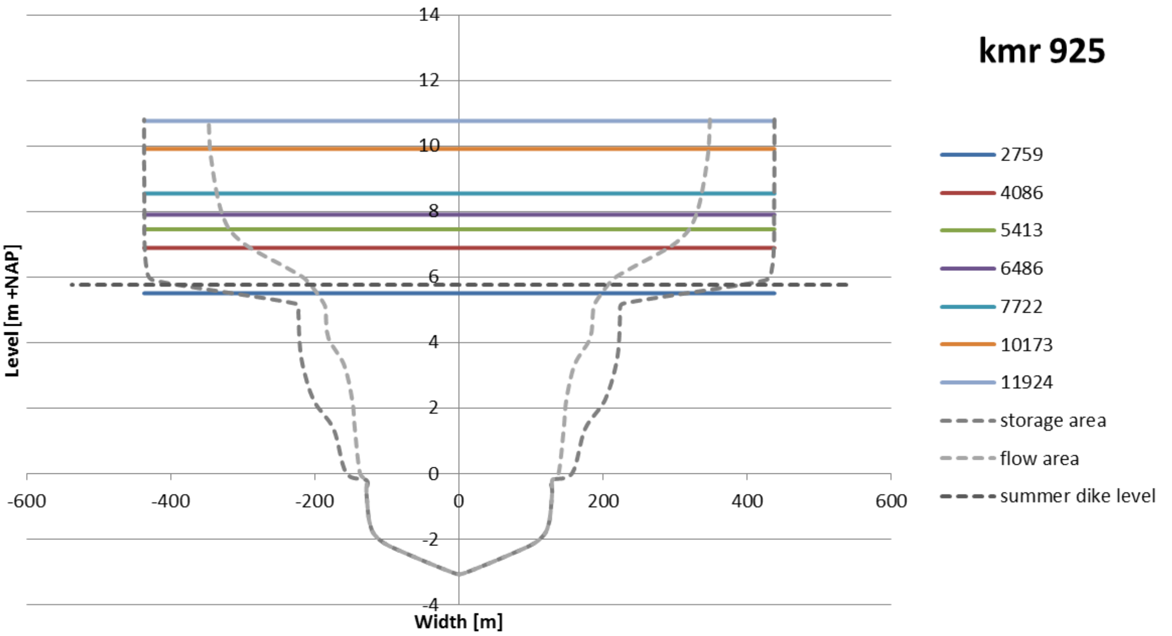

Figure 49 Bed profile and water level at various discharge levels at the location 925 kmr in the reference scenario

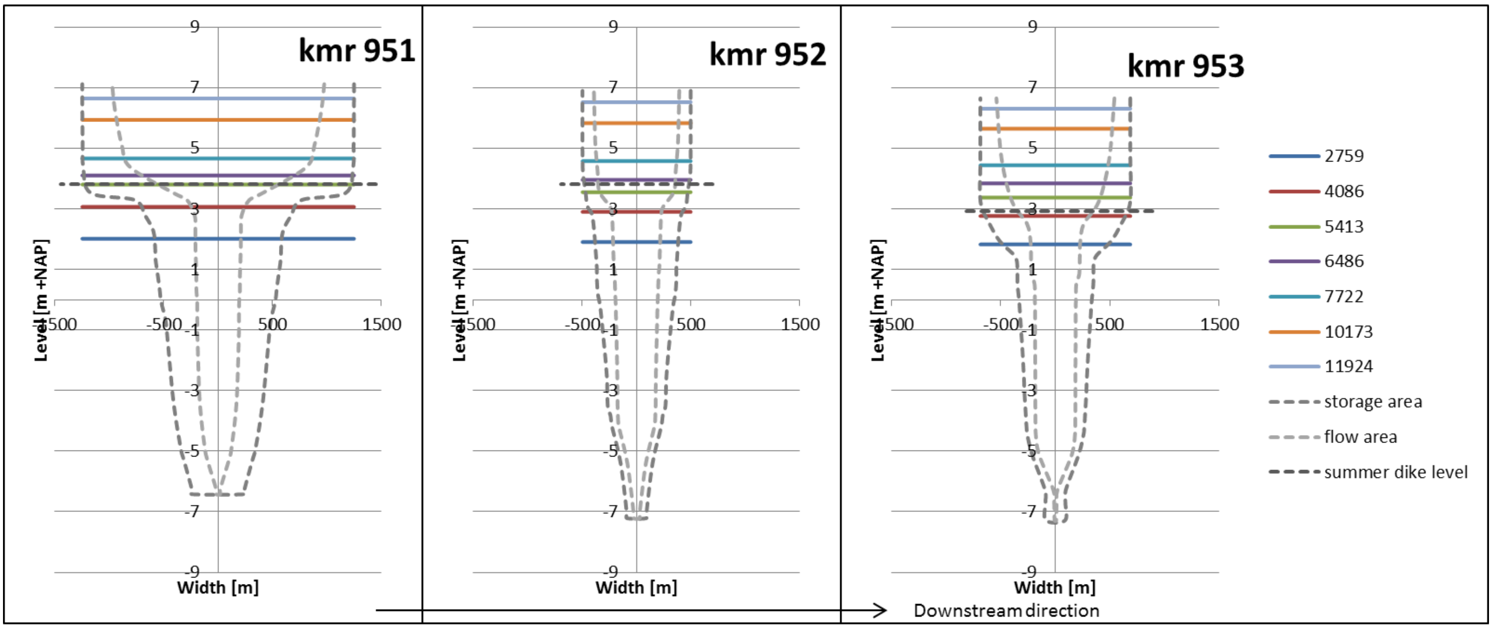

Figure 50 Bed profiles and water level at various discharge levels for downstream locations 851-853 kmr in the reference scenario, to interpret the effect of the downstream water level for the discharge 5.413-6.486 m^3/s

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