TU Delft

Tidal influence on sediment transport and bed level in the river Merwede




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Tidal influence on sediment transport and bed level in the river Merwede

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PREFACE

This report is the result of my master thesis project about the tidal influence on sediment transport and bed level of the Merwedes. This graduation research completes my Master of Science program at the section Hydraulic Engineering of the faculty Civil Engineering and Geosciences at Delft University of Technology. The master thesis project has been carried out at the group Coastal and River Engineering Rotterdam of Witteveen+Bos.

I want to thank the members of my master thesis committee for their valuable counsel. In particular, I express my appreciation to Kees Sloff for his support and enthusiastic response. I also thank Alfons Smale for providing a workplace at Witteveen+Bos, the professional guidance and the useful advices. I thank the employees of the group Coastal and River Engineering Rotterdam for their interest and their sociability. Further, I thank Ary van Spijk and Vincent Beijk of Rijkswaterstaat Dienst Zuid-Holland for their interest and comments. I also thank my parents and Liesbeth for their support and encouragement. Furthermore, my thanks is directed to the Lord God for all He gives to me.

Leon de Jongste

Rotterdam, June 2010

SUMMARY

The area of the Merwedes is a transition zone between a tide-dominated area and a river-dominated area. With increasing river discharge, the influence of river flow dominates in this part of the Rhine-Meuse Delta. The composition of the river bed of the Merwedes is also a transitional area, because of the presence of both sand and mud. It is unknown how sediment transport and morphology in this area are influenced by the complex interaction of tidal flow and river flow.

To be able to explain the morphological changes in the area of the Merwedes and to be able to anticipate on these changes, there is a need for better understanding of the hydraulic and morphological processes. This research contributes to a refinement of the system description of the Rhine-Meuse Delta by determining the influence of the tide on sediment transport and bed level in the river Merwedes. Furthermore, the obtained knowledge has been applied to the case of floodplain excavation at Avelingen.

The aim of this graduation research is to gain insight into the contributions of tidal flow and river flow to sediment transport and bed level changes in the Merwedes, with a view to application of the obtained knowledge to Room for the River projects in this reach. The Room for the River project 'floodplain excavation Avelingen' has been chosen as case study.

Method
Three methods have been used to gain insight in the contribution of the tide to sediment transport and bed level changes in the Merwedes:

1. Analysis of simulated flow
- The flow has been simulated with a one-dimensional SOBEK TMR 2006 model of the Rhine-Meuse Delta.
- The relative influence of tide and river discharge on flow has been analysed by Fourier analysis of location depended time series.

2. Analysis of simulated sediment transport
- Sediment transport in the Merwedes has been simulated in Matlab by means of post-processing of the SOBEK results of the flow computations, because the morphological schematisation for the Merwede rivers is not available in the SOBEK TMR 2006 model. The model can therefore only be used for hydrodynamic simulations. In addition, SOBEK-RE has limited possibilities to compute the total sediment transport, because only the sediment transport models of Engelund and Hansen (1967) and Van Rijn (1993) can be used in SOBEK-RE.
- The analysis of simulated sediment transport focuses on the mean (or tidal-averaged) sediment transport. The mean sediment transport can be determined by means of a Fourier analysis of local time series of the sediment transport.

3. Analysis of simulated bed level changes
- At this moment, there is no up to date calibrated one-dimensional morphological model available for the Rhine-Meuse Delta in which the flow is accurately described. Therefore, it has been decided to extend the hydraulic one-dimensional SOBEK model of the Rhine-Meuse Delta with the processes sediment transport and morphology. The flow in this adjusted model has been simplified by neglecting salt intrusion, because SOBEK-RE cannot compute both salt intrusion and morphology.
- A uncalibrated and unverified model has been used in this study. Therefore, the analysis of the simulated bed level changes has been limited to determining the relative differences between simulations.

These methods also have been applied to case study Avelingen.

System description Merwedes

Based on the mentioned one-dimensional analysis of flow, sediment transport and morphology, the system description of the Merwedes can be refined. To improve the hydrodynamic a morphological simulations of the Merwedes, it is recommended to use the following ranking of modelling aspects. This ranking applies to the yearly sediment transport (or the expected value) and is relevant to simulations of the autonomous development of the bed level of the Merwedes.

1. Influence of river discharge

The influence of the river discharge on the mean sediment transport in the Merwedes is much larger than the tidal influence. The tidal influence depends strongly on the magnitude of the upstream river discharge. Therefore, the way in which the river discharge is schematised, has a large influence on simulations of flow, sediment transport and morphology.

2. Influence of choice of sediment transport model

The choice of a sediment transport model also has a larger influence on the mean sediment transport in the Merwedes than the presence of tidal flow. In addition, the results of morphological simulations are very sensitive to the choice of a transport model.

The adaptation time and length scales of the sediment transport in the Merwedes are such that the actual transport can be taken equal to the sediment transport capacity. The sediment transport in the Merwedes should be computed with a transport model for total load which includes both suspended load and bed load. For the Boven and Beneden Merwede, the sediment transport model of Van Rijn 2007 gives the best approximation of the measured sedimentation. The measured bed level of the Nieuwe Merwede covers only the shipping lane. It is therefore uncertain which sediment transport model gives the best results for the Nieuwe Merwede.

The occurring sediment transport mechanisms in the Merwedes should be studied in more detail to reduce the uncertainty in the simulated sediment transport.

3. Tidal influence

The presence of the tide has a significant effect on the flow, sediment transport and morphology of the Merwedes. The tidal influence in the Merwedes cannot be neglected, because of the following reasons:

- Neglecting the tide has a significant effect on the discharge distribution at the Merwedekop. The averaged inflow in the Beneden Merwede will be overestimated by 12.2 %. In addition, the tidal motion causes a flow circulation from the Beneden Merwede via the Merwedekop into the Nieuwe Merwede. Furthermore, the tide has a significant influence on sediment transport up to Sint Andries (Waal, 926 km).
- The tide decreases the mean sediment transport in the Boven Merwede and increases the mean sediment transport in the Beneden and Nieuwe Merwede.
- The tide decreases the effective (Waal) discharge of the Beneden Merwede with 850 m^3/s and decreases the effective (Waal) discharge of the Nieuwe Merwede with 150 m^3/s.

Both variations in river discharge and the tidal influence should be included in morphological studies of the Merwedes, because of interaction between river flow and tidal flow.

The influence of the tide on sediment transport in the Merwedes can best be represented by a spring-neap cycle. However, a less detailed tidal cycle is a reasonable approximation of the tidal influence on sediment transport in the Merwedes. Using a less detailed tidal cycle instead of a spring-neap cycle gives a small underestimation of the expected value of sediment transport and the expected value of sedimentation.

It is recommended to extend the theory of Van de Kreeke and Robaczewska (1993) about tidal-averaged sediment transport for cases in which tidal flow is dominated by residual flow, because the mean sediment transport in the Merwedes cannot be estimated by the present approximation of Van de Kreeke and Robaczewska. Flow in the Merwedes is not dominated by the M_2 tidal current, but by the residual current. Van de Kreeke and Robaczewska expressed the mean sediment transport in the ratio of tidal components of the flow velocity. This method is much faster than averaging time series of sediment transport over a long period.

4. Influence of salt intrusion
Salt intrusion in the Rhine-Meuse Delta also has a significant effect on flow and sediment transport in the Merwedes, because salt intrusion causes a increase of the mean water level in the Merwedes which leads to a decrease in mean flow velocity and mean sediment transport in the Merwedes. Neglecting salt intrusion gives deviations in mean sediment transport with the same order of magnitude as neglecting the tide in the Merwedes. Furthermore, the presence of salt in the Rhine-Meuse Delta leads to a decrease of sedimentation in the Boven Merwede and Beneden Merwede and an increase of sedimentation in the Nieuwe Merwede. The influence of salt intrusion on morphology is unknown, but could be serious.

Recommendations system description
It is recommended to make a calibrated one-dimensional model of the Rhine-Meuse Delta which includes the following processes: flow, salt intrusion, sediment transport and morphology. The model should be suitable to simulate the influence of tidal fluctuations, times series of upstream discharges and dredging activities. Such a model can be used for a further refinement of the system description of the Rhine-Meuse Delta.

A two-dimensional analysis of the tidal influence on sediment transport and bed level changes could give insight in the usability of a one-dimensional analysis. So, it can be assessed whether cross-section averaged parameters are representative for a two-dimensional situation.

Case Avelingen
Floodplain excavation Avelingen at Gorinchem is one of the measures within the framework of Room for the River. The buildings of industrial zone Avelingen cause a local narrowing of the river Boven Merwede. This increases the water level in case of extreme discharges. To give the river more space, the floodplain near the industrial zone Avelingen will be excavated and a side channel will be dug under the bridge.

Part of this graduation research is a case study of Avelingen. A qualitative morphological study has been compared with an one-dimensional analysis of the effects of floodplain excavation Avelingen on flow, sediment transport and morphology. A qualitative morphological study was done by Witteveen+Bos (2008) based on flow patterns as part of an environmental impact assessment of the Room for the River project Avelingen.

The results of case study Avelingen correspond reasonably well with the assessment by Witteveen+Bos (2008). Floodplain excavation Avelingen will cause a reduction of the sediment transport capacity in the main channel near the side channel and the inflow opening of the side channel. This is based on post-processing of hydraulic SOBEK results. In addition, the morphological effects of floodplain excavation Avelingen could be restricted to sedimentation of the main channel at the inflow opening of the side channel. This is based on one-dimensional morphological modelling with a uncalibrated, unverified model.

The morphological effects of floodplain excavation Avelingen should be studied in more detail by a two-dimensional model, because the effects on sediment transport and morphology of this measure cannot determined accurately with the used one-dimensional analysis. This could be combined with the study of other planned measures within the framework Room for the River.

1. INTRODUCTION

1.1. Motivation
The area of the Merwedes is a transition zone between a tide-dominated area and a river-dominated area. With increasing river discharge, the influence of river flow dominates in this part of the Rhine-Meuse Delta. The composition of the river bed of the Merwedes is also a transitional area, because of the presence of both sand and mud. It is unknown how sediment transport and morphology in this area are influenced by the complex interaction of tidal flow and river flow.

1.2. Problem description
There is a need for better understanding of the hydraulic and morphological processes to be able to explain the morphological changes in the area of the Merwedes and to be able to anticipate on these changes. This research contributes to a refinement of the system description of the Rhine-Meuse Delta by determining the influence of the tide on sediment transport and bed level of the Merwedes. Furthermore, the obtained knowledge has been applied to the case of floodplain excavation at Avelingen.

1.3. Objective
The aim of this study is to gain insight into the contributions of tidal flow and river flow to sediment transport and bed level changes in the Merwedes, with a view to application of the obtained knowledge to Room for the River projects in this reach. The Room for the River project “floodplain excavation Avelingen” has been chosen as case study.

1.4. Research questions
The following research questions have been formulated to achieve this aim:
1. What is the contribution of the tide to the occurring sediment transport in the Merwedes?
2. What is the tidal influence on bed level changes of the Merwedes?
3. To what extent will the application of acquired knowledge give other results of the qualitative study of the morphological effects of floodplain excavation Avelingen (Witteveen+Bos, 2008)?

1.5. Methods
Three methods have been used to gain insight in the contribution of the tide to sediment transport and bed level changes in the Merwedes:
1. Analysis of simulated flow
2. Analysis of simulated sediment transport
3. Analysis of simulated bed level changes

These methods also have been applied to case study Avelingen.

1.5.1. Analysis of simulated flow
The aim of the flow analysis is to gain insight into the tidal influence on the flow in the Merwedes, as flow is the driving force behind sediment transport.

The flow has been computed with a one-dimensional SOBEK TMR 2006 model of the Rhine-Meuse Delta.[1] The choice of this hydraulic model is based on the accurate description of the flow, the driving force behind sediment transport. This model is calibrated on water levels (De Deugd, 2007, p. 13) and salt intrusion (Van Zetten, 2005, p. 19). The model is verified for the year 2004 (De Deugd, 2007, p. 16) and is used by the river manager for the assessment of the flood defences (De Deugd, 2007, p. 5). A time step of 10 minutes and a spatial step of 500 up to 1000 m have been used in this model.

The simulated flow has been analysed by means of a Fourier transformation with a discretization along the frequency axis, a discrete variant of a Fourier analysis. A harmonic analysis is in this case not

[1] In Dutch: SOBEK TMR 2006 Benedenrivierengebied.

necessary, because the simulated time series does not contain any additional noise of wind and flood waves.[2] The relative influence of tide and river discharge on flow has been determined by this Fourier analysis.

The length of the analysed time series are long enough to distinguish a spring-neap cycle, the interaction between M_2 and S_2. The length of the time series is 30 days and 13 hours which corresponds to the analysis of the Ems estuary by Van de Kreeke and Robaczewska (1993, p. 215). The corresponding frequency resolution is $3.78 \cdot 10^{-7}$ Hz (Deltares 2009, p. 76). To distinguish M_2 and S_2, the duration of the time series must be at least 14 days and 18 hours according to the Rayleigh criterion (Deltares 2009, p. 76). The Rayleigh criterion requires that the relative phase difference over the total duration of the times series must be at least 360 degrees to distinguish two neighbouring tidal components. In addition, the time step of 10 minutes gives a Nyquist frequency of $8.33 \cdot 10^{-4}$ Hz.

1.5.2. Analysis of simulated sediment transport

The aim of the one-dimensional analysis of sediment transport is to gain insight into the contribution of the tide to sediment transport in the Merwedes.

Sediment transport in the Merwedes has been simulated in Matlab by means of post-processing of the SOBEK results of the flow computations, because the morphological schematisation for the Merwede rivers is not available in the SOBEK TMR 2006 model. The model can therefore only be used for hydrodynamic simulations. In addition, SOBEK-RE has limited possibilities to compute the total sediment transport, because only the sediment transport models of Engelund and Hansen (1967) and Van Rijn (1993) can be used in SOBEK-RE.

The analysis of simulated sediment transport focuses on the mean sediment transport. The mean sediment transport is defined as a sediment transport which is averaged over a tidal period. The mean sediment transport can be determined by means of a Fourier analysis of local time series of the sediment transport.

An indication of the expected value of the sediment transport (or the yearly sediment transport) can be obtained by including the probability of a certain upstream river discharge. The way in which the expected value of the sediment transport has been determined, is described in Appendix III.

A simple sediment balance has been used to calculate sedimentation and erosion per river branch. The sediment balance is defined by the difference between inflow of sediment at the upstream side and outflow of sediment at the downstream side. Sedimentation and erosion are strongly related to the next part of this research: the tidal influence on the bed level of the Merwedes. The simulated expected value of sedimentation and erosion which is derived from post-processing of flow simulations, have been compared with measured bed volume changes and data of dredging volumes.

1.5.3. Analysis of simulated bed level changes

The aim of the analysis of bed level changes is to gain insight into the contribution of the tide to bed level changes in the Merwedes, taking into account variations and uncertainties of the river discharge, maintenance dredging and sand mining.

At this moment, there is no up to date calibrated one-dimensional morphological model available for the Rhine-Meuse Delta in which the flow is accurately described. Therefore, it has been decided to extend the hydraulic one-dimensional SOBEK model of the Rhine-Meuse Delta[3] with the processes sediment transport and morphology. The flow in this adjusted model has been simplified by neglecting salt intrusion, because SOBEK-RE cannot compute both salt intrusion and morphology.

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[2] According to dr.ir. G. Klopman, personal note on April 1, 2010.

[3] In Dutch: SOBEK TMR 2006 Benedenrivierengebied.

In this study, a uncalibrated, unverified model has been used. Therefore, the analysis of the simulated bed level changes has been limited to determining the relative differences between simulations.

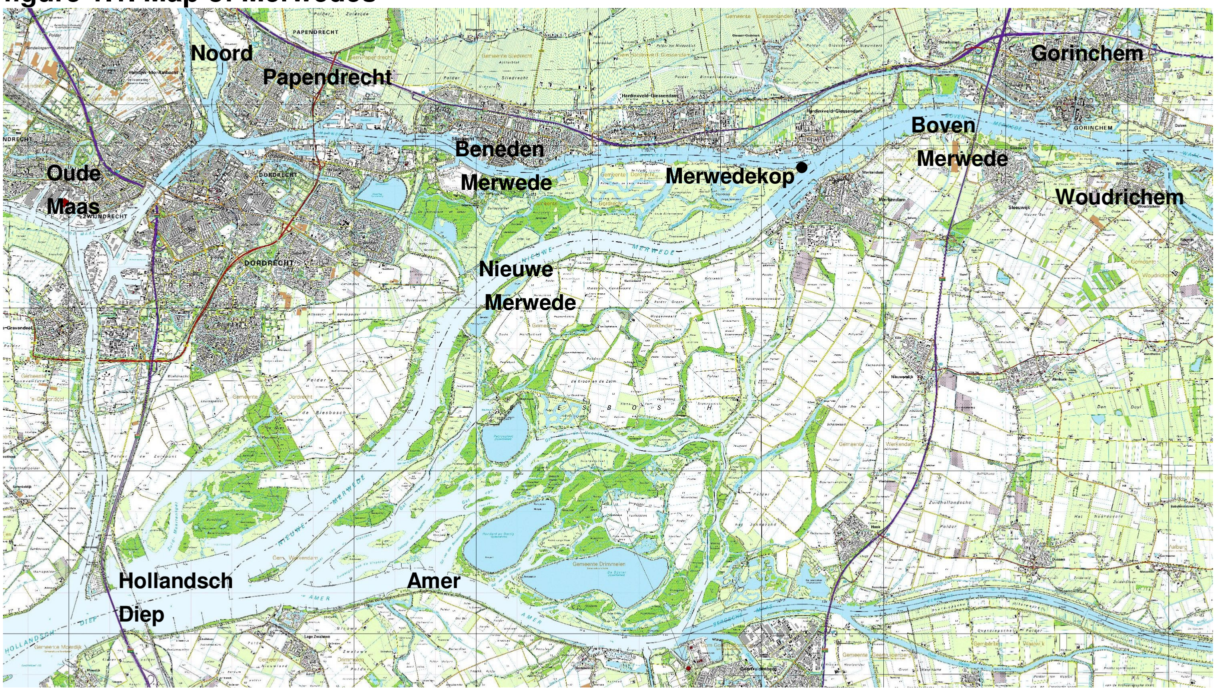
1.6. Characteristics of the study area

1.6.1. Area of interest

This research has been oriented towards the river reaches Boven Merwede, Beneden Merwede and Nieuwe Merwede (figure 1.1). However, the Merwedes cannot be separated from the larger system: the Rhine-Meuse Delta (figure 1.2). The Rhine-Meuse Delta also is named the Northern Delta Basin and the Lower River Area.[4]

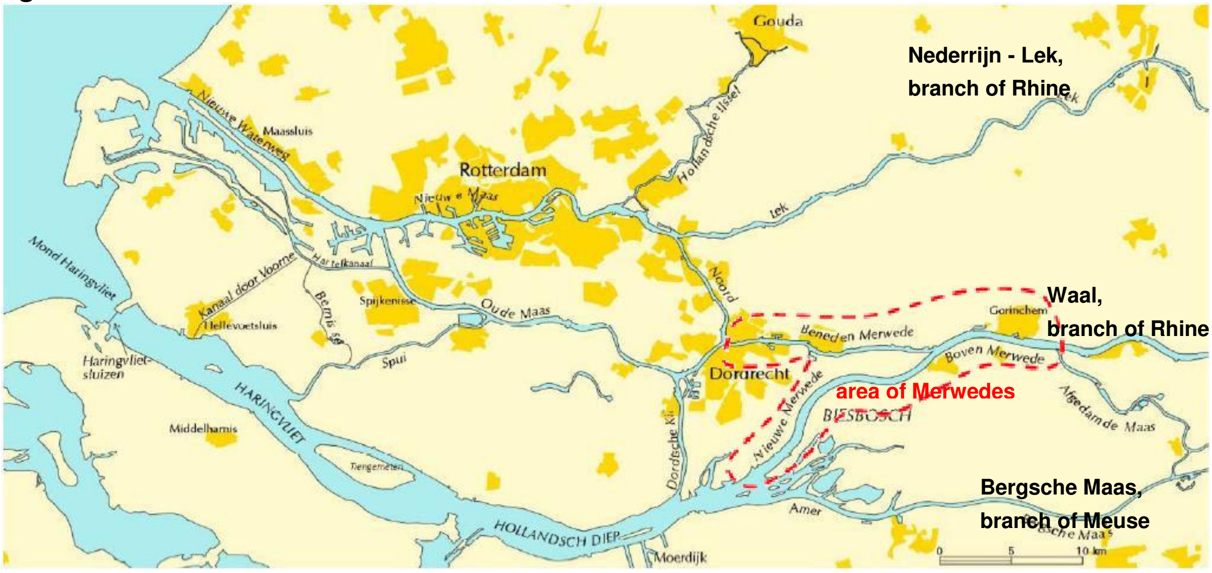
The extension of the Waal has the name Boven Merwede downstream of Woudrichem. At the Merwedekop, the Boven Merwede bifurcates into the Beneden Merwede and Nieuwe Merwede. The Beneden Merwede flows in western direction and bifurcates near Papendrecht in the Noord and the Oude Maas. The Nieuwe Merwede flows in south-western direction, cuts through the Biesbosch and confluences with the Amer in the Hollandsch Diep.

figure 1.1. Map of Merwedes



[4] In Dutch: Rijn-Maasmonding, Noordelijk Deltabekken en Benedenrivierengebied.

figure 1.2. Overview of Rhine-Meuse Delta



Source: Snippen, E., et al. (2005, p. 13)

1.6.2. Relevant processes

This section describes the relevant processes with respect to flow, sediment transport and morphology.

Flow

Rhine-Meuse Delta

The flow in the Rhine-Meuse Delta is mainly influenced by the discharge of the rivers Rhine and Meuse, the intrusion of the tide from the North Sea and the flushing regime of the Haringvliet sluices. The tidal wave enters via the Nieuwe Waterweg near Hook of Holland the Rhine-Meuse Delta. The Haringvliet sluices are the tap of the Rhine-Meuse Delta. The distribution of the discharges of the Rhine and the Meuse over the Nieuwe Waterweg and the Haringvliet are influenced by (partly) opening or closing of the gates of the Haringvliet sluices. In this way, a residual discharge of at least 1500 m^3/s is maintained in the Nieuwe Waterweg. This is very important for counteracting the salt intrusion into the river. The residual discharge is the difference between the ebb discharge and the flood discharge over one tidal period. At the current management of the Haringvliet sluices (LPH ’84), the sluice gates are always closed at flood and the size of the openings of the sluices at ebb depends on the river discharge.

The wind also influences the water level in the Rhine-Meuse Delta. Rise of the water level due to wind action in the North Sea causes higher water levels in the delta which has a backwater effect on the water levels of the rivers. In addition, local wind affects flow in the Rhine-Meuse Delta.

Further, flow is influenced by the density difference between fresh river water and salt sea water. This density difference causes stratified flow in the western part of the Rhine-Meuse Delta.

Merwedes

The flow in the Merwedes varies both by variations in river discharge as by tidal motion. The flow distribution at bifurcation Merwedekop is not constant, because of the tidal influence (Frings, 2005) and the management of the Haringvliet sluices. The tidal variations of the water level in the area of interest are between 0.3 and 0.8 m under averaged circumstances. Flow reversal occurs only in the Beneden Merwede in case of low river discharges.

Sediment transport and morphology

Flow is the driving force behind sediment transport. Spatial variations in sediment transport cause bed level changes. Large-scale bed level changes will influence flow and sediment transport.

The bed material in the Merwedes has a spatially varying composition. The Boven Merwede mainly contains coarse sand. A mud fraction is present in the downstream part of the Nieuwe Merwede and in a part of the Beneden Merwede. Furthermore, fine sand fractions are present in the Merwedes (Medusa, 2002; Snippen, E., et al., 2005).

Based on variations in hydrodynamic conditions and spatial variations in bed composition, there are different transport mechanisms in the Merwedes. Frings (2005) concluded that both suspended load and bed load are of importance.

1.6.3. Relevant developments

Recent historical developments

In the recent history, several human interventions are carried out in the Rhine-Meuse Delta.

Constructing the Haringvlietdam (1957 – 1970) and the Haringvliet sluices (1970) caused large differences in flow and sediment balance of the Rhine-Meuse Delta. In the seventies, this gave large-scale sedimentation in the Haringvliet, the Hollandsch Diep and the Merwedes. But they also initiated large-scale erosion in the Oude Maas and Dordtse Kil.

The fairways are maintained by means of dredging. In addition, sand mining takes place in the Merwedes. This causes deepening of the Merwedes. This deepening lowers the water level which has a backwater effect. To prevent continued decrease of the bed level of the Boven Merwede and to prevent an upstream water level decrease, the volume of sand mining is halved since 2007 (Ciarelli, 2009).

The last years, the following projects have been realised:

- Opening Beerdam
- Clean-up of the Sliedrechtse Biesbosch
- Nature development in the polders ‘Kort en Lang Ambacht’ and ‘Ruigten bezuiden den Perenboom’ in the Sliedrechtse Biesbosch
- Room for the River project Zuiderklip in the Brabantse Biesbosch
- Nature development in the Noordwaard as part of Room for the River

Future developments

Several relevant measures are planned in the area of the Merwedes and in the Rhine-Meuse Delta.

From December 2010 onwards, the management of the Haringvliet sluices will be changed. The actual flushing regime LPH ’84 will be replaced by a management in which the Haringvliet sluices are not only open during ebb, but are also partly open during flood. The tidal intrusion in the Rhine-Meuse Delta will practically not change by the new regime “de Kier” of Haringvliet sluices (Burgers, 2004).

The following interventions are planned as part of Room for the River in the area of the Merwedes:

- Depoldering of the Noordwaard
  Inflow openings and outflow openings are created by partly excavation of dikes.
- Floodplain excavation Avelingen
  A side channel will be excavated in the floodplain of industrial zone Avelingen near Gorinchem.
- Dike improvement Steurgat
- Embankment lowering Biesbosch

In addition, the floodplain excavation of the Brakelse Benedenwaarden and the dike relocation of Buitenpolder Het Munnikenland are planned direct upstream of the Boven-Merwede

A prospective lowering of the waterway of the Beneden Merwede will be investigated in another study. To maintain the waterways of the Merwedes, maintenance dredging is also needed in future.

1.7. Outline

The outline of this report is as follows:

The refinement of the system description of the Merwedes is included in chapter 2, 3 and 4. Flow in the Merwedes is described in chapter 2. Chapter 3 contains a description of sediment transport in the Merwedes. A description of bed level changes in the Merwedes is included in chapter 4.

Chapter 5 describes the case study Avelingen.

A brief overview of the conclusions and recommendations of this study is given in chapter 6.

2. FLOW

2.1. Introduction

Flow is the driving force behind sediment transport. Therefore, insight into the interaction of tidal flow, river flow and salt intrusion forms the basis of the system description of the Merwedes. The approach of analysing flow in the Merwedes is included in section 2.2. Section 2.3 describes the interaction of the tide and the river discharge. The influence of salt intrusion on flow in the Merwedes is included in section 2.4. Section 2.5 contains the conclusions with respect to flow in the Merwedes.

2.2. Approach

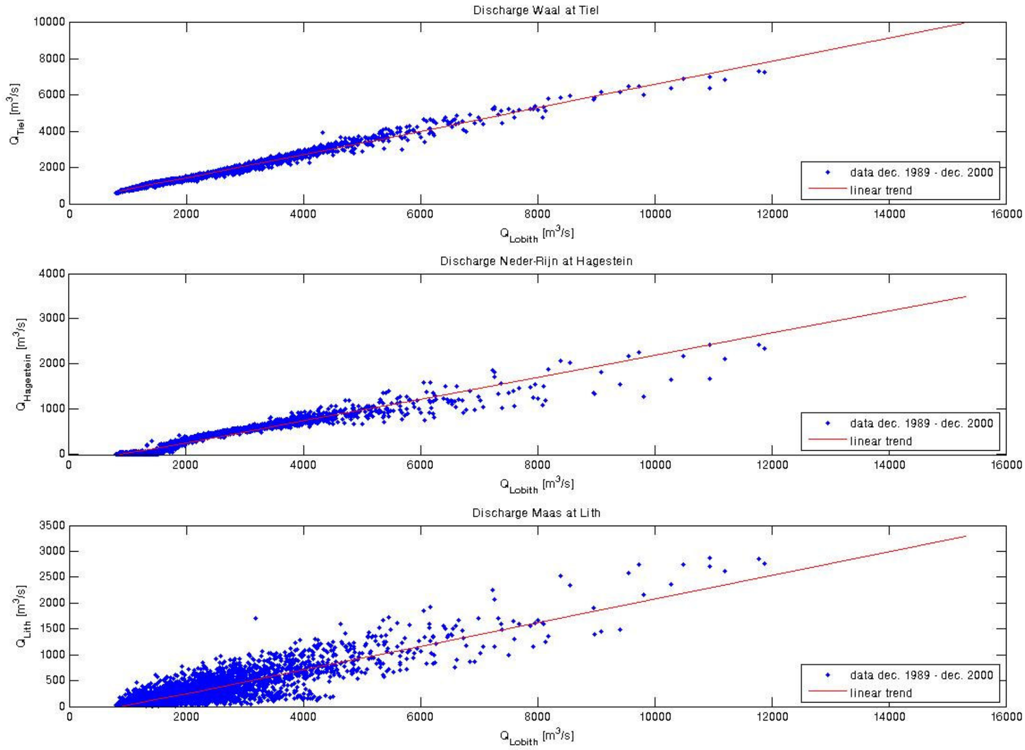
Flow in the Merwedes is influenced by the magnitude of the river discharge, the presence of the tide and by salt intrusion. The way in which these influences have been studied, is described in this section. In addition, this section contains the underlying assumptions of the analysis of flow in the Merwedes.

2.2.1. Influence of river discharge

The influence of the upstream river discharge on flow in the Merwedes has been studied by means of flow simulations with several stationary discharges. All variations in time during a flow simulation are attributed by tidal variations, when stationary upstream discharges are used. That serves to make studying tidal effects easier. A disadvantage of using stationary discharges is that time effects of flood waves are neglected.

At the upstream boundaries of the SOBEK model of the Rhine-Meuse Delta a river discharge has been imposed on the Waal at Tiel, the Nederrijn at Hagestein and the Meuse at Lith. The magnitude of the river discharges of the Waal, the Nederrijn and the Meuse has been estimated by plotting the daily averaged discharge from the period December 1989 - December 2000 (Rijkswaterstaat, 2010) against the daily averaged discharge of the Boven-Rijn at Lobith. A trend line has been determined with this data. This is visible in figure 2.1. The relation between the discharge at Lobith and the discharges at Tiel and Hagestein follows logically from the fact that Lobith lies upstream of Tiel and Hagestein. There is also a link between the discharge at Lobith and Lith. High Rhine discharges often coincide with high Meuse discharges (De Waal 2007, p. 36). According to Van der Linden (2001, p. 15), the discharges of the Rhine and Meuse are reasonably correlated, because of the correlation between the rainfall in the catchments. In this analysis, stationary discharges have been used according to the trend lines.

figure 2.1. Discharges of the Waal, Nederrijn and Meuse as function of the discharge at Lobith



The applied stationary upstream boundary conditions are given in table 2.1. The discharge of the Waal at Tiel is important for the flow in the Merwedes, because the upstream inflow of the Boven Merwede comes from the Waal. The discharges have been chosen such that the almost entire reach of discharges has been studied. The differences between two successive discharges in table 2.1 has been chosen such that the differences are relative small around the mean discharge of the Waal. The mean discharge of the Waal at Tiel is 1591 m^3/s, which is based on daily averaged time series derived from the period January 1989 to January 2005 (Rijkswaterstaat (2009)).

table 2.1. Simulated upstream boundary conditions

discharge at Lobith [m^3/s]	discharge at Tiel [m^3/s]	discharge at Hagestein [m^3/s]	discharge at Lith [m^3/s]
857	700	0	0
1478	1100	125	128
2178	1550	295	288
2878	2000	465	447
4121	2800	767	731
5987	4000	1219	1158
9097	6000	1974	1868
12206	8000	2728	2578
15315	10000	3482	3288

A restricted number of stationary discharges has been simulated in the flow analysis. The used differences between successive discharges are 450 m^3/s up to 2000 m^3/s. Doing more simulations with other discharges could give a more detailed insight in the flow in the Merwedes.

2.2.2. Tidal influence

Water level time series should be imposed at the seaward side of the SOBEK model at the mouth of the Haringvliet and at the mouth of the Nieuwe Waterweg near Hook of Holland. Three types of sea boundary conditions have been studied, each with an interval of 10 minutes:

- a spring-neap cycle,
- a schematised tidal cycle,
- a constant water level.

Spring-neap cycle

A spring-neap cycle is a realistic description of the tidal motion on the North Sea. The used spring-neap cycle is not a spring-neap cycle in strict sense, but also contains diurnal tidal components. The data of the spring-neap cycle comes from tidal predictions at the locations Haringvliet-10 and Hook of Holland in the period March to May 2008 (Rijkswaterstaat, 2009). To convert the tidal predictions to boundary conditions for the SOBEK model, the methodology of De Deugd (2007, p. 18) has been followed. A water level amplitude spectrum of the spring-neap cycle is given in the left subfigure of figure 2.2. The narrow peaks of at the frequencies of the tidal components are striking in this figure. This water level amplitude spectrum also shows the principle of Fourier analysis. In the tidal analysis, the main tidal components have been highlighted: O_1, M_2, S_2, M_4 and M_6, but the other tidal components, like SM, K_1, N_2, MU_2, MS_4, $2MS_6$ and $3MS_8$ also have been included in this study.

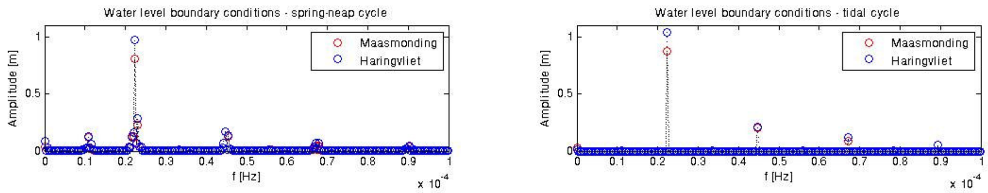
Schematised tidal cycle

A schematised tidal cycle is a simplification of a spring-neap cycle. This schematised tide contains just the lunar M_2 tide and the shallow water components M_4, M_6 and M_8. The length of this tidal cycle is 12 hours and 25 minutes which is much shorter than the length of the spring-neap cycle. The tidal cycle comes from the basis series of the normal tide[5], described in De Deugd (2007, p. 18). This series is derived for TMR 2006 model. The lunar component is in the schematised tide larger than in the spring-neap cycle, because the lunar component also contains contributions of other semi-diurnal components. Through this, the tidal cycle looks like a morphological tide. A water level amplitude spectrum of the schematised tidal cycle is given in the right subfigure of figure 2.2.

Constant water level

A constant water level at sea means neglecting the tidal influence. The used constant water level is equal to the mean tide level of the schematised tidal cycle.

figure 2.2. Water level amplitude spectrum of boundary conditions; spring-neap cycle (left subfigure) and tidal cycle (right subfigure)



An overview of the main tidal components in the boundary conditions is presented in table 2.2.

[5] In Dutch: basisreeks gemiddeld getij.

table 2.2. Main tidal components in boundary conditions

Name	Frequency [Hz]	Period [h]	Amplitude Maasmonding spring-neap cycle [m]	Amplitude Maasmonding tidal cycle [m]	Amplitude Haringvliet spring-neap cycle [m]	Amplitude Haringvliet tidal cycle [m]
mean			0.041	0.031	0.083	0.011
O_1	$1.081 \cdot 10^{-5}$	25.70	0.120	-	0.126	-
M_2	$2.237 \cdot 10^{-5}$	12.42	0.808	0.874	0.967	1.041
S_2	$2.312 \cdot 10^{-5}$	12.01	0.231	-	0.287	-
M_4	$4.474 \cdot 10^{-5}$	6.21	0.172	0.205	0.170	0.214
M_6	$6.711 \cdot 10^{-5}$	4.14	0.045	0.091	0.068	0.122

2.2.3. Influence of salt intrusion

If the influence of sea boundary conditions is studied, also the relevant properties of sea water should be studied. The density of sea water also is a sea boundary condition. The salt sea water and the fresh river discharge meet each other in the Rhine-Meuse Delta. The influence of salt intrusion on flow in the Merwedes has been studied by a comparison of simulations with salt intrusion and simulations without salt intrusion.

2.2.4. Assumptions

It is assumed that the one-dimensional SOBEK model “TMR 2006 Benedenrivierengebied” gives an accurate description of the flow in the Rhine-Meuse Delta so that calibration and validation is unnecessary. This has been shown by verification by RIZA (De Deugd, 2007, p. 51).

In the flow computations with SOBEK the following aspects have been neglected:
- The influence of storm set-up at the seaward boundary
- The influence of local wind within the model area
- The influence of two-dimensional and three-dimensional effects
- Time effects of flood waves (e.g. hysterese)
- The influence of changes in the control of the Haringvliet sluices

The effects of planned river widening projects have not been included, except the Room for the River project Noordwaard. Phase I of the project Noordwaard has been included, as described in De Waal (2007, p. 65).

The mean tide level of the tidal cycle and the constant water level corresponds to a mean tide level in 2006. According to De Deugd (2007, p. 18), the sea level rise at the mouth of the Haringvliet and Nieuwe Waterweg is 5 cm in the period 1985 to 2006. This has been based on the assumption that the sea level rise has an order of magnitude of 0.25 m per century.

2.3. Tide versus river

This section describes the influence of the tide relative to the upstream discharge on flow in the Waal and Merwedes.

Waal - Boven Merwede

The influence of the tide and upstream discharge on flow in the Waal - Boven Merwede is visualized in figure 2.3. The left subfigures show the mean and tidal amplitudes of the discharge. The right subfigures show the mean and tidal amplitudes of the flow velocity. The horizontal axis represents the location along the river.[6] The upstream discharge at Tiel is on the vertical axis.

[6] In the figures in this report, the upstream side is at the right side.

figure 2.3. Mean and amplitudes of the discharge (left subfigures) and flow velocity (right subfigures) in the Waal - Boven Merwede as function of the location and upstream discharge

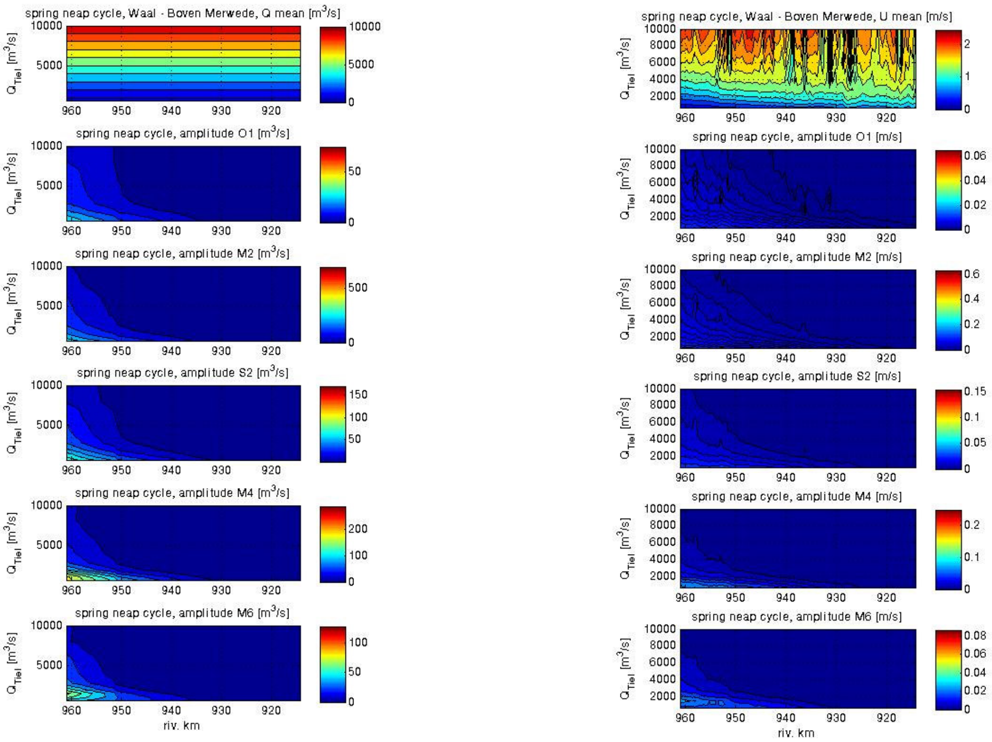
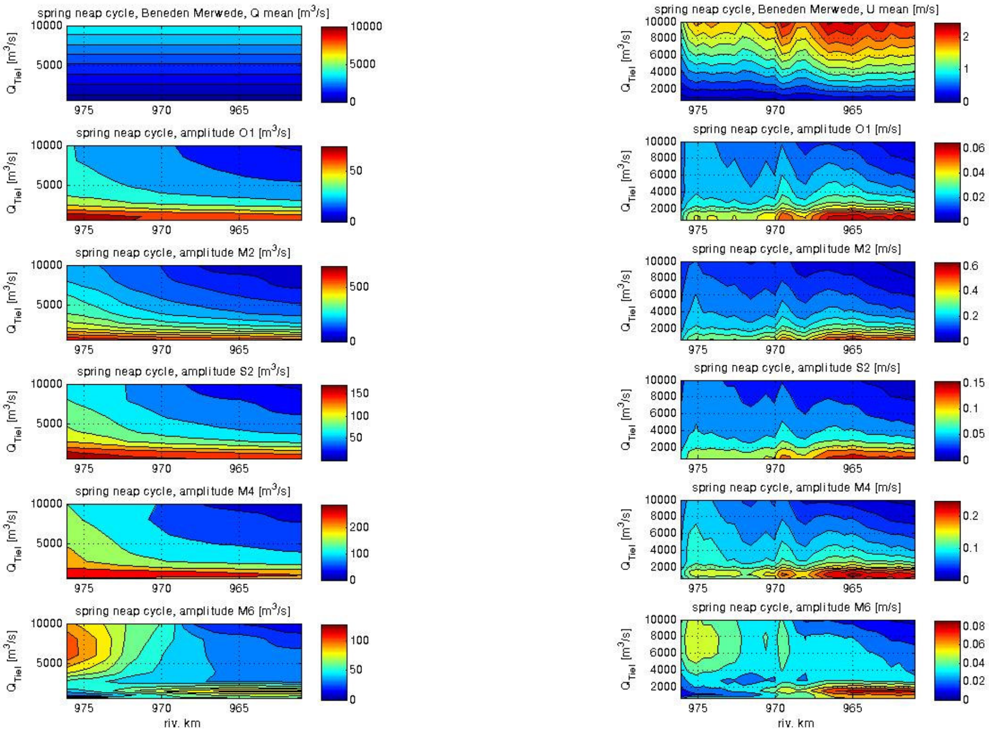


Figure 2.3 shows that the flow in the Waal - Boven Merwede is dominated by the river discharge. This is visible in the right top subfigure: the mean flow velocity increases strongly with increasing river discharge. The spatial variations in mean flow velocity shows that flow in the Waal - Boven Merwede is not uniform along the river.

Tidal intrusion is affected by the magnitude of the upstream river discharge. This is visible in the subfigures of the discharge amplitude between 940 and 961 km. For increasing river discharge, the tidal intrusion in the Waal - Boven Merwede decreases.

Beneden Merwede
The influence of the tide and upstream discharge on flow in the Beneden Merwede is visualized in figure 2.4. The left subfigures show the mean and tidal amplitudes of the discharge. The right subfigures show the mean and tidal amplitudes of the flow velocity. The horizontal axis represents the location along the river. The upstream discharge at Tiel is on the vertical axis.

figure 2.4. Mean and amplitudes of the discharge (left subfigures) and flow velocity (right subfigures) in the Beneden Merwede as function of the location and upstream discharge



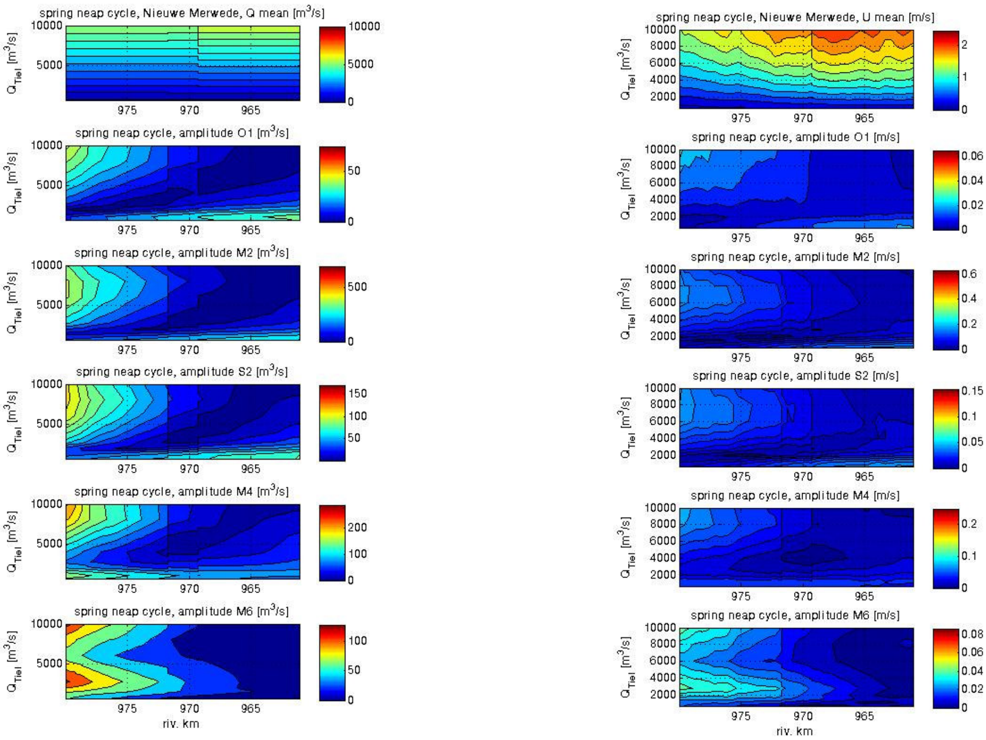
The tidal influence in the Beneden Merwede is much larger than in the Waal - Boven Merwede. As can be seen by comparing figure 2.4 with figure 2.3 in which the same scale is used for each subfigure. This is not surprising, because the Beneden Merwede is downstream of the Waal - Boven Merwede. The influence of the tide in the Beneden Merwede decreases with increasing river discharge.

Tidal fluctuations of the discharge Q are largest in the downstream part of the Beneden Merwede. However, tidal fluctuations of the flow velocity U are largest in the upstream part of the Beneden Merwede. This indicates a downstream widening of the cross-section of the river branch. The deceleration of the mean flow velocity (right top subfigure) also indicates a downstream widening of the Beneden Merwede.

Nieuwe Merwede

The influence of the tide and upstream discharge on flow in the Nieuwe Merwede is visualized in figure 2.5. The left subfigures show the mean and tidal amplitudes of the discharge. The right subfigures show the mean and tidal amplitudes of the flow velocity. The horizontal axis represents the location along the river. The upstream discharge at Tiel is on the vertical axis.

figure 2.5. Mean and amplitudes of the discharge (left subfigures) and flow velocity (right subfigures) in the Nieuwe Merwede as function of the location and upstream discharge



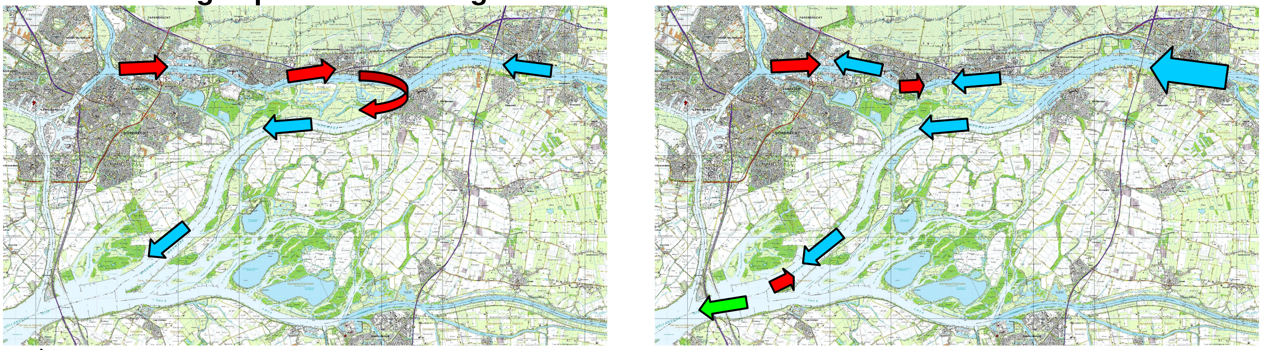
Abrupt spatial changes in discharge and flow velocity are visible in figure 2.5 at 969 km and 972 km. These abrupt spatial changes are caused by the schematisation of the Nieuwe Merwede in the one-dimensional SOBEK model. Several branches of the Biesbosch are connected to the Nieuwe Merwede. The deceleration of the mean flow velocity (right top subfigure) in the Nieuwe Merwede is caused by downstream widening of this river branch.

The tidal influence on flow in the Nieuwe Merwede is considerably less than in the Beneden Merwede. As can be seen by comparing figure 2.5 with figure 2.4 in which the same scale is used for each subfigure.

The upstream river discharge has a remarkable influence on the flow in the Nieuwe Merwede. This is visible in the subfigures with tidal amplitudes O_1, M_2 and S_2 of the discharge (figure 2.5).

- In situations with a small upstream river discharge, the tide comes via the upstream side of the Nieuwe Merwede. In these situations, the tidal wave intrudes via the Northern part of the Rhine-Meuse Delta into the Beneden Merwede and via the Beneden Merwede into the Nieuwe Merwede and Boven Merwede. An overview of these situations is given in the left subfigure of figure 2.6.
- In the situation with a large upstream river discharge, the tidal wave enters through the downstream side. This could be the effect of periodical outflow at the Haringvliet sluices. At the current management of the Haringvliet sluices (LPH ’84), the sluices are always closed at flood (Ministerie van Verkeer en Waterstaat, 2009, p. 5). At ebb tide, the gates of the sluices are further opened for increasing river discharge. The shallow water components M_4 and M_6 seem to come always from the downstream side of the Nieuwe Merwede. An overview of these situations is given in the right subfigure of figure 2.6.

figure 2.6. Overview of influence of upstream discharge on flow in the Nieuwe Merwede; at the left side a situation with a small upstream discharge; at the right side a situation with a large upstream discharge

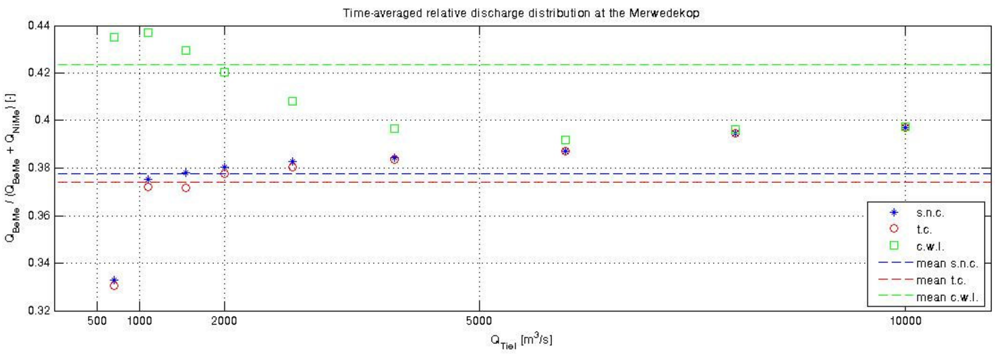


river discharge
tidal intrusion
discharging via Haringvliet sluices

Merwedekop

At the Merwedekop the Boven Merwede bifurcates into the Beneden Merwede and the Nieuwe Merwede. The discharge distribution at the Merwedekop is influenced by both tidal flow and river flow. This is visualised in figure 2.7, which gives the time-averaged relative discharge distribution at the Merwedekop: $\frac{\overline{Q_{Beneden\_Merwede}}(Q_{Tiel})}{\overline{Q_{Beneden\_Merwede}}(Q_{Tiel})+\overline{Q_{Nieuwe\_Merwede}}(Q_{Tiel})}$. The horizontal axis represents the influence of river flow by means of the upstream discharge. The time-averaged relative discharge distribution is on the vertical axis. The markers correspond to simulations with various upstream discharges. The effect of three types of sea boundary conditions have been simulated: a spring-neap cycle (s.n.c), a less detailed tidal cycle (t.c.) and a constant water level.

figure 2.7. Time-averaged relative discharge distribution at the Merwedekop as a function of the upstream discharge for 3 different types of sea boundary conditions: spring-neap cycle (s.n.c.), tidal cycle (t.c.) and a constant water level (c.w.l.)



On average, 37.7 % of the upstream river discharge flows into the Beneden Merwede. This is consistent with the findings of Frings (2005, p. 32). If the discharge is smaller than 1100 m^3/s, the relative inflow of the Beneden Merwede is smaller. The relative inflow of the Beneden Merwede is larger in case of a high river discharge. This could have to do with the fact of the decreasing tidal influence for increasing upstream discharge. According to Frings (2005, p. 3), the river discharge in the Beneden Merwede is hampered during flood. When the tidal influence becomes smaller, the obstruction of the river discharge in the Beneden Merwede also decreases.

Neglecting the tide has large effects on the discharge distribution at the Merwedekop. The use of a downstream constant water level gives significant deviations in the discharge distribution. On average, 42.3 % of the upstream river discharge flows into the Beneden Merwede when a constant water level is used. The use of a constant water level instead of a spring-neap cycle causes an increase in the average discharge of the Beneden Merwede of 12.2 %. In accordance with Buschman (2010, p. 10), the effect of the tide is to enhance unequal river discharge distribution for large width differences between two sea-connected channels: the tide increases the inflow to the wider Nieuwe Merwede.

The use of a tidal cycle instead of a spring-neap cycle as a seaward boundary condition is a reasonable approximation, because the differences in flow results between a spring-neap cycle and a tidal cycle are small. The differences in mean flow velocity between these two types of boundary conditions are also small. The lunar component M_2 is slightly higher for a tidal cycle. The shallow water components M_4 and M_6 are larger for a spring-neap cycle. On average, 37.4 % of the upstream river discharge flows into the Beneden Merwede when a tidal cycle is used. The use of a tidal cycle instead of a spring-neap cycle causes a decrease in the average discharge of the Beneden Merwede of 0.8 %.

The discharge distribution at the Merwedekop varies during a spring-neap cycle. This is visible in figure 2.8, which shows the expected value of the relative discharge distribution at the Merwedekop during a spring-neap cycle: $\frac{Q_{Beneden\_Merwede}(t)}{Q_{Beneden\_Merwede}(t)+Q_{Nieuwe\_Merwede}(t)}$.

- When the sign of the relative discharge distribution is positive in figure 2.8, the discharge of the Boven Merwede is divided over the Beneden Merwede and Nieuwe Merwede. This is the case during ebb and during a neap tide. These situations are visualised in the left subfigure of figure 2.9.
- When the sign of the relative discharge distribution is negative in figure 2.8, the tide causes reversal of flow in the Beneden Merwede. The tidal wave intrudes via the Beneden Merwede into the Boven Merwede and Nieuwe Merwede. The upstream discharge of the Waal - Boven Merwede goes in that case into the Nieuwe Merwede. This is the case during flood at small upstream discharges (see figure 2.5. An qualitative overview of these situations is given in the right subfigure of figure 2.9. Therefore, the tidal motion causes a flow circulation from the Beneden Merwede via the Merwedekop into the Nieuwe Merwede.

figure 2.8. Expected value of the relative discharge distribution at the Merwedekop during a spring-neap cycle

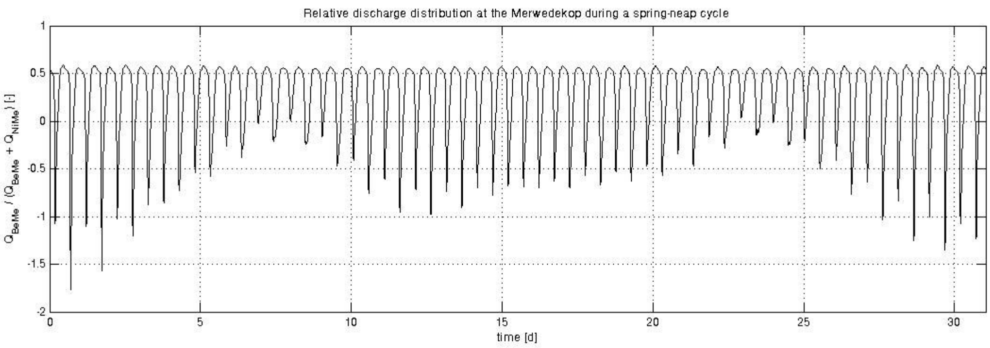
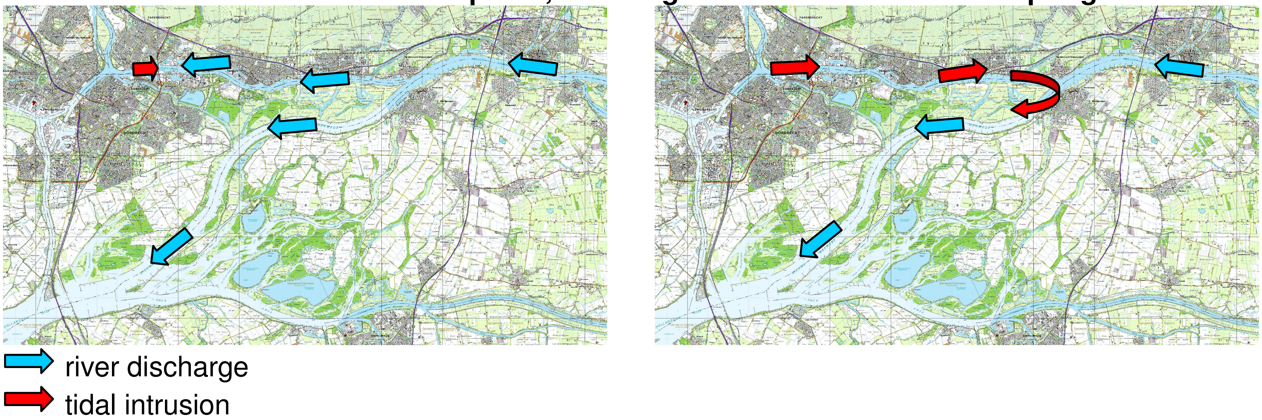


figure 2.9. Overview of influence of tidal motion on flow in the Nieuwe Merwede; at the left side a situation with ebb or neap tide; at the right side a situation with a spring tide

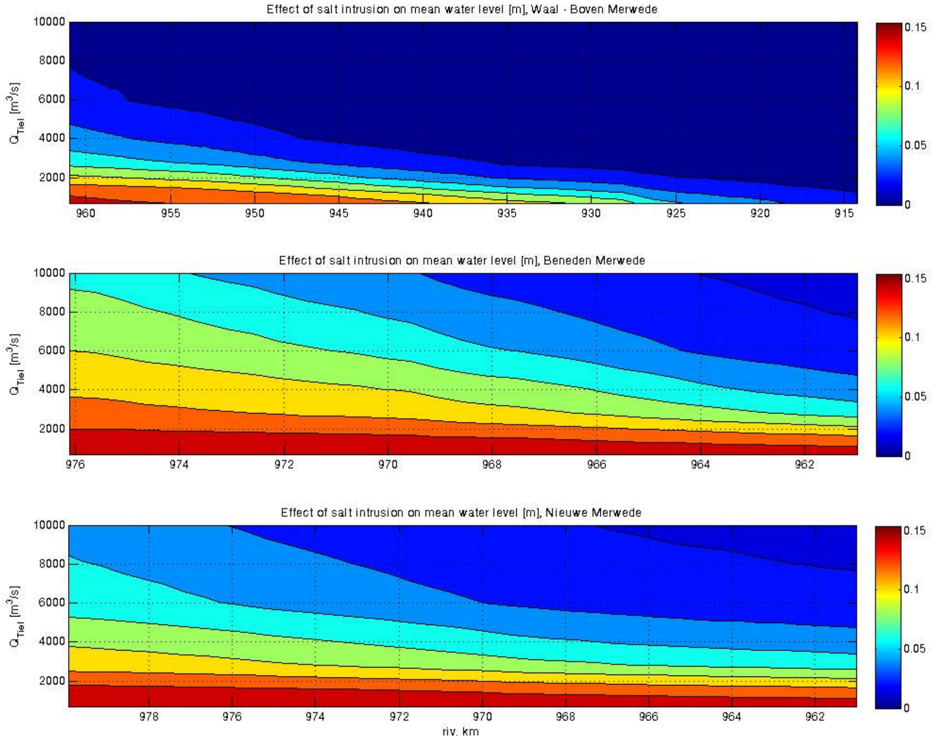


2.4. Salt intrusion

Salt intrusion in the Rhine-Meuse Delta increases the mean water level in the Waal and Merwedes. The effect of salt intrusion on the mean water level in the Merwedes is visualised in figure 2.10. The horizontal axis represents the location along the river. The upstream discharge is on the vertical axis. The effect of salt intrusion decreases for increasing river discharge and decreases in upstream direction. The maximum effect of salt intrusion on the mean water level in the Merwedes is 0.15 m. This is in accordance with Van der Linden and Van Zetten (2001, p. 51).

The salt does not intrude the Merwedes (not visualised), but the downstream presence of salt affects the water movement in a large part of the Rhine-Meuse estuary. At the location of the salt wedge, the water level gradient is enlarged by the horizontal density gradient between salt and fresh water. In addition, the effective water depth is smaller by the presence of the salt wedge. This also increases the water level gradient. This increase in water level has a backwater effect which extends to the Waal and Merwedes which is visible in figure 2.10.

figure 2.10. Effect of salt intrusion in Rhine-Meuse Delta on mean water level of Waal and Merwedes



The averaged discharge distribution at the Merwedekop is affected to a small extend by salt intrusion in the Rhine-Meuse Delta. Salt intrusion causes an increase of the relative tidal-averaged inflow in the Beneden Merwede with 2.5 % (not visualised).

2.5. Conclusions

Based on (Fourier) analysis of flow simulations, the following conclusions can be drawn with respect to flow in the Merwedes.

Tidal influence

- The tidal influence on flow in the Merwedes cannot be neglected, because of the following reasons:
  - Neglecting the tide has a significant effect on the discharge distribution at the Merwedekop: the tidal averaged inflow in the Beneden Merwede will be overestimated by 12.2 %.
  - The tidal motion causes a flow circulation from the Beneden Merwede via the Merwedekop into the Nieuwe Merwede.
- The tidal fluctuations in the Beneden Merwede are much larger than in the Waal, Boven Merwede and Nieuwe Merwede.

Influence of river discharge

- The Waal, Boven Merwede and Nieuwe Merwede are dominated by river flow.
- For increasing river discharge, the tidal intrusion decreases in the Boven Merwede.
- The influence of tidal components decreases for increasing river discharge.

Influence of salt intrusion

Salt intrusion in the Rhine-Meuse Delta has a significant effect on flow in the Merwedes.

- The mean water level in the Merwedes is increased by the backwater effect of salt intrusion.
- The influence of salt intrusion decreases for increasing river discharge.

Influence of human intervention

- Flow in the Nieuwe Merwede is influenced by the management of the Haringvliet sluices.

3. SEDIMENT TRANSPORT

3.1. Introduction

This chapter describes the sediment transport in the Merwedes. The approach followed for analysis of sediment transport in the Merwedes is included in section 3.2. Section 3.3 describes the influence of the tide relative to the upstream discharge on sediment transport. The effect of salt intrusion in the Rhine-Meuse Delta on mean sediment transport in the Merwedes is presented in section 3.4. Sediment transport mechanisms in the Merwedes are described in section 3.5. Section 3.6 contains a comparison of the simulated expected sedimentation with measurements. The conclusions with respect to sediment transport in the Merwedes are summarized in section 3.7.

3.2. Approach

The following aspects have been studied with respect to sediment transport:

1. Influence of river discharge
2. Tidal influence
3. Influence of salt intrusion
4. Sediment transport mechanisms

The way in which the first three aspects have been studied, is the same as the approach of the flow analysis. This is described in section 2.2.

Sediment transport in the Merwedes has been simulated in Matlab by means of post-processing of the SOBEK results of the flow computations, because the morphological schematisation for the Merwede rivers is not available in the SOBEK TMR 2006 model. The model can therefore only be used for hydrodynamic simulations. In addition, SOBEK-RE has limited possibilities to compute the total sediment transport, because only the sediment transport models of Engelund and Hansen (1967) and Van Rijn (1993) can be used in SOBEK-RE.

3.2.1. Sediment transport mechanisms

The used sediment transport models computes the total sediment transport, because both bed load and suspended load is present in the Merwedes (Frings, 2005). In this analysis the following sediment transport models are applied:

- Total sediment transport model of Engelund and Hansen 1967
- Bed load and suspended load model of Van Rijn 1984
- Simplified bed load and suspended load model of Van Rijn 1993
- Bed load and suspended load model of Van Rijn 2007

The choice of these transport models is based on the scope of these models with respect to the grain size of the bed material. A description of these methods to quantify the sediment transport is represented in Appendix I.

The influence of the presence of mud in parts of the Beneden Merwede and Nieuwe Merwede is included in the sediment transport model of Van Rijn 2007. The effect of the presence of mud is not included in the other sediment transport models. However, the sediment transport model of Van Rijn 1984 gives better results in river areas than Van Rijn 2007. Van Rijn 2007 had been formulated to improve the influence of wind waves on sediment transport. It has been decided to apply Van Rijn 2007 with the settings of Van Rijn 1984 to study the effect of the presence of mud.[7] The adaptations to Van Rijn 2007 are described in Appendix I.

Local flow parameters and a local bed composition have been used to calculate local time series of the sediment transport capacity. The calculation of the sediment transport capacity is based on parameters

[7] According to prof. dr. ir. L.C. van Rijn, via a personal comment of dr. ir. Z.B. Wang on March 17, 2010.

of the main channel (WL | Delft Hydraulics, 2000, p. 31). The applied sediment transport models have been adjusted to make them applicable in situations of flow reversal.

Roughness
Both the total roughness and the grain-related roughness have been used as input of the sediment transport models.

- Total roughness
  The Chezy value from SOBEK has been be used as total roughness in the sediment transport models instead of a roughness predictor. This value has been used because it is assumed that the flow is accurately described by the SOBEK TMR 2006 model, although the calibrated hydraulic roughness contains shortcomings of the model schematisation. This aspect of uncertainty has not been studied in this research project. This total roughness has been used in the sediment transport model of Engelund and Hansen (De Vriend, 2007, p. 4.13). The total roughness also has been used in the sediment transport models of Van Rijn 1984 and 2007 (Van Rijn, 2007a, p. 658) to calculate the bed-shear velocity and to derive the bed form height.
- Grain-related roughness
  The effective bed shear stress in the sediment transport models of Van Rijn 1984 and 2007 has been calculated with a grain-related roughness. This grain-related roughness is based on D90 (Van Rijn, 1993, p. 7.26).

3.2.2. Methods to analyse sediment transport

Mean sediment transport
The influence of the tide on sediment transport can be quantified by comparing the mean sediment transport under different flow conditions. The mean sediment transport is defined as a sediment transport which is averaged over a tidal period. The mean sediment transport can be determined by means of a Fourier analysis of local time series of the sediment transport.

The sediment transport depends strongly on flow velocity. However, flow velocities are not calibrated in the SOBEK TMR2006 model of the Rhine-Meuse Delta. Therefore, it is recommended to compare simulated flow velocities by measured flow velocities to get insight in this uncertainty.

Finally, it has been studied whether the mean sediment transport in the Merwedes can be approximated. It is much easier if the mean sediment transport in the Merwedes can be calculated by amplitudes and phases of harmonic components of the flow velocity instead of by time series of the sediment transport. Therefore, the mean sediment transport will be compared by an approximation of the tidally averaged sediment transport of Van de Kreeke and Robaczewska (1993). In the analytical solution of Van de Kreeke and Robaczewska, the mean sediment transport is expressed in harmonic components of the flow velocity. The theory of Van de Kreeke and Robaczewska is briefly described in Appendix II.

Sediment balance
A simple sediment balance has been used to calculate sedimentation and erosion per river branch. The sediment balance is defined by the difference between inflow of sediment at the upstream side and outflow of sediment at the downstream side. These sedimentation and erosion also have been derived from post-processing of flow simulations.

The best performing sediment transport model has been determined for each river branch by comparing the simulated sedimentation and erosion with measured bed volume changes. The measured bed volume changes are analysed by means of calculating the differences in multibeam data between successive measurements. The measured bed volume changes have been corrected with data of dredging volumes.

Expected value

An indication of the expected value of the sediment transport (or the yearly sediment transport) can be obtained by including the probability of a certain upstream river discharge. The way in which the expected value of the sediment transport has been determined, is described in Appendix III.

3.2.3. Bed composition

A one-dimensional schematisation of the bed composition has been applied because a one-dimensional analysis of sediment transport has been used. The applied one-dimensional schematisation of the bed composition is described is this section. The bed composition of the Merwedes can be described by the grain size distribution and the presence of mud. The assumption that the grain size distribution of the bed material is stationary, is the starting point of the schematisation of the bed material.

Available data

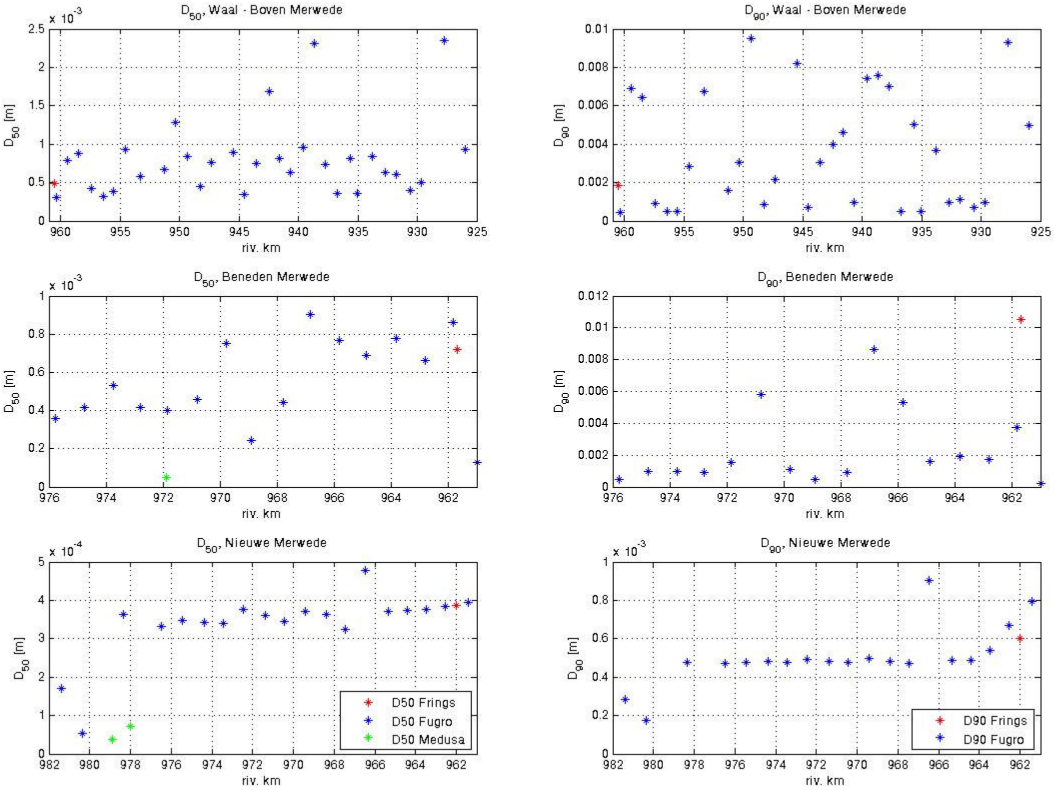
Several data sets contain data about the grain size distribution of the bed material of the Merwedes:

- Frings
  During the measurement campaign in November 2004 the composition of the bed material is determined for 3 locations near the Merwedekop. The percentiles D_{90}, D_{65}, D_{50}, D_{35} and D_{10} are calculated from these data (Frings, 2004). This measurement campaign is described by Frings (2005).
- Fugro
  In 2002, Fugro determined the bed composition of the Northern Delta Basin (Rhine-Meuse Delta) by river-bed samples. From this data the percentiles D_{90}, D_{65}, D_{50} and D_{35} are calculated.
- Medusa
  Medusa (2002) determined the grain size fraction for 2, 16, 63, 125 and 210 μm. Beside it, for locations with very fine bed material the D_{50} can be calculated by interpolation. This is the case for 3 of the 25 measuring locations. The D_{50} cannot be determined from this data set for locations where the cumulative grain size fraction of 210 μm is smaller than 50 %.

An overview of the available data is given in figure 3.1. The horizontal axis represents the location along the river.[8] The left subfigures contain the D_{50}. The D_{90} is in the right subfigures. It is striking that the spatial variations of the grain size characteristics in the Waal - Boven Merwede and the Beneden Merwede are much larger than in the Nieuwe Merwede. It is noted that different vertical scales are used in the subfigures.

[8] In the figures in this report, the upstream side is at the right side.

figure 3.1. Grain size characteristics of Waal - Boven Merwede, Beneden Merwede and Nieuwe Merwede



The Fugro data have been used to schematise the bed composition of the Waal and Merwedes. The river-bed samples of Fugro give the most complete description of the bed composition of the Merwedes, because the number of measurements by Fugro is much larger than the number of measurements by Frings or by Medusa. Respectively 47, 3 and 3 measurements. Errors by differences in measurement methods of the different data sets have been prevented by the choice of one data set. The disadvantage of this choice is that not all available measurements have been used (47 instead of 53 measurements).

Schematisation of bed composition

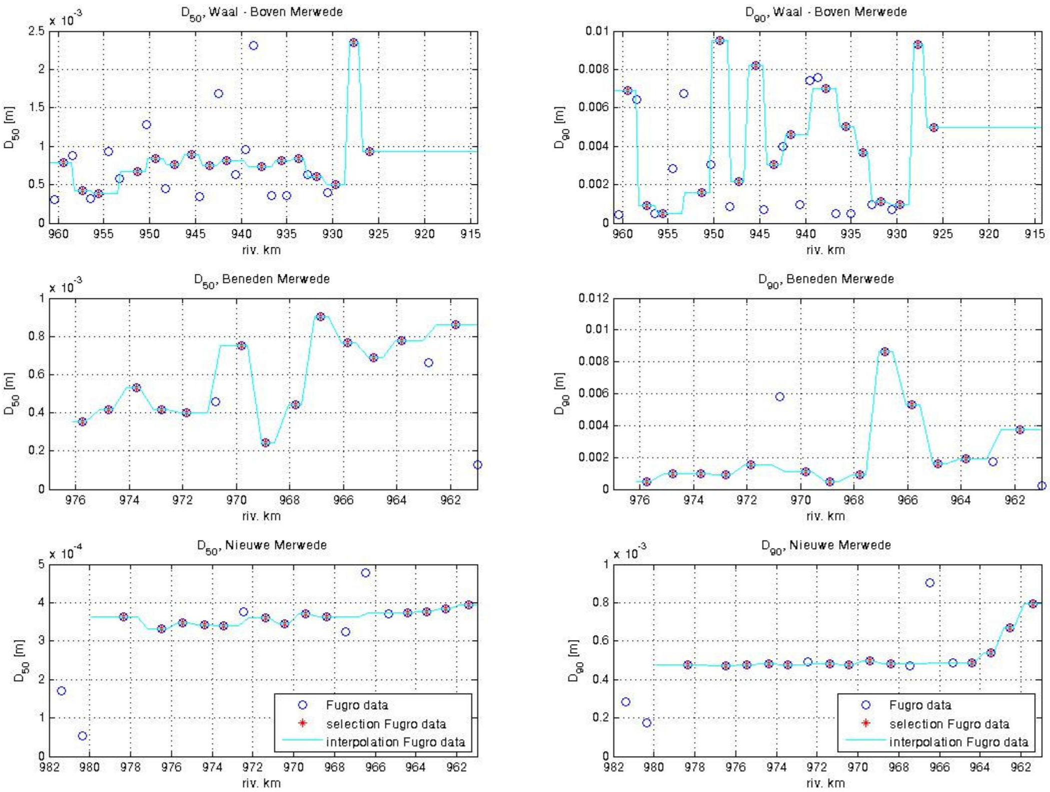
The Fugro data may contain undesirable two-dimensional effects such as bend sorting, because some locations of the bed samples do not lie on the axis of the river. Using visual analysis of the coordinates, the position of the measurement locations with respect to river axis has been estimated. Only the bed samples near the river axis have been used to schematise the bed composition. For the Waal, Boven Merwede and Beneden Merwede a criterion of 25 % of the normal width has been used. For the Nieuwe Merwede, a stricter criterion of 10 % of the normal width has been used, because of the high degree of curvature of this river branch.

An alternative method to avoid two-dimensional effects is averaging of the available data over the cross-section. The natural spreading of the bed composition is than better covered, because more measurements will be used with this alternative method. The natural spreading of the bed composition could be caused by the presence of dunes. This alternative method has not been studied in this analysis, but it is recommended to do this in a future study.

A nearest-neighbour interpolation has been used to schematise the bed composition of the Waal and Merwedes, because it gives plausible results for extrapolation. A disadvantage of this interpolation technique is that the resulting schematisation contains all spatial variations of the measurements. A linear trend in case of downstream fining or a constant bed composition could be more realistic. Another disadvantage of the applied schematisation of the bed composition that the sediment balance depends on just two measurements of the bed composition. The effect of the way of schematisation of the bed composition has not been studied in this research project. It is highly recommended to investigate the effects of the schematisation of the bed composition on sediment transport.

The resulting schematised grain size (D_{50} and D_{90}) is represented in figure 3.2. The left subfigures contain the D_{50}. The D_{90} is in the right subfigures. It is noted that different vertical scales are used in the subfigures.

figure 3.2. Schematised grain size of the bed material in the Waal and Merwedes, for sediment transport model



The geometric standard deviation of the bed material σ_g and the relationship between D_{50} and D_{10} are based on data of Frings (2004), because this data contains a complete grain size distribution. The data sets of Fugro and Medusa contain insufficient information to estimate this parameters. The geometric standard deviation of the bed material and the ratio of D_{50} and D_{10} are needed for the sediment transport models of Van Rijn 1984 and 2007.
It follows that:

- $\sigma_g = 0.5(D_{84} / D_{50} + D_{50} / D_{16})$ = 2.938
- D_{50} / D_{10} = 1.501

Presence of mud
The river bed of the downstream part of the Nieuwe Merwede and a part of the Beneden Merwede

contain mud (< 63 µm). This is visualized in figure 3.3. Based on this figure and on Medusa (2003), the percentage of mud in the river bed is schematised:

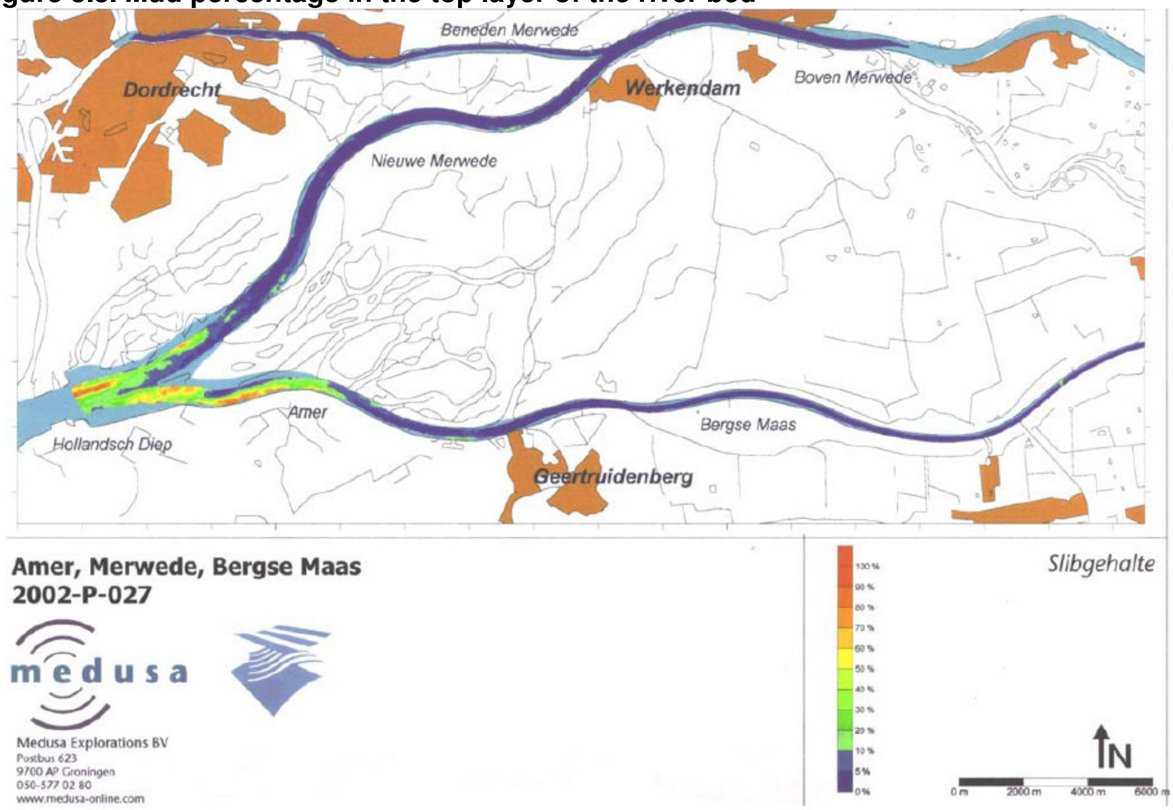
- The mud percentage in the Beneden Merwede is 5 % between 966.96 and 972.00 km.
- The mud percentage in the Nieuwe Merwede is 10 % between 969.55 and 976.00 km and 15 % downstream of 976.00 km.

This corresponds to Van Ledden (2003, p. 24), stating that the mud percentage at the mouth of the Nieuwe Merwede does not exceed 15 %. According to Van Rijn (2005, p. 3.66), sediment is cohesive if the percentage of mud is higher than 20 to 30 %. Therefore, the bed material of the Merwedes consists of a non-cohesive sand-mud mixture.

In contrast to figure 3.3, it is assumed that the bed composition does not vary in a cross-section. This assumption affects the uncertainties of this analysis.

The presence of mud causes a local increase of the critical bed-shear stress (Van Rijn, 2007a, p. 652). The influence of the presence of mud has been quantified with the sediment transport model of Van Rijn 2007. According to Van Rijn (2007a, p. 650), the clay-silt ratio is assumed to be 0.50.

figure 3.3. Mud percentage in the top layer of the river bed



Source: Snippen (2005, p. 44).

3.2.4. Assumptions

The following aspects have been neglected in the sediment transport computations:

- The influence of storm set-up at the seaward boundary
- The influence of local wind within the model area
- The influence of two-dimensional and three-dimensional effects
- Time effects of flood waves (e.g. hysterese)
- The influence of changes in the control of the Haringvliet sluices

- Possible restricted availability of sediment by for instance fixed bed layers
- Sand-mud interaction
- Bed level changes by gradients in sediment transport
- Sediment sorting processes
- The presence of wash load
  Wash load does not contribute to the morphology of the low water bed in the Merwedes, but it is important for the morphology of groyne fields and floodplains.

It is assumed that the adaptation time scale and length scale of suspended load are such that the actual sediment transport can be taken equal to the sediment transport capacity. If this is the case, the effects of lagging of suspended load can be neglected in this analysis. Then, it is permitted to apply a sediment transport model. This assumption is valid in the Merwedes if the following criteria are met:
- The adaptation time scale of suspended load is smaller than or equal to the time step of the simulations. The time step of the simulations is 10 minutes.
- The adaptation length scale of suspended load is smaller than or equal to the grid size of the simulations. The grid size of the SOBEK model is between 500 and 1000 m.

This assumption has been verified in this analysis.

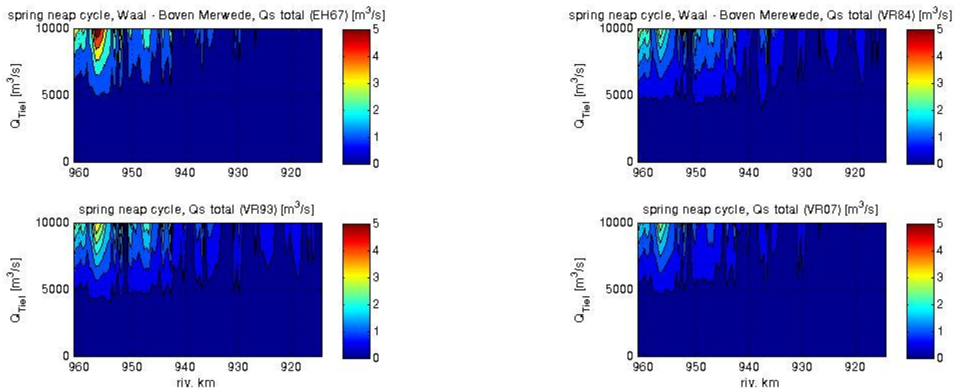
3.3. Tide versus river

3.3.1. Mean sediment transport

Waal - Boven Merwede

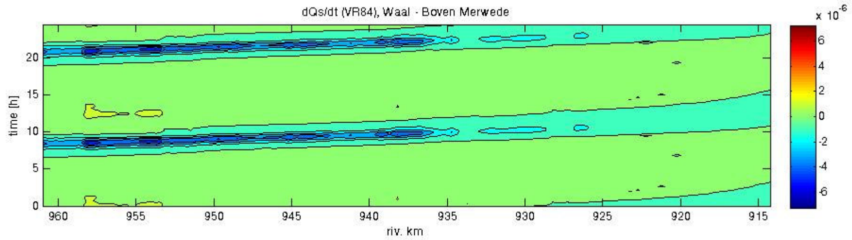
The mean sediment transport in the Waal - Boven Merwede is dominated by the influence of the river discharge. This is visible in figure 3.4. This figure shows the mean sediment transport as function of the location along the river (horizontal axis) and the upstream discharge (vertical axis) for four different sediment transport models. The sediment transport models are Engelund and Hansen 1967 (EH67, left upper subfigure), Van Rijn 1984 (VR84, right upper subfigure), Van Rijn 1993 (VR93, left bottom subfigure) and Van Rijn 2007 (VR07, right bottom subfigure). The increase in mean sediment transport with increasing river discharge is mainly caused by increasing flow velocities with increasing discharge.

figure 3.4. Mean sediment transport in the Waal - Boven Merwede as function of location and upstream discharge for 4 different sediment transport models



Up to Sint Andries (926 km), there is a significant influence of the tide on sediment transport. The tidal intrusion is shown by the variations of the local sediment transport in time. Figure 3.5 shows the time derivative of the sediment transport (Van Rijn 1984) in the Waal - Boven Merwede as function of location along the river (horizontal axis) and time (vertical axis).

figure 3.5. Time derivative of the sediment transport, based on Van Rijn 1984 as function of location and time



The expected value of the sediment transport at the upstream side (952.18 km) and the downstream side (961.00) of the Boven Merwede is presented in table 3.1. The expected value of sediment transport is the yearly sediment load or the sum of the contributions of all discharges to the yearly sediment transport. It is striking that the upstream sediment transport is much larger than the downstream sediment transport. This gives an indication for sedimentation of the Boven Merwede. The differences between the various transport models are also large. The simulation of sediment transport in the Boven Merwede is thus sensitive to the choice of a sediment transport model.

table 3.1. Expected value of the mean sediment transport for the situation with spring-neap cycle

Branch	Location	EH67 [m^3/s]	VR84 [m^3/s]	VR93 [m^3/s]	VR07 [m^3/s]
Boven Merwede	952.18 km	$4.4 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
Boven Merwede	961.00 km	$2.3 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$

The relative effect of various types of sea boundary conditions on the expected value of the sediment transport is quantified in table 3.2. Using a constant water level instead of a spring-neap cycle, or neglecting the tide, gives a significant increase of the mean sediment transport. Using a schematised tidal cycle instead of a spring-neap cycle causes a small reduction of the mean sediment transport.

The tide decreases the mean sediment transport in the Boven Merwede. The water level gradient and the effective resistance in the branches downstream of the Boven Merwede are enlarged by the tide, because of nonlinear frictional interaction. This causes a smaller the water level gradient (and mean sediment transport) in the Boven Merwede.[9]

table 3.2. Effect of sea boundary condition on expected value of mean sediment transport relative to spring-neap cycle - Boven Merwede

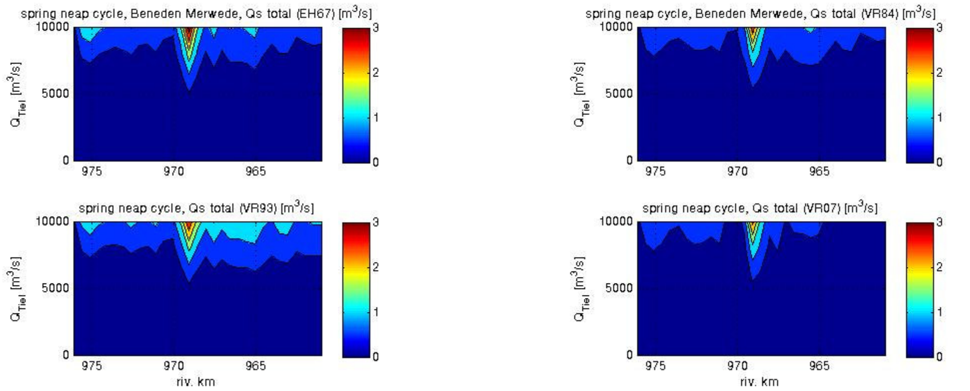
Location	Type of boundary condition	EH67	VR84	VR93	VR07
952.18 km	Tidal cycle	-1.9%	-2.3%	-2.4%	-2.1%
952.18 km	Constant water level	5.2%	6.2%	6.3%	5.9%
961.00 km	Tidal cycle	-2.4%	-2.7%	-2.8%	-2.7%
961.00 km	Constant water level	5.0%	5.1%	5.5%	5.0%

Beneden Merwede

Figure 3.6 describes the influence of the upstream discharge on the mean sediment transport in the Beneden Merwede as function of the location along the river and the upstream discharge. The mean sediment transport increases also in this branch with increasing upstream discharge.

[9] According to dr. ir. Z.B. Wang, personal note on March 15, 2010.

figure 3.6. Mean sediment transport in the Beneden Merwede as function of location and upstream discharge for 4 different sediment transport models



The expected value of the sediment transport at the upstream side (961.00 km) and the downstream side (976.12) of the Beneden Merwede is presented in table 3.3. The mean sediment transport at the upstream side is an order of magnitude larger than the downstream sediment transport. This gives an indication for sedimentation of the Beneden Merwede. The differences between the various sediment transport models are large in this branch. The simulation of sediment transport in the Beneden Merwede is thus sensitive to the choice of a sediment transport model.

table 3.3. Expected value of the mean sediment transport for the situation with spring-neap cycle

Branch	Location	EH67 [m³/s]	VR84 [m³/s]	VR93 [m³/s]	VR07 [m³/s]
Beneden Merwede	961.00 km	$7.1 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$	$8.2 \cdot 10^{-3}$	$5.1 \cdot 10^{-3}$
Beneden Merwede	976.12 km	$1.4 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$8.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$

Table 3.4 contains the effect of using a schematised tidal cycle or a constant water level instead of a spring-neap cycle on the expected value of the sediment transport. Both neglecting the tide, as well as using a tidal cycle gives a substantial underestimation of the sediment transport.

The tide increases the mean sediment transport in the Beneden Merwede. This is caused by the fact that the sediment transport is proportional to the power of the flow velocity. The relation between sediment transport and flow velocity is therefore a convex function. For instance, in the sediment transport model of Engelund and Hansen $Q_s \sim u^5$. A property of a convex function is that $f\left(\frac{a+b}{2}\right) \le \frac{f(a)+f(b)}{2}$, according to Jensen's inequality.

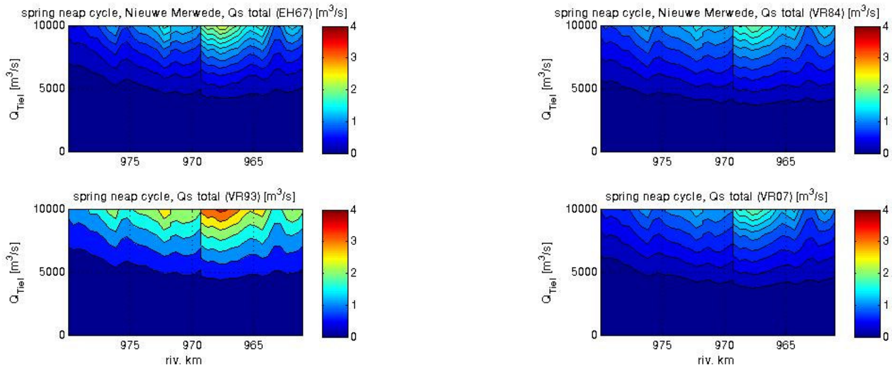
table 3.4. Effect of sea boundary condition on expected value of mean sediment transport relative to spring-neap cycle - Beneden Merwede

Location	Type of boundary condition	EH67	VR84	VR93	VR07
961.00 km	Tidal cycle	-3.8%	-4.3%	-3.8%	-3.8%
961.00 km	Constant water level	-10.4%	-11.2%	-9.6%	-14.8%
976.12 km	Tidal cycle	-5.9%	-7.5%	-7.8%	-7.4%
976.12 km	Constant water level	-22.7%	-15.4%	-14.1%	-15.7%

Nieuwe Merwede

Figure 3.7 shows the influence of the upstream discharge on the mean sediment transport in the Nieuwe Merwede as function of the location along the river and the upstream discharge. The mean sediment transport increases with increasing upstream discharge. The abrupt spatial changes in sediment transport are caused by the bifurcations of several branches of the Biesbosch.

figure 3.7. Mean sediment transport in the Nieuwe Merwede as function of location and upstream discharge for 4 different sediment transport models



The expected value of the sediment transport at the upstream side (961.00 km) and the downstream side (979.92 km) of the Nieuwe Merwede is given in table 3.5. It is striking that the upstream sediment transport is much larger than the downstream sediment transport. This gives an indication for sedimentation of the Nieuwe Merwede. Also the differences between the results of various transport models are large. The simulation of sediment transport in the Nieuwe Merwede is thus also sensitive to the choice of a sediment transport model.

table 3.5. Expected value of the mean sediment transport for the situation with spring-neap cycle

Branch	Location	EH67 [m^3/s]	VR84 [m^3/s]	VR93 [m^3/s]	VR07 [m^3/s]
Nieuwe Merwede	961.00 km	$9.7 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
Nieuwe Merwede	979.92 km	$2.3 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$

The relative effect of using a less detailed sea boundary condition on the expected value of the sediment transport is presented in table 3.6. Using a tidal cycle and neglecting the tide gives an underestimation of the sediment transport. The tide increases the mean sediment transport in the Nieuwe Merwede.

The tide also increases the mean sediment transport in the Nieuwe Merwede. This is caused by the fact that the sediment transport is proportional to the power of the flow velocity.

table 3.6. Effect of sea boundary condition on expected value of mean sediment transport relative to spring-neap cycle - Nieuwe Merwede

Location	Type of boundary condition	EH67	VR84	VR93	VR07
961.00 km	Tidal cycle	-2.4%	-1.7%	-1.7%	-2.1%
961.00 km	Constant water level	-9.9%	-13.6%	-11.3%	-12.2%
979.92 km	Tidal cycle	-7.2%	-7.8%	-8.3%	-8.0%
979.92 km	Constant water level	-9.2%	-8.7%	-9.8%	-8.7%

3.3.2. Approximation of mean sediment transport

The analytical solution of Van de Kreeke and Robaczewska (1993) is an approximation of the mean sediment transport. In the analytical solution of Van de Kreeke and Robaczewska, the mean sediment transport is expressed in harmonic components of the flow velocity. The main input for the analytical expression of Van de Kreeke is the ratio of amplitudes of the flow velocity: $\varepsilon_0 = \hat{U}_{mean} / \hat{U}_{M2}$, the ratio of the residual flow velocity and the amplitude of the M_2 tidal current; and $\varepsilon_4 = \hat{U}_{M4} / \hat{U}_{M2}$, the ratio of the amplitude of the M_4 tidal current and the amplitude of the M_2 tidal current. Figure 3.8 shows these ratios in the Waal - Boven Merwede (upper subfigures), Beneden Merwede (central subfigures) and Nieuwe Merwede (bottom subfigures): the left figures contains the inverse of ε_0, the right figures contains ε_4. The horizontal axis represents the location along the river with the upstream side at the right side and the vertical axis represents the upstream river discharge.

figure 3.8. Ratio of amplitudes of flow velocity as a function of location and upstream discharge in the Waal - Boven Merwede, Beneden Merwede and Nieuwe Merwede; at the left side the ratio $\hat{U}_{M2}/\hat{U}_{mean}$; at the right side the ratio $\hat{U}_{M4}/\hat{U}_{M2}$.

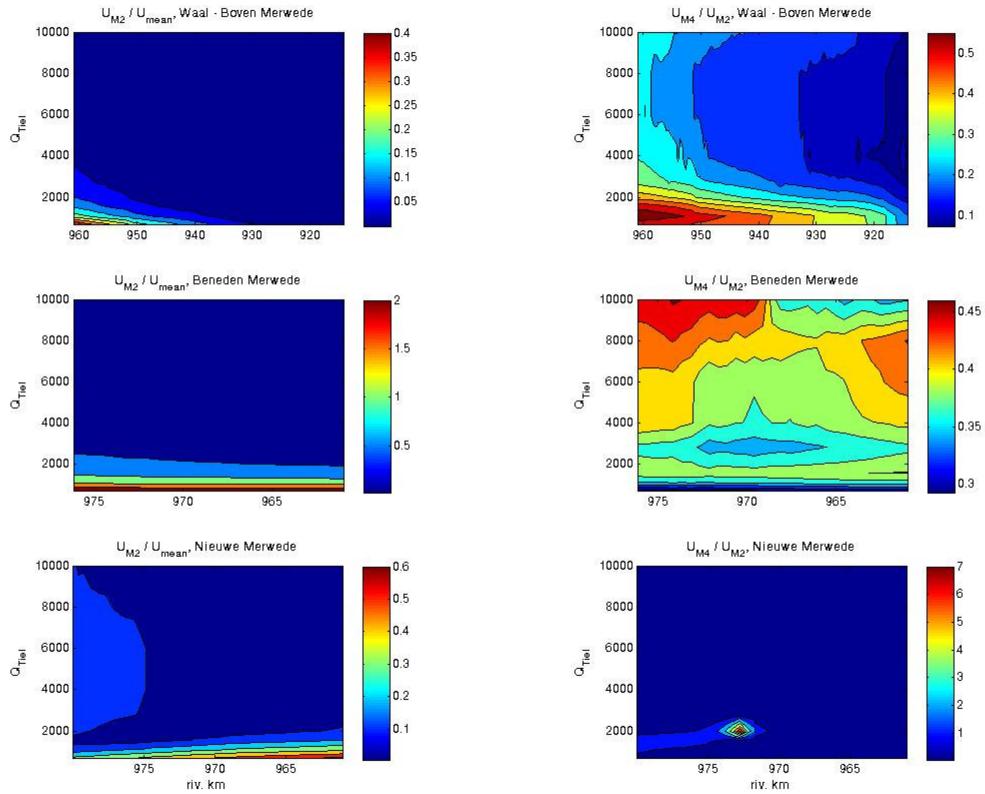


Figure 3.8 shows that the approximation of Van de Kreeke and Robaczewska is not valid in the Merwedes, because the flow in the Merwedes is dominated by the residual current. The flow in the Merwedes is not dominated by the M_2 tidal current, but by the residual current $\hat{U}_{mean}$. Almost in each case (except small river discharges in the Beneden Merwede) the amplitude of the M_2 tidal current is smaller than the residual flow velocity. In the Waal - Boven Merwede and Beneden Merwede, the amplitude of the M_2 tidal current is at least twice the amplitude of the M_4 tidal current. In the Nieuwe Merwede, the amplitude of the M_2 tidal current is in some cases smaller than the amplitude of the M_4 tidal current. In these cases the tidal amplitudes are very small.

A detailed comparison of the approximation of Van de Kreeke and Robaczewska with the simulated mean sediment transport can be found in Appendix II.

It is recommended to extend the present theory of Van de Kreeke and Robaczewska (1993) about mean sediment transport for cases in which flow is dominated by residual flow. This adjusted approximation could be applied in the Merwedes when residual flow is stronger than tidal flow.

3.3.3. Sediment balance

The difference between inflow and outflow of sediment in a river branch gives an indication of sedimentation and erosion. This sediment balance has been based on post-processing of flow simulations with different stationary discharges.

Boven Merwede

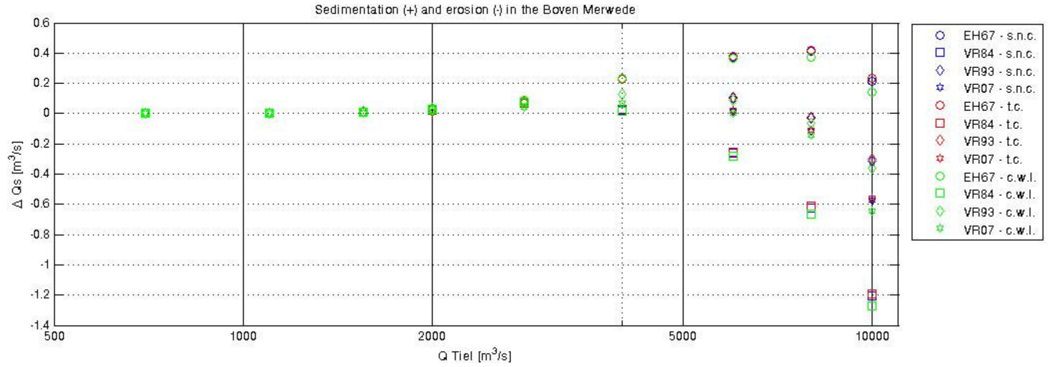
The top subfigure of figure 3.9 shows the sedimentation and erosion in the Boven Merwede for four different sediment transport models and three different sea boundary conditions as function of the upstream discharge (horizontal axis). The applied sediment transport models are Engelund and Hansen 1967 (EH67), Van Rijn 1984 (VR84), Van Rijn 1993 (VR93) and Van Rijn 2007 (VR07). The applied sea boundary conditions are a spring-neap cycle (s.n.c.), a schematised tidal cycle (t.c.) and a constant water level (c.w.l.). Sedimentation and erosion per river branch have been determined by the difference between the upstream and downstream sediment transport capacity for several stationary river discharges.

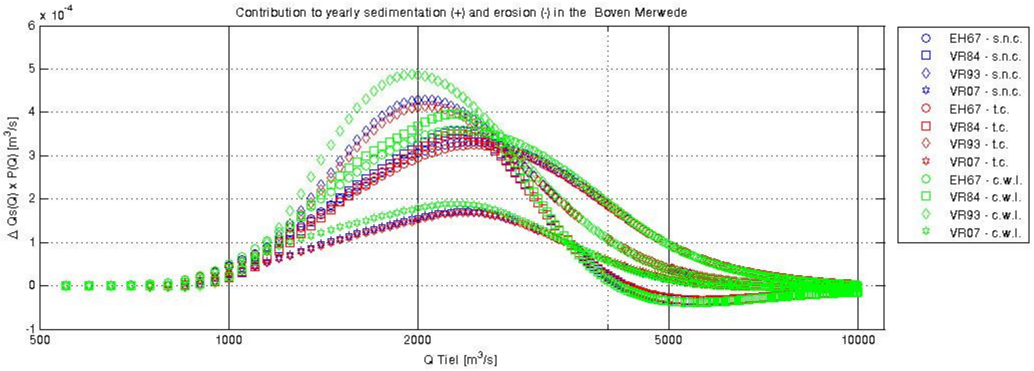
Up to a discharge of 4000 m^3/s, sedimentation takes place. For higher discharges the sediment transport models shows both sedimentation and erosion. The largest contribution to the expected sedimentation and erosion comes from situations with an upstream discharge of about 2900 m^3/s. The contributions of situations with an extremely large discharge or extremely small discharge are negligible.

The contribution of an upstream discharge to the yearly sedimentation and erosion is visualised in the bottom subfigure of figure 3.9. This contribution is the product of the probability of an upstream discharge and the consequence at this upstream discharge (sedimentation or erosion). Upstream discharges between 1000 and 6000 m^3/s have a significant contribution to the sedimentation and erosion of the Boven Merwede. The differences between the various transport models are large in the Boven Merwede. For instance, the difference between Van Rijn 1993 and Van Rijn 2007 is about factor 2.5. The differences between the sea boundary conditions is much smaller than the differences between the transport models.

The discharge with the largest contribution to the yearly sedimentation and erosion is called the effective discharge. This corresponds with the maxima in figure 3.9. The effective discharge in the Boven Merwede is between 2000 m^3/s and 2400 m^3/s, which depends on the choice of a sediment transport model.

figure 3.9. Sedimentation (+) and erosion (-) at the Boven Merwede as a function of the upstream discharge





The sum of all contributions is equal to the yearly sedimentation and erosion (or the expected value of sedimentation and erosion). The expected value of sedimentation and erosion in the Boven Merwede is quantified in table 3.7. The influence of the sea boundary condition is small compared with the choice of a sediment transport model. This yearly sedimentation and erosion corresponds with the sedimentation and erosion at a upstream discharge of 1700 up to 2000 m^3/s.

table 3.7. Expected value of sedimentation (+) and erosion (-) in the Boven Merwede

Type of boundary condition	EH67 [m^3/s]	VR84 [m^3/s]	VR93 [m^3/s]	VR07 [m^3/s]
Spring-neap cycle	$2.1\cdot10^{-2}$	$9.5\cdot10^{-3}$	$1.8\cdot10^{-2}$	$7.8\cdot10^{-3}$
Tidal cycle	$2.0\cdot10^{-2}$	$9.4\cdot10^{-3}$	$1.8\cdot10^{-2}$	$7.8\cdot10^{-3}$
Constant water level	$2.2\cdot10^{-2}$	$1.1\cdot10^{-2}$	$1.9\cdot10^{-2}$	$8.5\cdot10^{-3}$

The effect of river-tide interaction on sedimentation and erosion in the Boven Merwede is visible in figure 3.10. The relative sedimentation and erosion is on the vertical axis and is defined as: $\frac{\Delta Q_{s;\text{ tidal cycle}} - \Delta Q_{s;\text{ spring-neap cycle}}}{\Delta Q_{s;\text{ spring-neap cycle}}}$ and $\frac{\Delta Q_{s;\text{ constant water level}} - \Delta Q_{s;\text{ spring-neap cycle}}}{\Delta Q_{s;\text{ spring-neap cycle}}}$. A positive sign indicates an overestimation of the sedimentation or erosion relative to the spring-neap cycle and a negative sign indicates an underestimation relative to the spring-neap cycle. The upstream discharge is on the horizontal axis. Table 3.8 gives the relative effect on the expected value of sedimentation and erosion as function of sea boundary condition and the choice of a sediment transport model.

Neglecting the tide gives differences in sedimentation between - 100 % at Q = 700 m^3/s and + 52 % at Q = 1100 m^3/s (see figure 3.10). The maximum overestimation of the expected value is 11.2 % at a constant water level.

The differences between a tidal cycle and a spring-neap cycle are smaller: between - 82 % and + 23 % (see figure 3.10). The underestimation of the expected value is up to - 2.1 % at a tidal cycle.

figure 3.10. Difference in sedimentation and erosion relative to the spring-neap cycle per river branch as function of the upstream discharge for the Boven Merwede

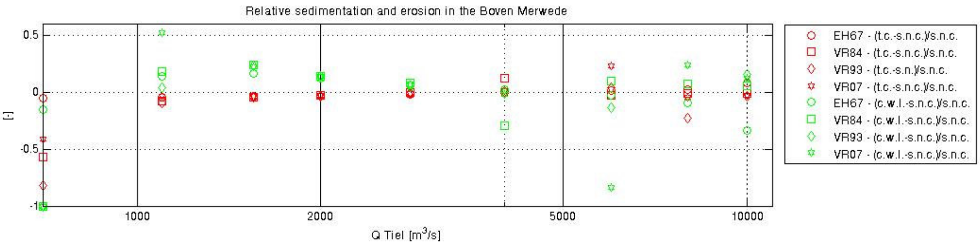


table 3.8. Difference in expected value of sedimentation and erosion in the Boven Merwede relative to the spring-neap cycle

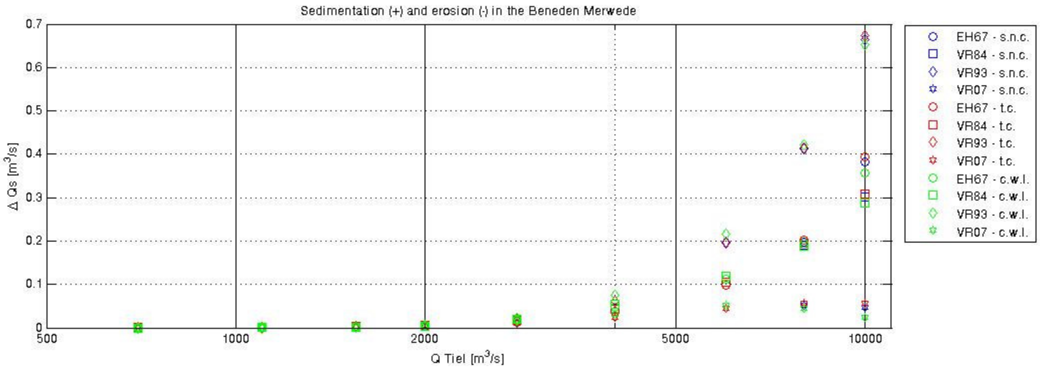
Type of boundary condition	EH67	VR84	VR93	VR07
Tidal cycle	-1.5%	-1.5%	-2.1%	-1.0%
Constant water level	5.7%	11.2%	8.1%	8.7%

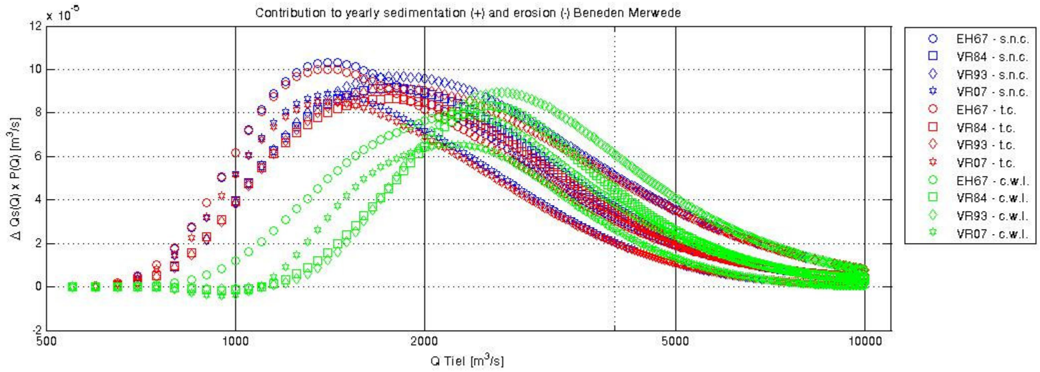
Beneden Merwede

The top subfigure of figure 3.11 describes the expected sedimentation in the Beneden Merwede for four different sediment transport models and three different sea boundary conditions as function of the upstream Waal discharge. The applied sediment transport models are Engelund and Hansen 1967 (EH67), Van Rijn 1984 (VR84), Van Rijn 1993 (VR93) and Van Rijn 2007 (VR07). The applied sea boundary conditions are a spring-neap cycle (s.n.c.), a schematised tidal cycle (t.c.) and a constant water level (c.w.l.). Sedimentation takes place for almost all upstream discharges in the Beneden Merwede.

The bottom subfigure of figure 3.11 shows that the presence of the tide in the Beneden Merwede lowers the effective discharge with about 850 m^3/s. This subfigure contains the contribution of an upstream discharge to the yearly sedimentation and erosion as function of the discharge. When a spring-neap cycle (s.n.c.) or schematised tidal cycle (t.c.) has been used the maximum contributions are at a lower discharge than when a constant water level is used (c.w.l.). This is the case for all applied transport models. In addition, between a discharge of 700 m^3/s and 6000 m^3/s, the tide has significant effect on the expected sedimentation. It is therefore recommended to include river-tide interaction in future sediment transport analyses of the Beneden Merwede.

figure 3.11. Sedimentation (+) and erosion (-) at the Beneden Merwede as a function of the upstream discharge





The sum of all contributions is equal to the yearly sedimentation and erosion (or the expected value of sedimentation and erosion). The expected value of sedimentation and erosion in the Beneden Merwede is quantified in table 3.9. The influence of the sea boundary condition on the expected value of sedimentation is somewhat smaller than the choice of a sediment transport model. This yearly sedimentation and erosion corresponds with the sedimentation and erosion at a upstream discharge of 1800 up to 2000 m^3/s.

table 3.9. Expected value of sedimentation (+) and erosion (-) in the Beneden Merwede

Type of boundary condition	EH67 [m^3/s]	VR84 [m^3/s]	VR93 [m^3/s]	VR07 [m^3/s]
Spring-neap cycle	$5.7\cdot10^{-3}$	$5.7\cdot10^{-3}$	$7.4\cdot10^{-3}$	$4.1\cdot10^{-3}$
Tidal cycle	$5.5\cdot10^{-3}$	$5.5\cdot10^{-3}$	$7.1\cdot10^{-3}$	$4.0\cdot10^{-3}$
Constant water level	$5.2\cdot10^{-3}$	$4.9\cdot10^{-3}$	$6.6\cdot10^{-3}$	$3.4\cdot10^{-3}$

The relative effect of a tidal cycle and a constant water level on sedimentation is visualised in figure 3.12 and summarised in table 3.10. A positive sign indicates an overestimation of the sedimentation or erosion relative to the spring-neap cycle and a negative sign indicates an underestimation relative to the spring-neap cycle.

Neglecting the tide causes a large underestimation of the sedimentation in the Beneden Merwede in situations with river discharges up to 2000 m^3/s. Neglecting the tide gives differences in sedimentation between - 100 % at Q = 700 m^3/s and + 28 % at Q = 4000 m^3/s (figure 3.12). The maximum underestimation of the expected value is 16.3 % at a constant water level (table 3.10).

The differences between a tidal cycle and a spring-neap cycle are much smaller: between - 6 % and + 17 % (figure 3.12). The underestimation of the expected value is up to - 3.7 % at a tidal cycle (table 3.10).

figure 3.12. Difference in sedimentation and erosion relative to the spring-neap cycle per river branch as function of the upstream discharge for the Beneden Merwede

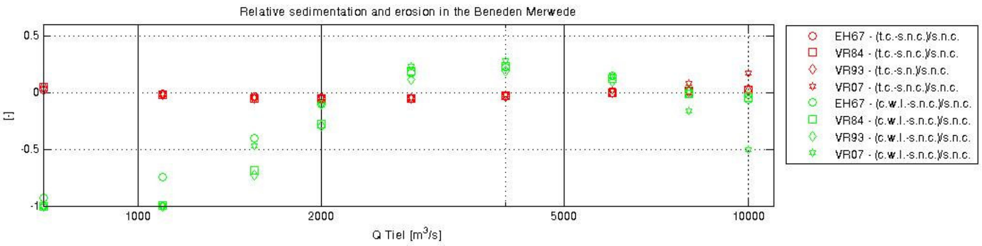


table 3.10. Difference in expected value of sedimentation and erosion in the Beneden Merwede relative to the spring-neap cycle

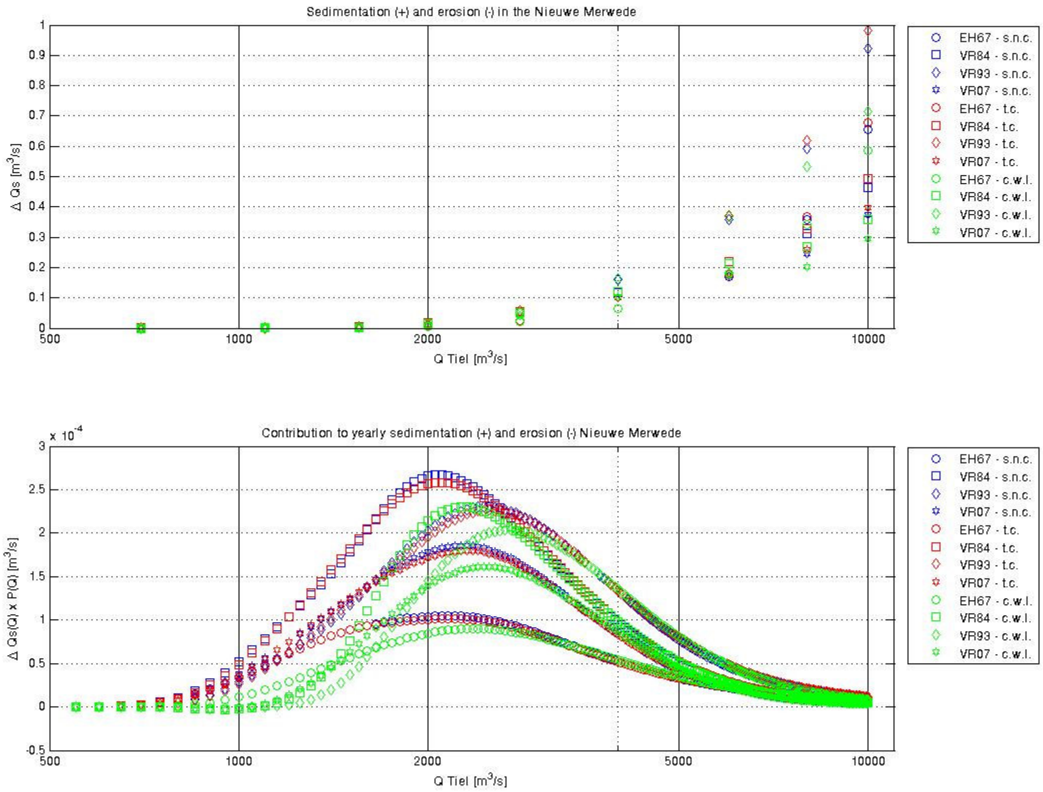
Type of boundary condition	**EH67**	**VR84**	**VR93**	**VR07**
Tidal cycle	-3.1%	-3.7%	-3.3%	-2.9%
Constant water level	-9.1%	-13.0%	-11.1%	-16.3%

Nieuwe Merwede

The top subfigure of figure 3.13 shows the expected sedimentation in the Nieuwe Merwede for four different sediment transport models and three different sea boundary conditions as function of the upstream Waal discharge. The applied sediment transport models are Engelund and Hansen 1967 (EH67), Van Rijn 1984 (VR84), Van Rijn 1993 (VR93) and Van Rijn 2007 (VR07). The applied sea boundary conditions are a spring-neap cycle (s.n.c.), a schematised tidal cycle (t.c.) and a constant water level (c.w.l.). Sedimentation takes place for almost all upstream discharges in the Nieuwe Merwede.

The presence of the tide in the Nieuwe Merwede lowers the effective discharge with about 150 m^3/s. This is visible in the bottom subfigure of figure 3.13. This subfigure contains the contribution of an upstream discharge to the yearly sedimentation and erosion as function of the discharge. When a spring-neap cycle (s.n.c.) or schematised tidal cycle (t.c.) has been used the maximum contributions are at a lower discharge than when a constant water level is used (c.w.l.). This is the case in the Nieuwe Merwede for all applied transport models. Furthermore, between a discharge of 800 m^3/s and 3000 m^3/s, the tide has significant effect on the expected sedimentation. The contribution to the expected value of the sedimentation is at these discharges much larger for a spring-neap cycle and a tidal cycle than for a constant water level. It is therefore recommended to include river-tide interaction in future sediment transport analyses of the Nieuwe Merwede.

figure 3.13. Sedimentation (+) and erosion (-) at the Nieuwe Merwede as a function of the upstream discharge



The sum of all contributions is equal to the yearly sedimentation and erosion (or the expected value of sedimentation and erosion). The expected value of sedimentation and erosion in the Nieuwe Merwede is quantified in table 3.11. The influence of the sea boundary condition is smaller than the choice of a sediment transport model. This yearly sedimentation and erosion corresponds with the sedimentation and erosion at a upstream discharge of 1900 up to 2000 m^3/s.

table 3.11. Expected value of sedimentation (+) and erosion (-) in the Nieuwe Merwede

Type of boundary condition	EH67 [m^3/s]	VR84 [m^3/s]	VR93 [m^3/s]	VR07 [m^3/s]
Spring-neap cycle	$7.5 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
Tidal cycle	$7.4 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
Constant water level	$6.6 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$9.3 \cdot 10^{-3}$

The relative effect of a tidal cycle and a constant water level on sedimentation is visualised in figure 3.14 and summarised in table 3.12. A positive sign indicates an overestimation of the sedimentation or erosion relative to the spring-neap cycle and a negative sign indicates an underestimation relative to the spring-neap cycle.

In general, neglecting the tide causes a underestimation of the sedimentation in the Nieuwe Merwede. The differences are between - 100 % at Q < 1000 m^3/s and + 4 % at Q = 4000 m^3/s (figure 3.14). The maximum underestimation of the expected value is 16.5 % at a constant water level (table 3.12).

The differences between a tidal cycle and a spring-neap cycle are much smaller: between - 11 % and + 7 % (figure 3.14). The differences in the expected value are about 1 % for a tidal cycle (table 3.12).

figure 3.14. Difference in sedimentation and erosion relative to the spring-neap cycle per river branch as function of the upstream discharge for the Nieuwe Merwede

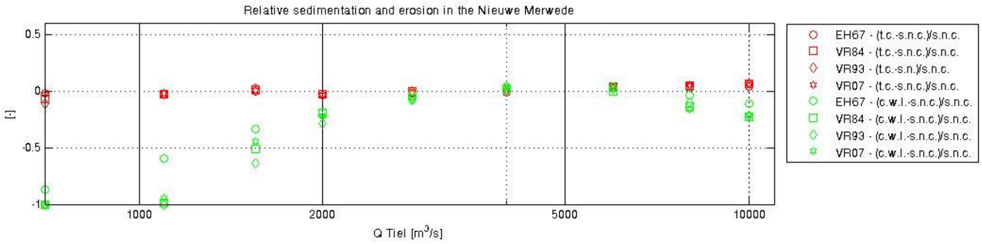


table 3.12. Difference in expected value of sedimentation and erosion in the Nieuwe Merwede relative to the spring-neap cycle

Type of boundary condition	EH67	VR84	VR93	VR07
Tidal cycle	-0.9%	0.0%	0.2%	-0.7%
Constant water level	-11.1%	-16.5%	-13.8%	-14.8%

3.4. Salt intrusion

3.4.1. Mean sediment transport

Salt intrusion in the Rhine-Meuse Delta decreases the expected value of mean sediment transport in the Merwedes. Table 3.13 shows the effect of neglecting salt intrusion the expected value of the mean sediment transport. Salt intrusion causes a increase of the mean water level in the Merwedes which leads to a decrease in mean flow velocity and mean sediment transport. Neglecting salt intrusion gives a overestimation of the sediment transport in the Merwedes up to 9.5 %.

table 3.13. Effect of neglecting salt intrusion on expected value of mean sediment transport

River branch	Location [km]	EH67	VR84	VR93	VR07
Boven Merwede	952.18	3.4%	4.4%	4.6%	4.0%
Boven Merwede	961.00	3.5%	4.3%	4.6%	4.4%
Beneden Merwede	961.00	7.3%	8.5%	7.4%	7.5%
Beneden Merwede	976.12	8.4%	9.5%	9.0%	9.5%
Nieuwe Merwede	961.00	1.7%	0.6%	0.2%	1.2%
Nieuwe Merwede	979.92	8.3%	8.8%	9.0%	8.8%

3.4.2. Sediment balance

The effect of neglecting salt intrusion on sedimentation is quantified in table 3.14 for Engelund and Hansen 1967 and in table 3.15 for Van Rijn 1993. Salt intrusion in the Rhine-Meuse Delta leads to a decrease of sedimentation in the Boven Merwede and Beneden Merwede and an increase of sedimentation in the Nieuwe Merwede. The effect of salt intrusion on sedimentation is largest in the Beneden Merwede, somewhat smaller in the Boven Merwede and smallest in the Nieuwe Merwede.

table 3.14. Effect of neglecting salt intrusion and sea boundary condition on sedimentation, based on Engelund and Hansen 1967

River branch	Sea boundary condition	Simulation with salt intrusion relative to reference simulation	Situation without salt intrusion relative to reference simulation
Boven Merwede	spring-neap cycle	reference simulation	3.2%
Boven Merwede	tidal cycle	-1.5%	1.6%

River branch	Sea boundary condition	Simulation with salt intrusion relative to reference simulation	Situation without salt intrusion relative to reference simulation
Boven Merwede	constant water level	5.7%	6.4%
Beneden Merwede	spring-neap cycle	reference simulation	7.1%
Beneden Merwede	tidal cycle	-3.1%	3.7%
Beneden Merwede	constant water level	-9.1%	-8.3%
Nieuwe Merwede	spring-neap cycle	reference simulation	-0.3%
Nieuwe Merwede	tidal cycle	-0.9%	-0.9%
Nieuwe Merwede	constant water level	-11.1%	-10.3%

table 3.15. Effect of neglecting salt intrusion and sea boundary condition on sedimentation, based on Van Rijn 1993

River branch	Sea boundary condition	Simulation with salt intrusion relative to reference simulation	Situation without salt intrusion relative to reference simulation
Boven Merwede	spring-neap cycle	reference simulation	4.7%
Boven Merwede	tidal cycle	-2.1%	2.5%
Boven Merwede	constant water level	8.1%	9.4%
Beneden Merwede	spring-neap cycle	reference simulation	7.2%
Beneden Merwede	tidal cycle	-3.3%	3.7%
Beneden Merwede	constant water level	-11.1%	-10.4%
Nieuwe Merwede	spring-neap cycle	reference simulation	-2.6%
Nieuwe Merwede	tidal cycle	0.2%	-2.1%
Nieuwe Merwede	constant water level	-13.8%	-13.3%

3.5. Sediment transport mechanisms

This section describes the sediment transport mechanisms. Section 3.5.1 contains a description of suspended load with respect to bed load and adjustments to flow fluctuations. The influence of the presence of mud on sediment transport is presented in section 3.5.2.

3.5.1. Suspended load

Suspended load versus bed load

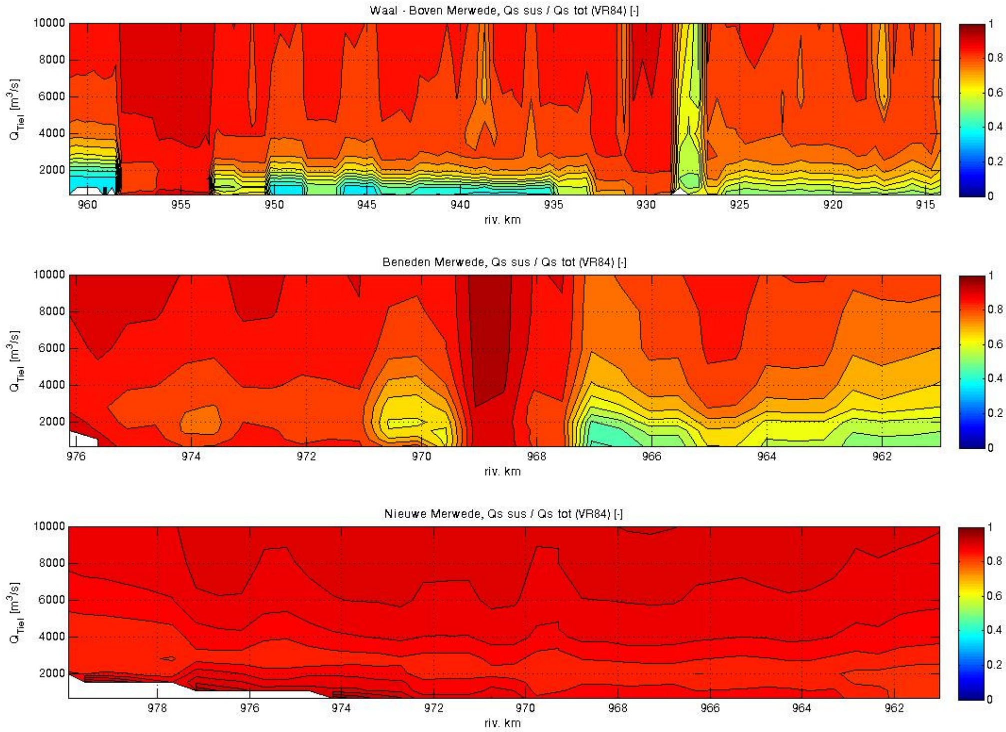
The presence of both bed load and suspended load in the Merwedes justifies the choice for sediment transport models which calculate the total load, including bed load and suspended load. The presence of suspended load is visualised in figure 3.15. In this figure the ratio between the mean suspended load and the mean total sediment transport (Van Rijn 1984) is plotted for the situation of a spring-neap cycle. The horizontal axis represents the location along the river branch. The upstream discharge is on the vertical axis.

In general, the quantity suspended load is larger than the quantity bed load. The upstream river discharge has a large effect on the percentage of suspended load. The percentage of suspended load is largest for large discharges. The variations of the relative suspended load are largest in the Waal - Boven Merwede: 38 % up to 94 %. The results of the relative suspended load in Beneden Merwede show a transition from bed and suspended load at the upstream part and mainly suspended load at the downstream part. The variations in relative suspended load are large in this branch: 44 % up to 98 %. The sediment transport in the Nieuwe Merwede is mainly suspended load (83 up to 97 %).

In addition, the schematisation of the bed composition influences the ratio of suspended load and total load. The low percentage of suspended load in the Waal at 928 km can be attributed to the artificial effect of a large grain size at this location. This is also the case in the Waal around 945 km and 951 km, in the Boven Merwede around 959 km and in the Beneden Merwede around 967 km. Compare figure

3.15 with figure 3.2. Therefore, it is recommended to study the sediment transport mechanisms in the Waal and Merwedes in more detail.

figure 3.15. Relative suspended load in the Waal - Boven Merwede, Beneden Merwede and Nieuwe Merwede as a function of the location and the upstream discharge, based on Van Rijn 1984

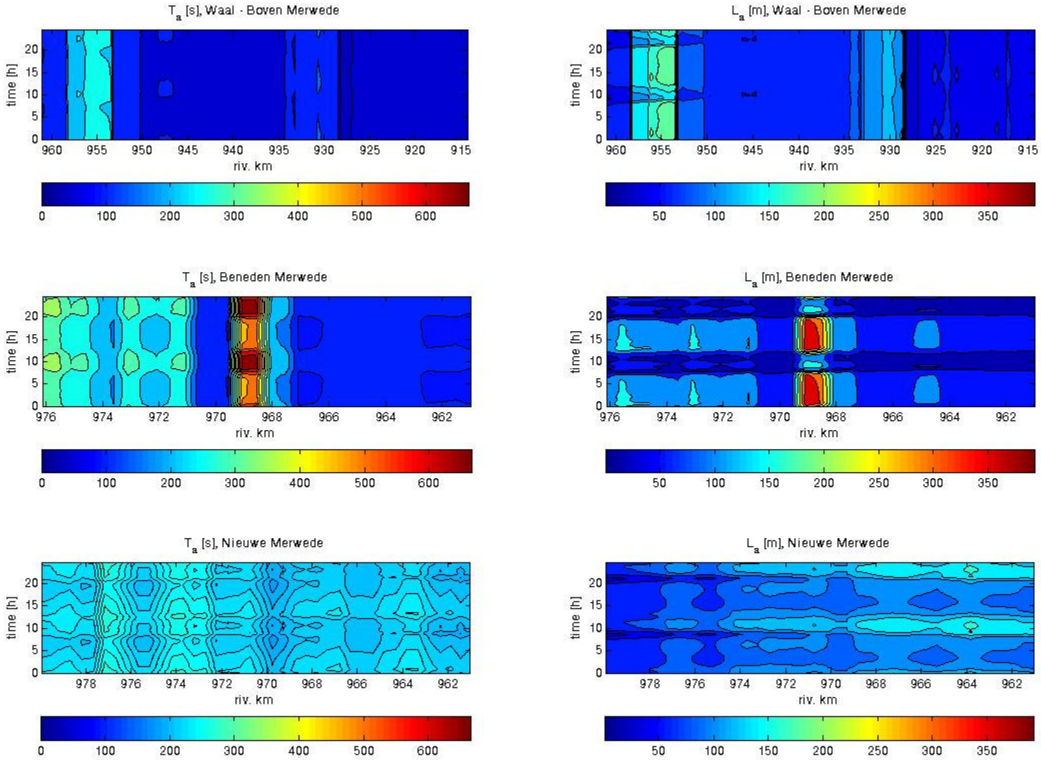


Adjustment of suspended load

The adjustment of suspended load to changes in flow can be estimated with a scale for the adaptation time and a scale for the adaptation length. The adaptation time indicates the time needed by a particle to settle. The adaptation length indicates the horizontal distance that a particle travels during settling.

Figure 3.16 shows the adaptation time scale (left subfigures) and adaptation length scale (right subfigures) of suspended load for the Merwedes. The horizontal axis gives the position along the river and represents spatial variations. The vertical axis gives the time. Variations along the vertical axis corresponds to tidal variations. The results are based on the situation with a tidal cycle and represent the expected value of the flow.

figure 3.16. Scale for the adaptation time (left subfigures) and adaptation length (right subfigures) of suspended load for the Waal and Merwedes as function of location and time



It’s striking that the adaptation time scale and the adaptation length scale in the Beneden Merwede varies in time. This is visible in the middle subfigures of figure 3.16 along the vertical axis. These variations in time are caused by the large tidal variations of the flow in this river branch. These variations are smaller in the Nieuwe Merwede and much smaller in the Waal - Boven Merwede.

The large adaptation time scale and large adaptation length scale in the Waal between 929 and 934 km and in the Boven Merwede between 953 and 957 km can be attributed to the local small grain size in the schematised bed composition. Compare figure 3.16 with figure 3.2. The percentage suspended load is at these locations larger than at neighbouring locations, because fine material comes easier in suspension than coarser material. See figure 3.15. Therefore, the way in which the bed composition has been schematised, influences the sediment transport mechanisms in the simulations.

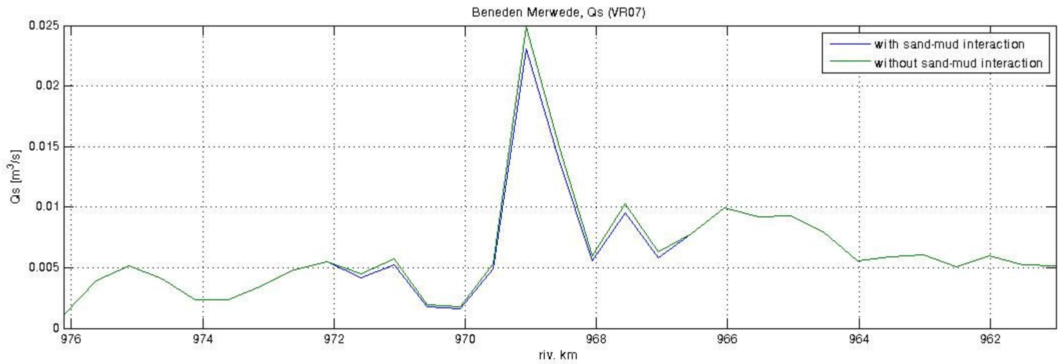
The scale for the adaptation time of suspended load is equal to or smaller than 665 s. This is approximately equal to or smaller than the time step of the flow calculations, 10 minutes. The scale for the adaptation length of suspended load is smaller than 385 m. This is smaller than the distance between two successive grid points and smaller than or equal to the local width of the river. Therefore, the effects of lagging of suspended load are negligible in this analysis. This means that the occurring sediment transport is nearly equal to the sediment transport capacity.

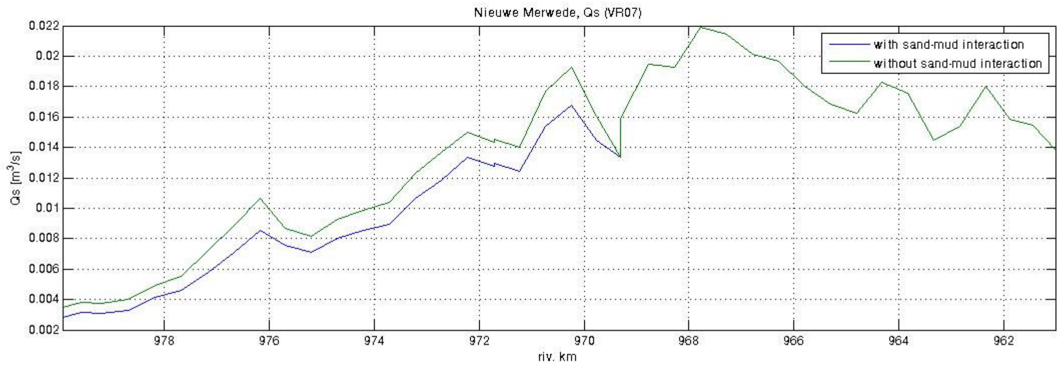
3.5.2. Presence of mud

The influence of mud on the sediment transport capacity can be quantified with the sediment transport model of Van Rijn 2007. Simulations with the influence of the presence of mud have been compared by simulations without the influence of mud. Figure 3.17 shows the influence of mud on the yearly sediment transport in the Beneden Merwede and Nieuwe Merwede as function of the location along the river.

The presence of mud causes a decrease of the simulated local sediment transport. The presence of mud causes an increase in the critical bed-shear stress (Van Rijn 2007a, p. 652), a decrease in the bed load (Van Rijn 2007a, p. 658) and a decrease in the reference concentration (Van Rijn 2007b, p. 673). Neglecting the sand-mud interaction gives an increase up to 10 % of the sediment transport in the Beneden Merwede and a large increase up to 25 % of the sediment transport in the Nieuwe Merwede. The schematisation of the presence of mud is clearly visible in the results of the Nieuwe Merwede. It is assumed that the mud fraction is zero upstream of 969.5 km and that the mud fraction is 10 up to 15 % downstream of this location.

figure 3.17. Influence of mud on the yearly sediment transport in the Beneden and Nieuwe Merwede





The influence of mud of the expected value of sedimentation in the Nieuwe Merwede is quantified in table 3.16. The influence of the presence of mud on the expected value of sedimentation is small in the Nieuwe Merwede.

table 3.16. Influence of mud on the expected value of sedimentation in the Nieuwe Merwede

Type of boundary condition	**VR07 with sand-mud interaction [m³/s]**	**VR07 without sand-mud interaction [m³/s]**
Spring-neap cycle	$1.1 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
Tidal cycle	$1.1 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
Constant water level	$9.3 \cdot 10^{-3}$	$8.7 \cdot 10^{-3}$

The presence of mud has no influence on sedimentation in the Beneden Merwede according to the applied sediment balance. This is caused by the way in which the sediment balance has been formulated: the difference between the upstream and downstream sediment transport capacity. Mud is only present in the middle part of the Beneden Merwede and has therefore no influence on the sediment balance.

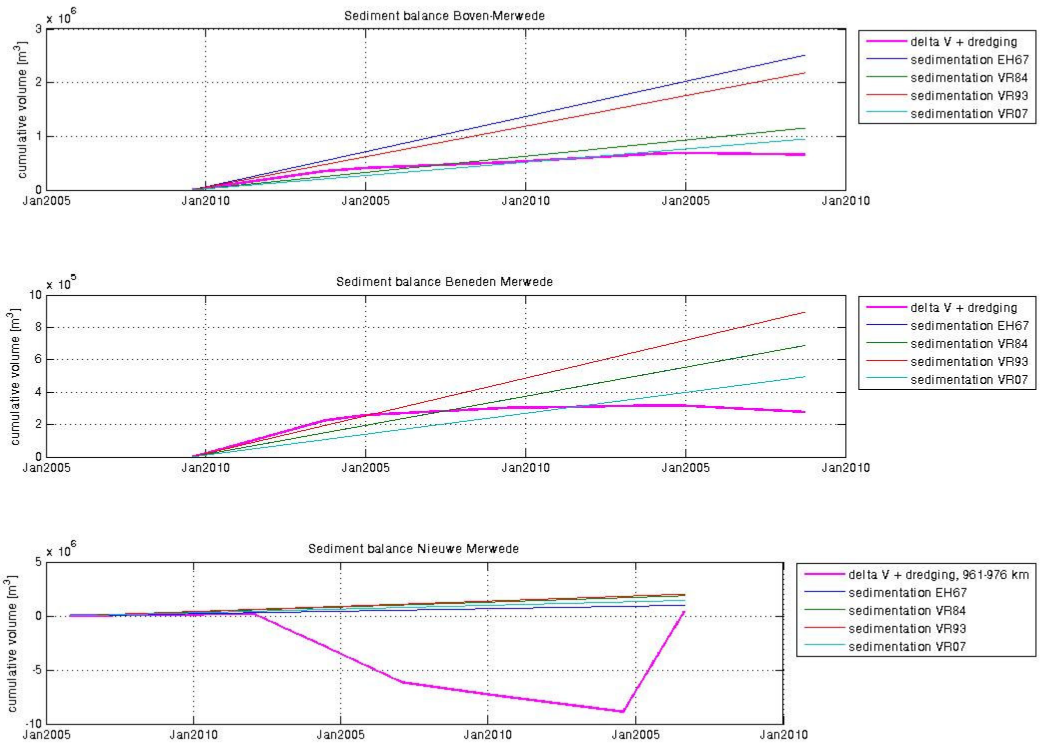
3.6. Comparison with measurements

The simulated expected sedimentation of the Merwedes has been compared with a measured change of the volume of the bed. In the ideal world, the simulated expected sedimentation should be equal to the sum of the measured volume change of the bed and the dredging volume. Figure 3.18 shows the sediment balance of the Boven, Beneden and Nieuwe Merwede for the period 2005 - 2009.

The measured volume change of the bed has been based on multibeam data of de Merwedes from the period 2005 up to 2009 (Rijkswaterstaat Dienst Zuid-Holland, 2009b). The measurements are available on just 5 times. The dredging volume has been based on the mean of dredging quantities in the period 2005 - 2009 (Rijkswaterstaat Dienst Zuid-Holland, 2009a).

The simulated expected sedimentation has been based on post processing of flow simulations in which a spring neap-cycle has been used as seaward boundary condition and the effects of salt intrusion have been included.

figure 3.18. Comparison of expected sedimentation with data of the period 2005 - 2009



The results of the different sediment transport models have been compared with the measured cumulative sedimentation. The comparison has been done over the total period of available measurements: for the Boven and Beneden Merwede over the period December 2005 until October 2009, and for the Nieuwe Merwede over the period March 2005 until May 2009.

Boven Merwede

The measured cumulative sedimentation in the Boven Merwede is $6.56 \cdot 10^5$ m^3. The cumulative expected sedimentation by simulations with four different sediment transport models is quantified in table 3.17. The sediment transport model of Van Rijn 2007 gives the best estimation of the expected sedimentation in the Boven Merwede. This model overestimates the measured sedimentation with 45 %. Van Rijn 1984 is second best with an overestimation of 76 %.

table 3.17. Comparison of the simulated expected sedimentation by measured cumulative sedimentation for the Boven Merwede

	EH67	VR84	VR93	VR07
Cumulative expected sedimentation by simulations [m^3]	$2.5\cdot10^6$	$1.2\cdot10^6$	$2.2\cdot10^6$	$9.5\cdot10^5$
Relative difference to measured sedimentation	283%	76%	233%	45%

Beneden Merwede
The measured cumulative sedimentation in the Beneden Merwede is $2.77\cdot10^5$ m^3. Table 3.18 contains the cumulative expected sedimentation by simulations with four sediment transport models. Van Rijn 2007 also gives the best prediction of the expected sedimentation in the Beneden Merwede. The relative difference is 79 %.

table 3.18. Comparison of the simulated expected sedimentation by measured cumulative sedimentation for the Beneden Merwede

	EH67	VR84	VR93	VR07
Cumulative expected sedimentation by simulations [m^3]	$6.9\cdot10^5$	$6.9\cdot10^5$	$8.9\cdot10^5$	$4.9\cdot10^5$
Relative difference to measured sedimentation	149%	149%	223%	79%

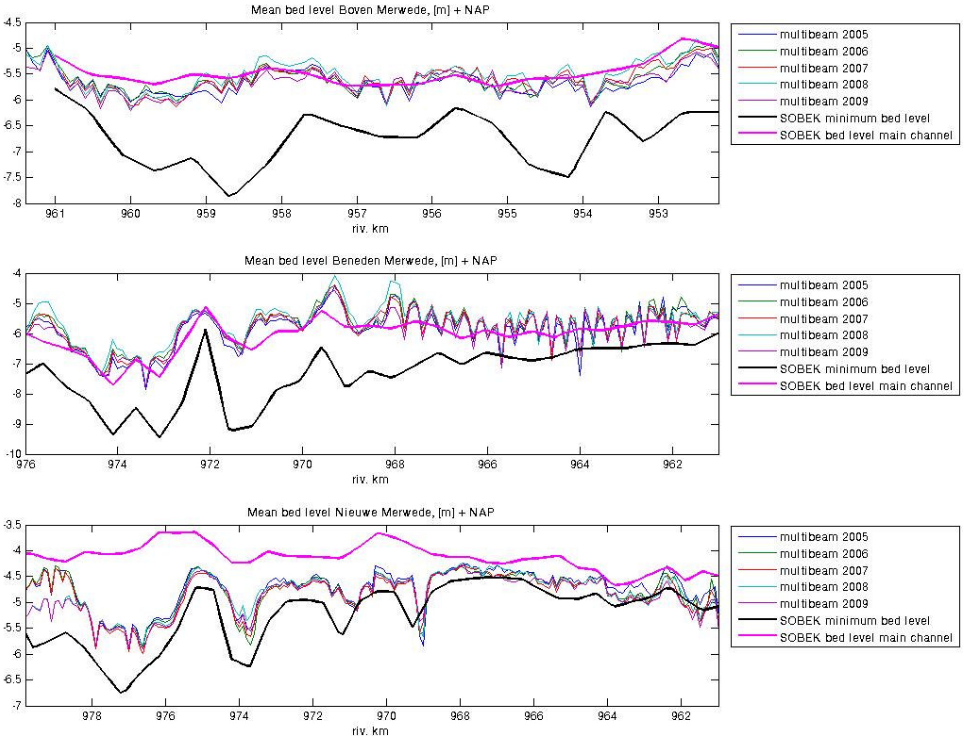
Nieuwe Merwede
The measured cumulative sedimentation in the Nieuwe Merwede is $3.93\cdot10^5$ m^3. Table 3.19 gives the cumulative expected sedimentation by simulations with four sediment transport models. Engelund and Hansen 1967 seems to give the best approximation of the expected sedimentation in the Nieuwe Merwede with a relative difference of 149 %. However, it is unknown which sediment transport model gives the best result for the Nieuwe Merwede, because of incomplete measurements.

The multibeam data of the Nieuwe Merwede cover only the shipping lane of the Nieuwe Merwede. The measured bed level corresponds to the minimum bed level of this branch in the SOBEK model and the measured bed level is much lower than the mean bed level of the main channel in SOBEK. This is visualised in the bottom subfigure of figure 3.19. This figure shows the cross-section averaged bed level of the Merwedes as function of the location along the river. The cross-section averaged bed level from multibeam data corresponds reasonably to the mean bed level of the main channel in SOBEK for the Boven Merwede (top subfigure) and Beneden Merwede (middle subfigure).

table 3.19. Comparison of the simulated expected sedimentation by measured cumulative sedimentation for the Nieuwe Merwede

	EH67	VR84	VR93	VR07
Cumulative expected sedimentation by simulations [m^3]	$9.8\cdot10^5$	$1.9\cdot10^6$	$2.0\cdot10^6$	$1.4\cdot10^6$
Relative difference to measured sedimentation	149%	375%	413%	265%

figure 3.19. Comparison of measured bed level and bed level in SOBEK



3.7. Conclusions

Based on the analysis of simulated time series of sediment transport, the following conclusions can be drawn.

Tidal influence

- The tidal influence on flow in the Merwedes cannot be neglected, because of the following reasons:
    - The tide decreases the mean sediment transport in the Boven Merwede and increases the mean sediment transport in the Beneden and Nieuwe Merwede. Up to Sint Andries (Waal, 926 km), there is a significant influence of the tide on sediment transport.
    - The tide decreases the effective (Waal) discharge of the Beneden Merwede with 850 m^3/s and decreases the effective (Waal) discharge of the Nieuwe Merwede with 150 m^3/s. The tide has no influence on the effective discharge of the Boven Merwede.
- The influence of the tide can best be represented by a spring-neap cycle. However, a less detailed tidal cycle is a reasonable approximation of the tidal influence on sediment transport in the Merwedes. Using a tidal cycle instead of a spring-neap cycle gives a small underestimation of the expected value of sediment transport and the expected value of sedimentation.
- The flow circumstances of the Merwedes are outside the scope of Van de Kreeke and Robaczewska (1993). The influence of the river discharge on the flow in the Merwedes is too large. Therefore, the long-term mean sediment transport in the Merwedes cannot be estimated by the approximation of Van de Kreeke and Robaczewska.

Influence of river discharge

- The influence of the river discharge on mean sediment transport in the Merwedes is much larger than the tidal influence.

Influence of salt intrusion

Salt intrusion in the Rhine-Meuse Delta has a significant effect on flow in the Merwedes.

- Salt intrusion causes a increase of the mean water level in the Merwedes which leads to a decrease in mean flow velocity and mean sediment transport in the Merwedes.
- Neglecting salt intrusion gives deviations in mean sediment transport with the same order of magnitude as neglecting the tide in the Merwedes.
- The presence of salt in the Rhine-Meuse Delta leads to a decrease of sedimentation in the Boven Merwede and Beneden Merwede and an increase of sedimentation in the Nieuwe Merwede.

Influence of choice of sediment transport model

- The choice of a sediment transport model has a larger influence on sediment transport than the sea boundary conditions. The sediment transport model of Van Rijn 2007 gives the best approximation of the measured sedimentation in the Boven and Beneden Merwede. This is based on post-processing of flow simulations. It is unknown which sediment transport model gives the best result for the Nieuwe Merwede, because of incomplete measurements.
- The adaptation time and length scales of the sediment transport are such that the actual transport can be taken equal to the sediment transport capacity. This justifies the use of a sediment transport model.
- The sediment transport in the Merwedes can be computed with a transport model for total load which includes both suspended load and bed load.
- The influence of the presence of mud on sedimentation in the Merwedes is small.

Sediment balance

- Based on the analysis of the results of the one-dimensional flow model of the Rhine-Meuse Delta, the general trend in the Merwedes is sedimentation.

4. BED LEVEL CHANGES

4.1. Introduction

Bed level changes in the Merwedes have been simulated to study the tidal influence on bed level changes in the Merwedes. The approach is described in section 4.2. Section 4.3 describes the reference simulation. Section 4.4 contains a sensitivity analysis of the effect of the simulated bed level on flow and sediment transport. The effects of the tide, the choice of a sediment transport model and dredging are included in section 4.5. Section 4.6 contain the conclusions with respect to bed level changes in the Merwedes.

4.2. Approach

At this moment, there is no up to date calibrated one-dimensional morphological model available for the Rhine-Meuse Delta in which the flow is accurately described. Therefore, it has been decided to extend the hydraulic one-dimensional SOBEK model of the Rhine-Meuse Delta with the processes sediment transport and morphology. The flow in this adjusted model has been simplified by neglecting salt intrusion, because SOBEK-RE cannot compute both salt intrusion and morphology.

A uncalibrated, unverified model has thus been used to simulate morphology in this study. Therefore, the analysis of the simulated bed level changes has been limited to determining the relative differences between simulations.

This section describes the approach of analysing bed level changes in the Merwedes. Section 4.2.1 contains a short description of the studied aspects. The adjustments to the hydraulic model are described in section 4.2.2. Section 4.2.3 includes the applied boundary conditions. The schematisation of the bed composition is described in section 4.2.4. Finally, the assumptions of the analysis of bed level changes are included in section 4.2.5.

4.2.1. Aspects

The following aspects have been studied with respect to bed level changes in the Merwedes:

Reference simulation

Starting point of the analysis of bed level changes is a reference simulation with a total duration of 12 years. The results of the first 7 years contain the effects of warming up of the model. The simulation of the last 5 years has been repeated by means of a restart to investigate the effects of various cases relative to the reference simulation.

Tidal influence

The type of tidal boundary condition has a significant effect on the magnitude of the sediment transport in the Merwedes. Therefore, morphological simulations with different sea boundary conditions have been compared with the reference simulation:

- a schematised tidal cycle,
- a constant water level.

A spring-neap cycle has been applied in the reference simulation.

Choice of sediment transport model

The analysis of simulated sediment transport has revealed a large effect of the choice of a sediment transport model on the estimation of the sediment transport. Therefore, a morphological simulation with the sediment transport model of Van Rijn 1993 has been compared with a morphological simulation with Engelund and Hansen.

Dredging

Due to the limited availability of data on dredging activities, the determination of the effect of dredging is limited to obtaining an indication of the effect of dredging on the bed level of the Merwedes.

The morphological effect of dredging has been simulated with a constant lateral withdrawal of sediment. Only dredging in the Boven and Nieuwe Merwede can be simulated, because of instability of the adjusted morphological model. The dredged volumes are based on the mean of the period 2005 until 2008 (Rijkswaterstaat Dienst Zuid-Holland, 2009a) and summarised in table 4.1.

table 4.1. Dredged volumes based on mean of 2005 - 2008

	Dredging volume per river branch [m^3/year]	**Length branch [km]**	**Dredging volume per river branch [m^3/year/m]**
Boven Merwede	159229	8.82	18.05
Beneden Merwede	0 (in reality 51085)	15.12	0 (in reality 3.38)
Nieuwe Merwede	199625	18.92	10.55

Bed level
After a duration of 12 years, the simulated bed level will differ from the initial bed level. The effect of this bed level on flow and sediment transport will be determined by means of a sensitivity analysis.

4.2.2. Adjustments to model
The following adjustments have been made to make the hydraulic model suitable for morphological simulations.

Salt intrusion
It is not possible to simulate simultaneously both salt intrusion and morphological changes in the Rhine-Meuse Delta with the current version of SOBEK-RE[10]. Therefore, the influence of salt intrusion has been neglected in morphological simulations. The area has been set to ‘River’ instead of ‘Estuary’ to eliminate salt intrusion in the SOBEK schematisation and this adjustment allows a simpler computational algorithm for morphology.

Sediment transport
It is assumed that the sediment transport width is equal to or smaller than the flow width and that sediment transport can only take place in the main channel (WL | Delft Hydraulics, 2000, p. 30). This means that sediment transport in the floodplains has been neglected. This assumption also has been made in the SOBEK model of the Rhine branches.

A nodal point relation must be defined for the distribution of sediment over the river branches for all bifurcations in the Rhine-Meuse Delta. Based on the findings of Frings (2005) and Mol (2003), the following power function has been applied:

$$\frac{S_i}{S_j} = \left(\frac{Q_i}{Q_j}\right)^k \cdot \left(\frac{B_i}{B_j}\right)^m$$ in which:

S: [m^3/s] sediment transport
Q: [m^3/s] discharge
B: [m] sediment transport width

The subscripts i and j represents the two downstream branches.
According to Frings (2005), k is 1.9 and m is -0.9 at the Merwedekop. It is assumed that k is 2.0 and m is -1.0 for all other bifurcations (Mol, 2003).

SOBEK-RE contains the sediment transport models of Engelund and Hansen 1967 and the simplified model of Van Rijn 1993. From practical point of view, Engelund and Hansen has been applied as default sediment transport model in this study: the combination of the current schematisation of the Rhine-Meuse Delta and the use of Van Rijn 1993 gives problems in simulations with a duration longer

[10] SOBEK-RE version 2.52.007

than 7 years. This is caused by inconsistency in the description of cross-sections. The effect of the sediment transport model of Van Rijn 1993 has been studied by a restart simulation with a duration of 5 years.

The TMR 2006 model of the Rhine-Meuse Delta is formulated for hydraulic computations and is not set up for morphological simulations. Morphological simulations give some problems after adjustment of the input. Especially in the dead ends of branches and in the western part of the Haringvliet, simulations do not run properly. Since the objective of this study is not preparing a morphological model of the Rhine-Meuse estuary, but describing the system of the Merwedes, the schematisation of the Rhine-Meuse estuary has not been modified. It has been decided to set the calibration factor of the sediment transport model equals to 0 for the following areas:

- A part of the Haringvliet, westerly of the Spui,
- All harbours and branches with dead ends, except the branches with dead ends near the Waal, Merwedes, Biesbosch and Meuse.

In this way, only flow has been computed in these branches and it is assumed that sediment transport is negligibly small in these river branches and estuaries. An overview of calibration factors of the river branches can be found in Appendix IV.

Morphology

To simulate morphological changes with SOBEK, it is necessary that each river branch contains at least 3 grid points. The river branches which consist of just a begin node and an end node, have been refined by adding a grid point.

The numerical settings for morphology have been adopted from the SOBEK model of the Rhine branches. The stability factor is 1.01 and the method of adapting cross-sections is proportional to the depth of the sediment transport width. An exception has been made for the maximum number of time step reductions. A maximum number of time step reductions of 100 instead of 10 has been chosen, because of the size of the network which contains about 140 branches.

For the branch between the Nieuwe Waterweg and the Hartelkanaal near Hook of Holland, a artificial fixed bed layer is used to prevent instability. Without a fixed bed layer, the courant number of the morphological module is larger than unity in this branch and the time step is automatically reduced. The inflow of sediment is then much smaller than the outflow of sediment at this location. This causes large bed level changes which induce numerical instability of the model.

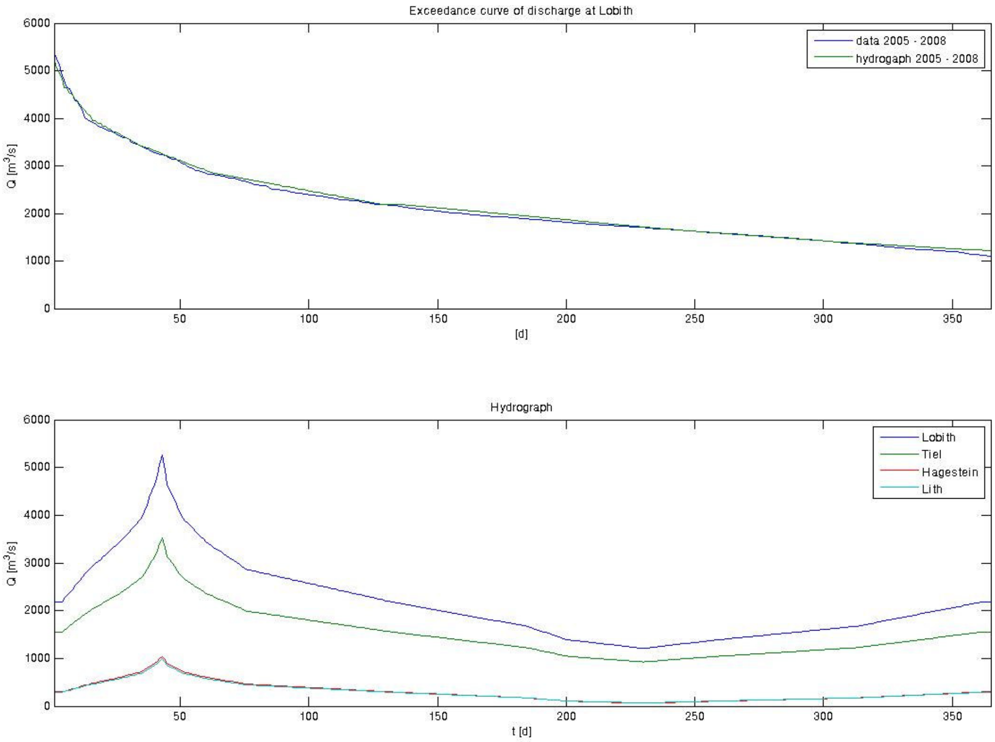
4.2.3. Boundary conditions

Upstream flow boundary conditions

At the upstream boundaries of the SOBEK model of the Rhine-Meuse Delta, a hydrograph has been imposed which has been derived from the time series of the discharge at Lobith from the period 2005 up to 2008 (Rijkswaterstaat, 2009). The hydrographs for the Waal at Tiel, the Nederrijn at Hagestein and the Meuse at Lith have been derived by means of a linear trend line.[11] The exceedance curve of the data and the exceedance curve of the applied hydrograph are visualised in the top subfigure of figure 4.1. The bottom subfigure of figure 4.1 shows the applied hydrographs.

[11] See section 2.2.1 Influence of river discharge

figure 4.1. Upstream boundary conditions: exceedance curve and hydrograph

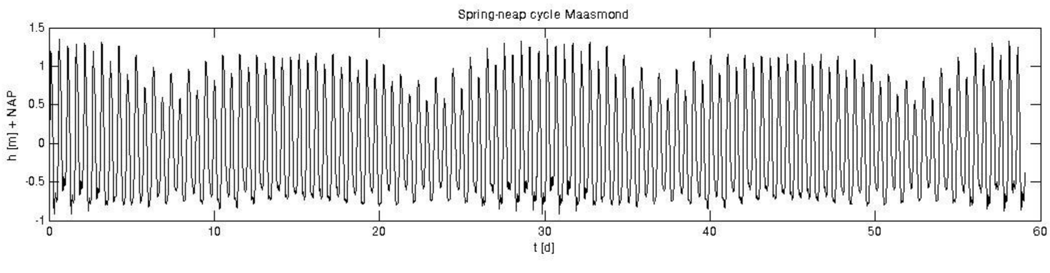


It is not possible to use (measured) time series with daily-averaged discharges as upstream boundary condition, because of the limited stability of the morphological model. According to WL | Delft Hydraulics (2002, p. 27), the maximum Courant number should be smaller than unity for morphological simulations with unsteady flow to guarantee stability. The flow conditions varies less when the hydrograph has been applied instead of time series of the discharge. Hereby, the morphological changes also varies less and the Courant condition can much easier be fulfilled.

Downstream flow boundary conditions

The default downstream flow boundary condition is a spring-neap cycle, because this type of sea boundary condition is a realistic description of the tidal motion on the North Sea. The spring-neap cycle has been based on tidal predictions at the locations Haringvliet-10 and Hook of Holland in the period April 7 2008 until May 6 2008 (Rijkswaterstaat, 2010). This cycle with a period of 29 days, 12 hours and 40 minutes is assumed to be representative and has been repeated continuously. This is visualized in figure 4.2.

figure 4.2. Downstream boundary conditions: spring-neap cycle at Maasmond



Morphological boundary conditions

A morphological boundary condition is needed at inflow boundaries. At outflow boundaries, no morphological boundary condition should be prescribed. Reversal of flow at a boundary complicates the choice of a boundary condition. It has been decided to apply a constant bed level at the sea boundaries, because both inflow and outflow of sediment take place.

It has been decided to apply a constant bed level as upstream morphological boundary condition. SOBEK computes the corresponding inflow of sediment transport to keep the bed on this level.

It is obvious to assume that the sediment transport is equal to zero at the dead end of river branches.

4.2.4. Bed composition

Rhine-Meuse Delta

The bed composition of the branches of the Rhine-Meuse Delta has been approximated by a constant bed composition per river branch (D_{50} and D_{90}) based on averaging of Fugro data (2002). It has been decided to use a constant bed composition per river branch, because of simplicity. The SOBEK schematisation of the Rhine-Meuse Delta consists of about 140 branches and it is outside the scope of this study to set-up a detailed one-dimensional morphological model of the whole Rhine-Meuse Delta. It is recommended to study the effects of the schematisation of the bed composition of the Rhine-Meuse Delta on the simulation results of the Merwedes.

An overview of the schematised bed composition of the river branches can find in Appendix IV.

Waal and Merwedes

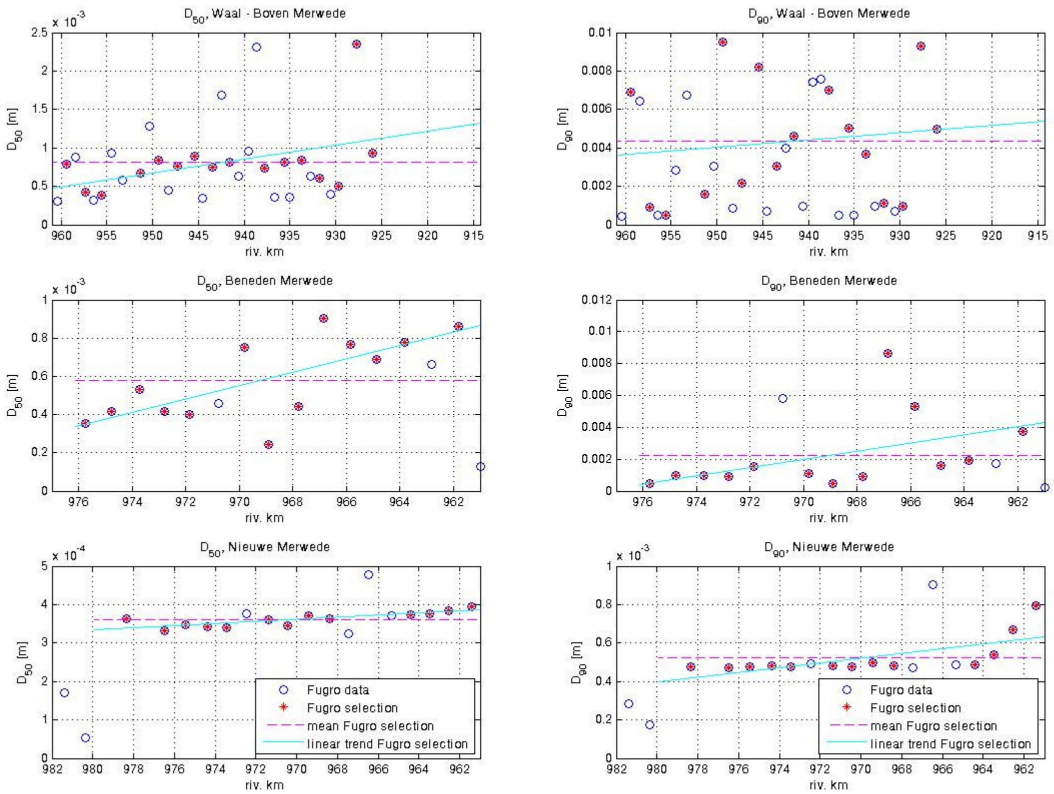
The applied schematisation of the bed composition of the Waal and Merwedes has been based on the data set of Fugro (2002). The Fugro data have been used to schematise the bed composition of the Waal and Merwedes. The river-bed samples of Fugro give the most complete description of the bed composition of the Merwedes, because the number of measurements by Fugro is much larger than the number of measurements by Frings or by Medusa. Respectively 47, 3 and 3 measurements. Errors by differences in measurement methods of the different data sets have been prevented by the choice of one data set. The disadvantage of this choice is that not all available measurements have been used (47 instead of 53 measurements).

The Fugro data may contain undesirable two-dimensional effects such as bend sorting, because some locations of the bed samples do not lie on the axis of the river. Using visual analysis of the coordinates, the position of the measurement locations with respect to river axis is estimated. Only the bed samples near the river axis has been used to schematise the bed composition. For the Waal, Boven Merwede and Beneden Merwede a criterion of 25 % of the normal width is used. For the Nieuwe Merwede, a stricter criterion of 10 % of the normal width is used, because of the high degree of curvature of this river branch.

An alternative method to avoid two-dimensional effects is averaging of the available data over the cross-section. The natural spreading of the bed composition is than better covered, because more measurements will be used with this alternative method. The natural spreading of the bed composition could be caused by the presence of dunes. This alternative method has not been studied in this analysis, but it is recommended to do this in a future study.

In contrast with the sediment transport analysis, another schematisation of the bed composition of the Merwedes has been applied in the morphological simulations. The selection of the Fugro data contains abrupt spatial changes and the inclusion of these large variations in the schematisation could contribute to instability of the model. Assumed is a linear decrease of the grain size in downstream direction of these branches based on a selection of Fugro data. This linear trend represents a downstream fining of the bed material The schematised bed composition is visualised in figure 4.3 (linear trend). The left subfigures contain the schematisation of D_{50}. The right subfigures show the schematisation of D_{90}. The horizontal axis represents the location along the river.[12] It is noted that different vertical scales are used in the subfigures. A linear interpolation seems to be acceptable, because the selection of the Fugro data of the Beneden Merwede (middle subfigures) and Nieuwe Merwede (bottom subfigures) shows a downstream fining of the bed material. The selection of Fugro data of the Waal - Boven Merwede also gives a downstream decrease of the grain size, but this is less clear (top subfigures). It is recommended to investigate the effects of the choice of a schematisation of the bed composition on the results of the simulations.

figure 4.3. Schematised grain size of the bed material in the Waal and Merwedes, for morphological model



4.2.5. Assumptions

It is assumed that the adjusted one-dimensional SOBEK model “TMR 2006 Benedenrivierengebied” gives a reasonable description of the flow in the Rhine-Meuse Delta. The influence of salt intrusion on flow, sediment transport and morphology in the Rhine-Meuse Delta has been neglected in this adjusted model. The influence of salt intrusion on flow in the Merwedes is described in section 2.4 and the consequences for sediment transport are described in section 3.4.

Also, the following aspects have been neglected in the morphological simulations:

- The influence of storm set-up at the seaward boundary
- The influence of local wind within the model area
- The influence of two-dimensional and three-dimensional effects
- Time effects of real flood waves (e.g. hysterese)
- The influence of changes in the control of the Haringvliet sluices

[12] In the figures in this report, the upstream side is at the right side.

- Possible restricted availability of sediment by for instance fixed bed layers
- Sand-mud interaction
- Transport and erosion of mud
- Sediment sorting processes
- The presence of wash load
  Wash load does not contribute to the morphology of the low water bed in the Merwedes, but it is important for the morphology of groyne fields and floodplains.
- Effects of local dredging
  It is assumed that the dredging volume is constant along a river branch.
- The real presence of fixed bed layers in the river bed.

It is assumed that the influence of variation in upstream discharge and the interaction of the river discharge with the tide can be represented by the combination of a hydrograph as upstream boundary condition and a spring-neap cycle as downstream boundary condition.

In addition, it is assumed is that the magnitude of the sediment inflow is such that the bed levels of the upstream boundaries remain the same. In reality, the bed level on these locations could change in time.

It is assumed is that the mean bed level of the main channel is a representative parameter of the bed level.

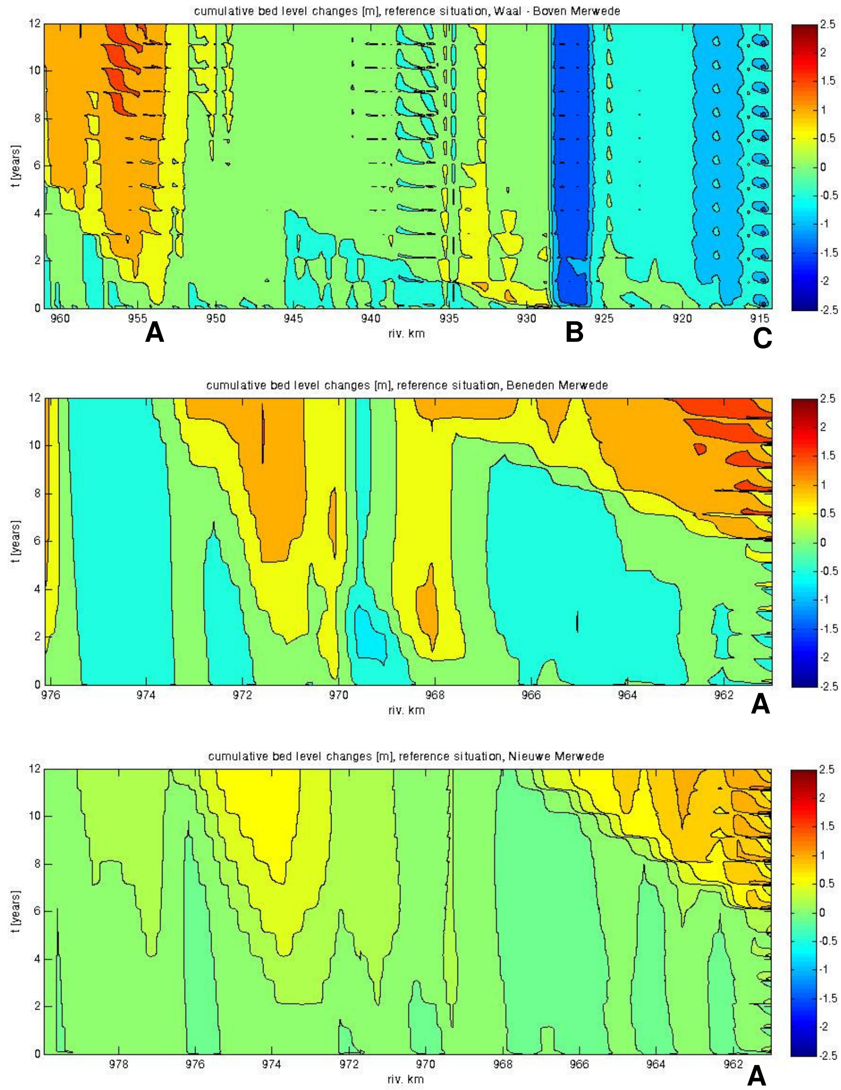
4.3. Reference simulation

Large bed level changes occur during the reference simulation. Figure 4.4 shows the cumulative bed level changes in this simulation for the Waal - Boven Merwede (top subfigure), Beneden Merwede (middle subfigure) and Nieuwe Merwede (bottom subfigure) relative to the initial bed level. The horizontal axis represents the location along the river. The vertical axis represents the simulation time of 12 years.

Three main types of bed level changes are visible:

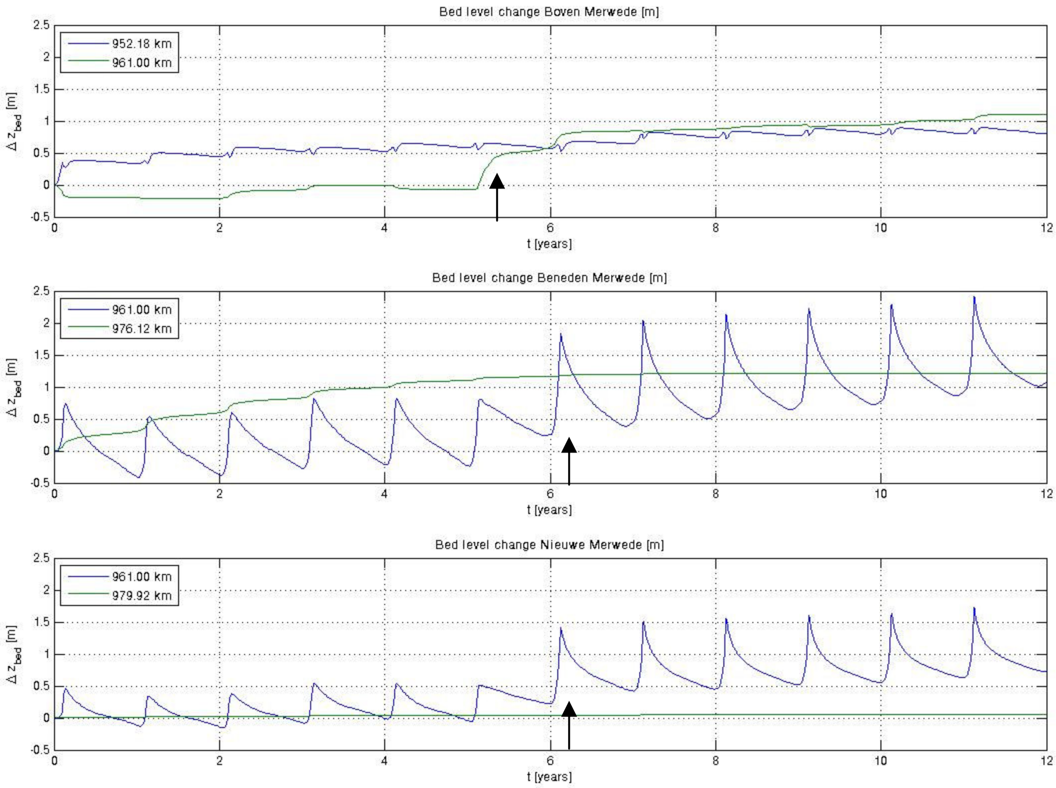
- Bed waves which move in downstream direction
  For instance, filling up of the main channel in downstream direction. This takes place in the Boven Merwede between 953 km and 961 km. This bed wave arrives at the Merwedekop (961 km) after 6 years and moves into the Beneden Merwede and Nieuwe Merwede. This situation is marked with a bold “A” in figure 4.4. This bed wave travels with a celerity of about 1 km/year.
- Bed level changes which do not move
  For instance, local erosion occurs in the Waal at 927 km (bold “B in figure 4.4). The initial local narrowing of the river at this location causes a local high sediment transport capacity. The sediment transport capacity decreases until the sediment transport capacity is equal to the sediment inflow. This is the case after an erosion of about 1.5 m.
- Bed level changes which have a period of one year
  For instance, both erosion and sedimentation occurs in the Waal at 915 km (bold “C” in figure 4.4). his is caused by the variations in sediment inflow (and river discharge). The period of one year corresponds to the duration of the hydrograph. This is an artificial seasonal influence. In reality, the discharge variation is irregularly.

figure 4.4. Cumulative bed level changes in reference simulation as function of location and time



The simulated bed level changes in the Merwedes have an order of magnitude of about 1 m. up to 2 m. This is also visible in figure 4.5. This figure shows the cumulative bed level change at the upstream and downstream side of the Boven Merwede, Beneden Merwede and Nieuwe Merwede during the reference simulation. The horizontal axis represents the simulation time. The large bed wave is also visible in all the subfigures of figure 4.5. This sedimentation front passes the Merwedekop (961 km) after 6 years (see arrows). Therefore, the starting point of the restart of the morphological simulations is chosen after 7 years.

figure 4.5. Development of bed level during reference simulation as function of time



The cumulative change of the mean bed level of the Merwedes after 7 years and after 12 years of simulation is quantified in table 4.2. It is striking that the mean bed level of the Merwedes is rising during the simulation.

- The bed level change in the Boven Merwede slows down during the simulation. This could indicate that the Boven Merwede is near a dynamic morphological equilibrium. This does not mean that it matches with the real physical equilibrium situation of this river branch.
- The bed level changes in the Beneden and Nieuwe Merwede accelerate during the simulation. These branches are not in equilibrium.

The main characteristics of the reference simulation can be found Appendix V.

table 4.2. Cumulative change of mean bed level of the Merwedes after 7 years and after 12 years

	Δz_{bed} [m] after 7 years	**Δz_{bed} [m] after 12 years**
Boven Merwede	1.08	1.33
Beneden Merwede	0.34	0.93
Nieuwe Merwede	0.18	0.49

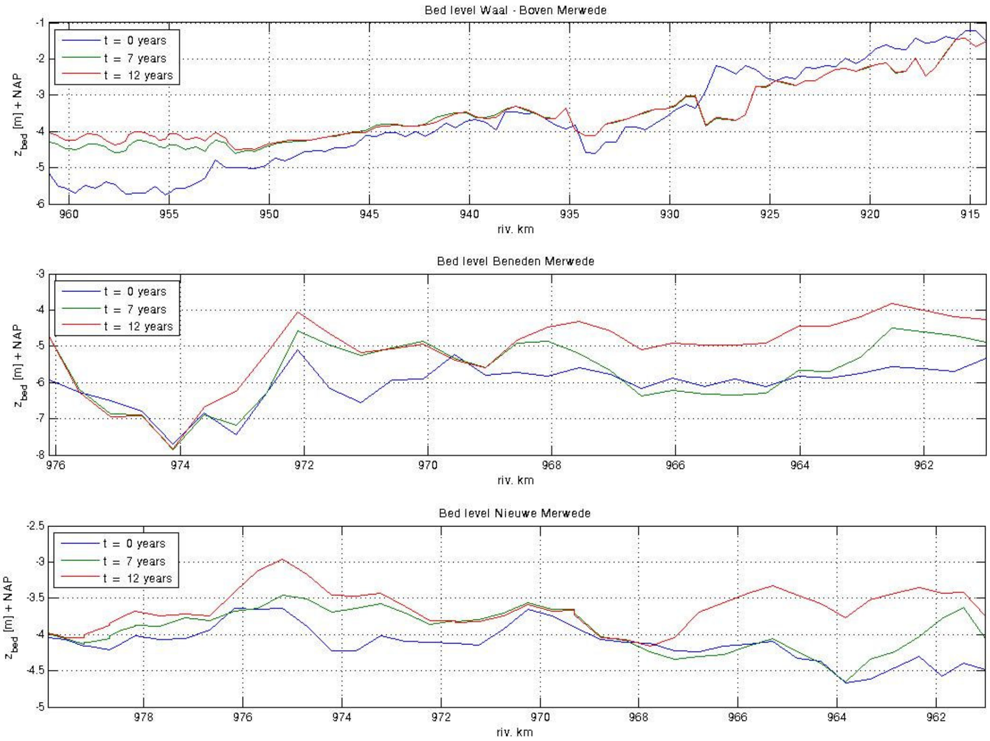
It is not possible to predict morphological changes of the Merwedes with the adjusted model, because the simulated bed level changes have another order of magnitude than the measured bed level changes. Compare table 4.2 with the multibeam bed level in figure 3.19. Therefore, the effect of sea boundary conditions, the effect of the choice of a sediment transport model and the effect of dredging will be determined relative to the reference simulation.

Furthermore, it is dubious whether the adjusted model is representative for the real situation of the Merwedes after 12 years of simulation. Therefore, a sensitivity analysis has been done to investigate the effect of the bed level on flow and sediment transport.

4.4. Sensitivity analysis - effect bed level on flow and sediment transport

The aim of this sensitivity analysis is to determine the interaction of morphology and flow in the Merwedes. The local differences between the simulated bed level and the initial bed level of the Merwedes are namely large: up to 1.7 m. This is visualised in figure 4.6. This figure shows the simulated bed level of the Waal and Merwedes at the beginning of the simulation, after 7 years of simulation and after 12 years of simulation.

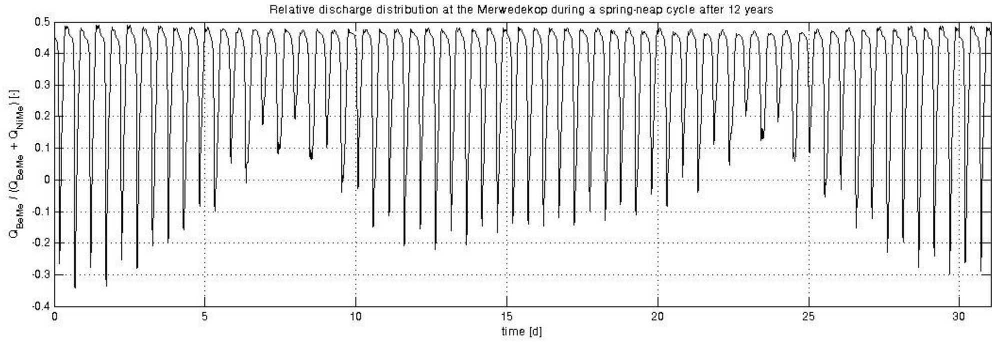
figure 4.6. Simulated bed level at t = 0 years, t = 7 years and t = 12 years



In addition, the bed level in the other branches of the Rhine-Meuse Delta also has been changed during the simulation.

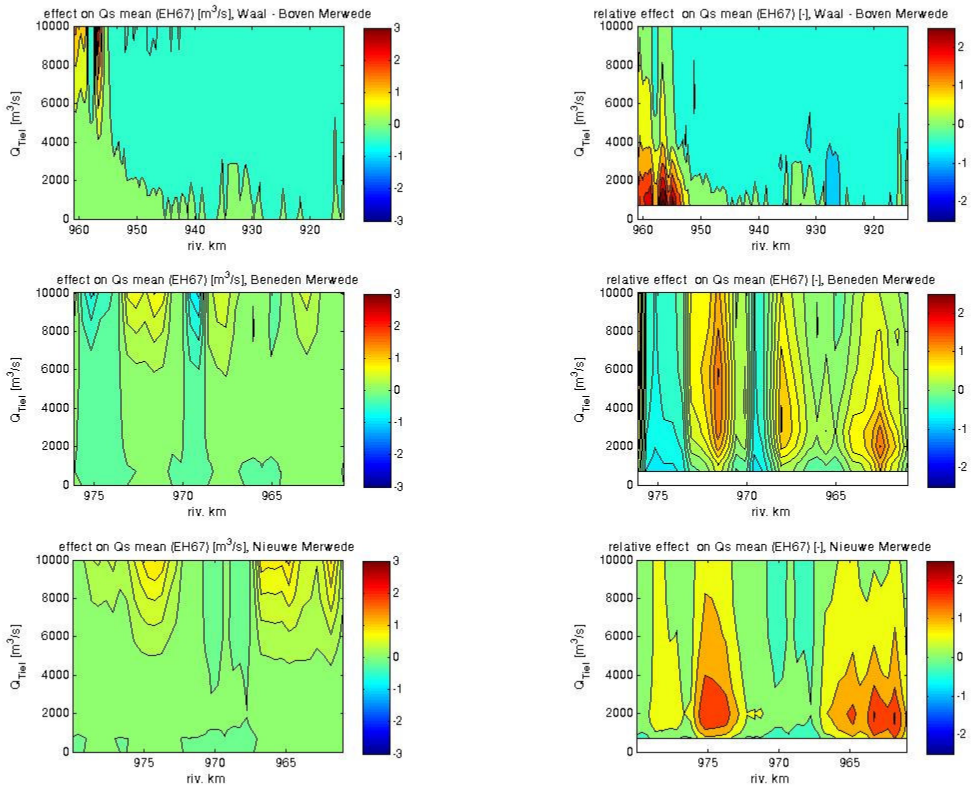
The simulated bed level influences interaction between tide and river discharge. This can be illustrated by the discharge distribution at the Merwedekop during a spring-neap cycle. Figure 4.7 shows the expected value of the relative discharge distribution at the Merwedekop during a spring-neap cycle with the bed level after 12 years morphological simulation. A comparison with figure 2.8 shows that the minimum relative discharge distribution is -0.35 (bed level at t = 12 years) instead of - 1.9 (initial bed level). This means that the flow circulation from the Beneden Merwede via the Merwedekop in the Nieuwe Merwede is weaker in the case of the simulated bed level than in the case of the initial bed level.

figure 4.7. Expected value of the relative discharge distribution at the Merwedekop during a spring-neap cycle in the case of the simulated bed level (t = 12 years)



The mean sediment transport in the Waal and Merwedes is strongly influenced by the bed level. The effect of the simulated bed level (t = 12 years) on the mean sediment transport is visualised in figure 4.8. The location along the river branch is on the horizontal axis. The vertical axis represents the upstream discharge at Tiel. The left subfigures shows the difference in mean sediment transport between the mean sediment transport after 12 years of simulation and the initial mean sediment transport. The right subfigures shows the relative effect of the bed level on mean sediment transport. The differences of the mean sediment transport (Engelund and Hansen) relative to the initial bed level are between - 92 % and + 314 %.

figure 4.8. Effect of the simulated bed level (t = 12 years) on the means sediment transport relative to the initial bed level, based on Engelund and Hansen 1967



The relative effect of the bed level on the expected value of sedimentation is quantified in tables 4.3 and 4.4. Using the simulated bed level gives an underestimation of the expected sedimentation in the Boven Merwede of about - 66 % (Engelund and Hansen 1967) or - 77 % (Van Rijn 1993). The effect on the sedimentation in the Beneden Merwede is much smaller: between - 7 % (Engelund and Hansen 1967) and + 13 % (Van Rijn 1993). The expected sedimentation in the Nieuwe Merwede is strongly influenced by the bed level: between + 68 % (Engelund and Hansen 1967) and + 78 % (Van Rijn 1993).

Furthermore, using the simulated bed level gives an underestimation of the effect of a sea boundary condition on the expected sedimentation.

table 4.3. Difference in expected value of sedimentation and erosion in the Merwedes relative to the case of a spring-neap cycle and the initial bed level, based on Engelund and Hansen 1967

River branch	Sea boundary condition	Simulation with initial bed level and with salt intrusion relative to reference simulation	Simulation with bed level after 12 years and without salt intrusion relative to reference simulation
Boven Merwede	spring-neap cycle	reference simulation	-66.2%
Boven Merwede	tidal cycle	-1.5%	-65.5%
Boven Merwede	constant water level	5.7%	-66.0%
Beneden Merwede	spring-neap cycle	reference simulation	-7.4%
Beneden Merwede	tidal cycle	-3.1%	-8.8%
Beneden Merwede	constant water level	-9.1%	-8.1%
Nieuwe Merwede	spring-neap cycle	reference simulation	67.6%
Nieuwe Merwede	tidal cycle	-0.9%	65.5%
Nieuwe Merwede	constant water level	-11.1%	61.4%

table 4.4. Difference in expected value of sedimentation and erosion in the Merwedes relative to the case of a spring-neap cycle and the initial bed level, based on Van Rijn 1993

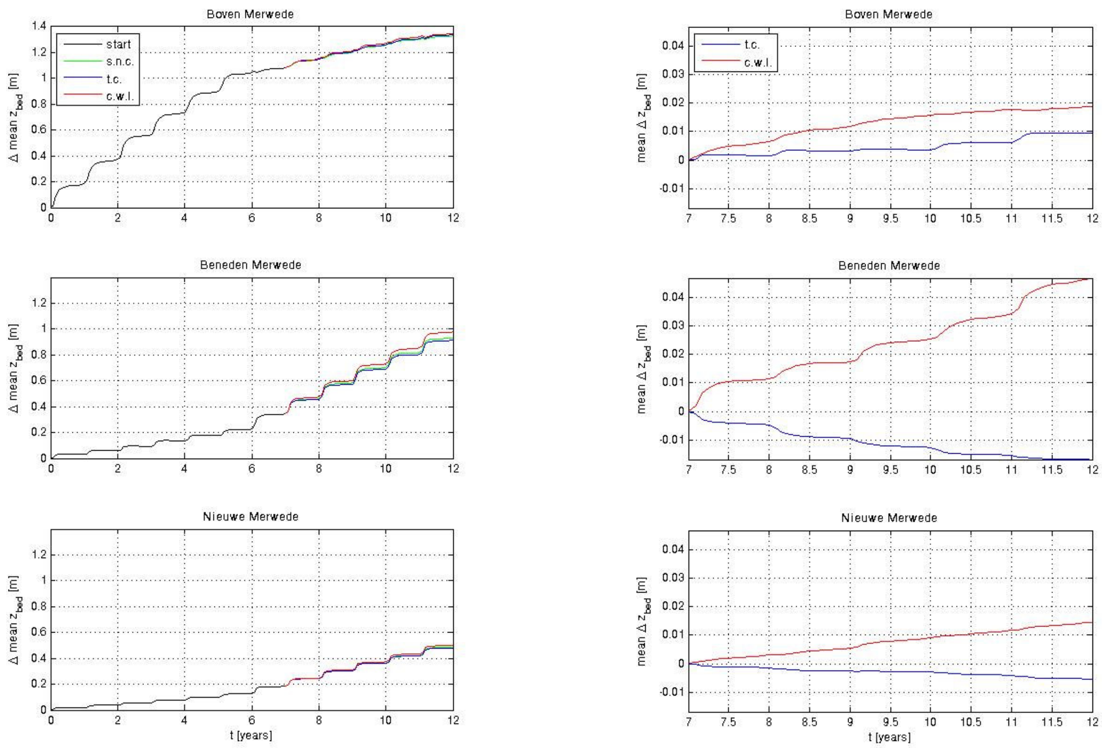
River branch	Sea boundary condition	Simulation with initial bed level and with salt intrusion relative to reference simulation	Simulation with bed level after 12 years and without salt intrusion relative to reference simulation
Boven Merwede	spring-neap cycle	reference simulation	-77.2%
Boven Merwede	tidal cycle	-2.1%	-75.9%
Boven Merwede	constant water level	8.1%	-75.6%
Beneden Merwede	spring-neap cycle	reference simulation	12.5%
Beneden Merwede	tidal cycle	-3.3%	10.1%
Beneden Merwede	constant water level	-11.1%	6.4%
Nieuwe Merwede	spring-neap cycle	reference simulation	78.1%
Nieuwe Merwede	tidal cycle	0.2%	77.3%
Nieuwe Merwede	constant water level	-13.8%	70.1%

4.5. Effects

4.5.1. Tidal influence

The effect of sea boundary conditions on bed level changes of the Merwedes has been determined relative to the reference simulation. In the reference simulation a spring-neap cycle is used as sea boundary condition. Figure 4.9 shows the effect of sea boundary conditions on the mean bed level of the Merwedes. The horizontal axis represents the time. The cumulative change of the mean bed level relative to the initial bed level is visualised in the left subfigures. The right subfigures show cumulative change of the mean bed level relative to the reference simulation.

figure 4.9. Effect of sea boundary conditions on the mean bed level relative to the reference simulation with a spring-neap cycle, based on Engelund and Hansen 1967



The model simulates an increase in sedimentation if the tide is neglected. Replacing the spring-neap cycle by a tidal cycle gives an increase of sedimentation in the Boven Merwede and a decrease in the Beneden and Nieuwe Merwede. The relative effect of the sea boundary condition on bed level changes, based on morphological simulations with the adjusted model, is summarised in table 4.5. The relative sedimentation rates are not real values, but show that the tide influences bed level changes. The main characteristics of the simulation with a tidal cycle and a constant water level can be found Appendix V.

table 4.5. Effect of sea boundary condition on mean bed level relative to spring-neap cycle

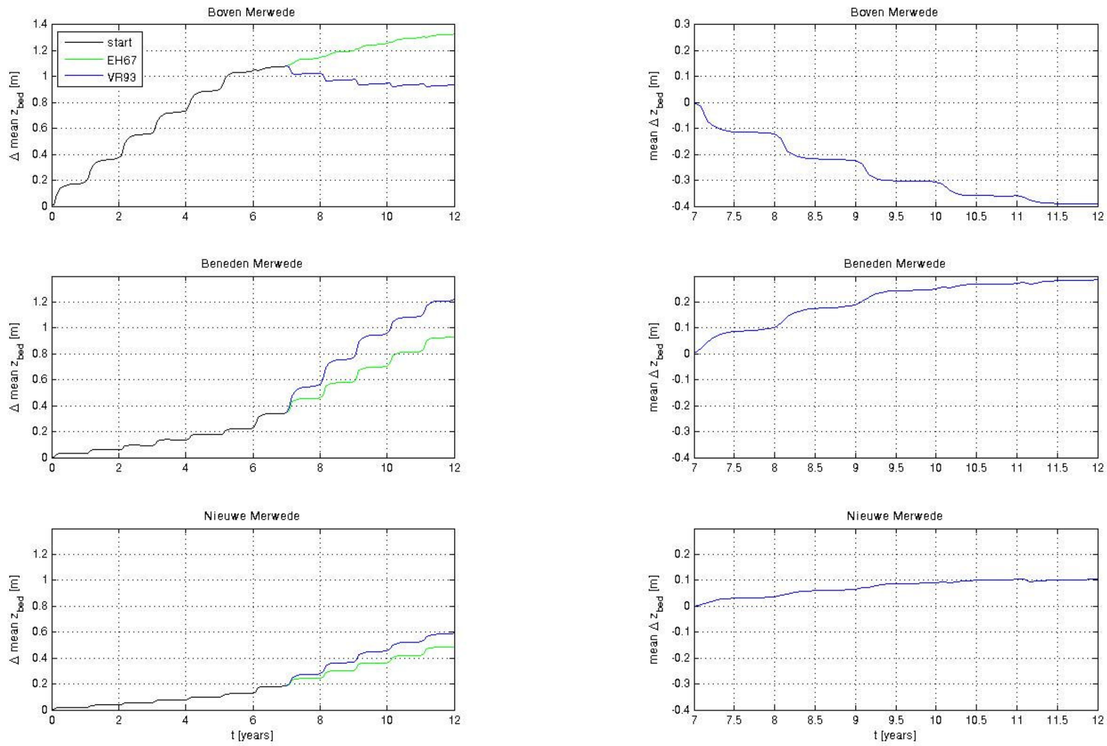
	relative effect on mean z_{bed} Boven Merwede [m / 5 years]	**relative effect on mean z_{bed} Beneden Merwede [m / 5 years]**	**relative effect on mean z_{bed} Nieuwe Merwede [m / 5 years]**
tidal cycle instead of spring-neap cycle	+0.009	-0.017	-0.005
constant water level instead of spring-neap cycle	+0.018	+0.047	+0.014

Based on the morphological simulations, it could be concluded that the type of the sea boundary condition has a small effect on bed level changes in the Boven and Nieuwe Merwede. The tidal influence on morphology seems to be a factor 3 larger in the Beneden Merwede than in the Boven Merwede and Nieuwe Merwede. The influence of neglecting of the tide is larger than using a schematised tidal cycle instead of a spring-neap cycle.

4.5.2. Choice of sediment transport model

The effect of the choice of a sediment transport model on bed level changes of the Merwedes has been determined by comparison of a simulation with Van Rijn 1993 by the reference simulation with Engelund and Hansen 1967. Figure 4.10 shows the effect of the choice of a sediment transport model on the mean bed level of the Merwedes. The horizontal axis represents the time. The cumulative change of the mean bed level relative to the initial bed level is visualised in the left subfigures. The right subfigures show cumulative change of the mean bed level relative to the reference simulation.

figure 4.10. Effect of the choice of Van Rijn 1993 instead of Engelund and Hansen 1967 on the mean bed level



Using Van Rijn 1993 instead of Engelund and Hansen 1967 gives erosion in the Boven Merwede and an increase of the sedimentation in the Beneden and Nieuwe Merwede. The relative effect of the choice of a sediment transport model on bed level changes, based on morphological simulations with the adjusted model, is summarised in table 4.6. The relative sedimentation rates are not real values, but show that the results of morphological simulations in the Merwedes are very sensitive to the choice of a sediment transport model.

Therefore, it is highly recommended to investigate the sediment transport mechanisms in the Merwedes to reduce the uncertainty in the morphological simulations.

table 4.6. Effect of sediment transport model of Van Rijn 1993 on bed level relative to Engelund and Hansen 1967

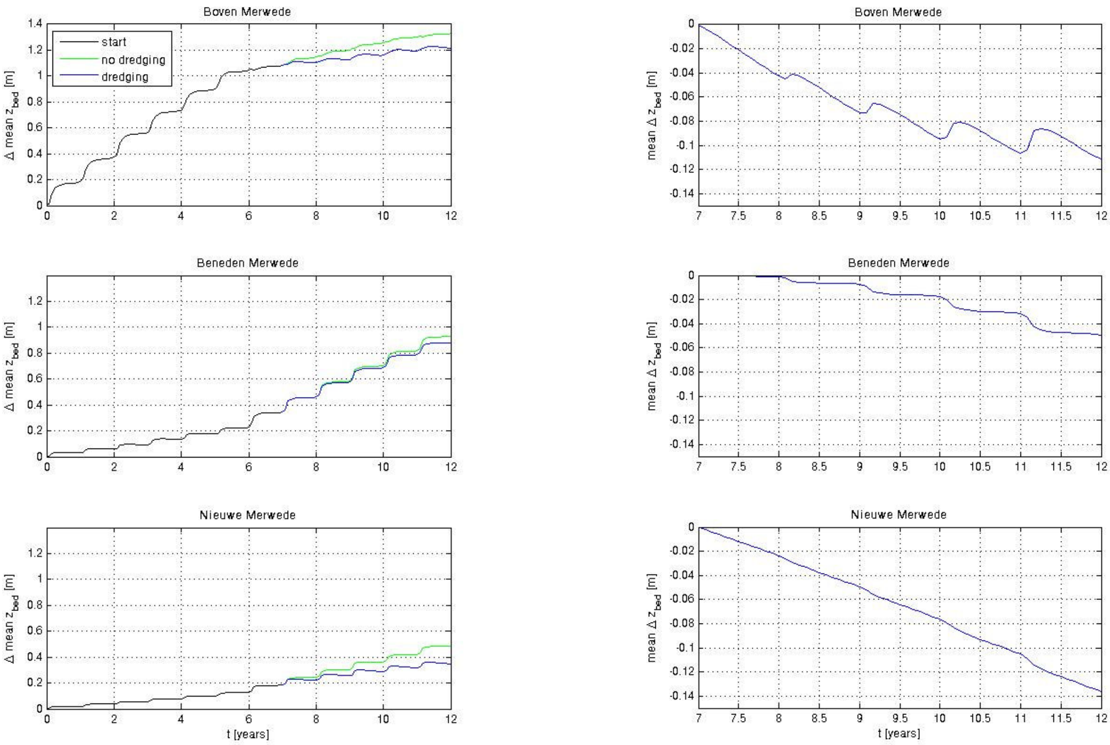
	relative effect on mean z_{bed} Boven Merwede [m / 5 years]	**relative effect on mean z_{bed} Beneden Merwede [m / 5 years]**	**relative effect on mean z_{bed} Nieuwe Merwede [m / 5 years]**
Van Rijn 1993 instead of Engelund and Hansen 1967	-0.391	+0.286	+0.105

The main characteristics of the simulation with Van Rijn 1993 can be found Appendix V.

4.5.3. Dredging

The morphological effect of dredging has been simulated with a constant lateral withdrawal of sediment in the Boven Merwede and Nieuwe Merwede. The effect of dredging in the Boven and Nieuwe Merwede on bed level changes in the Boven, Beneden and Nieuwe Merwede is visualised in figure 4.11. The horizontal axis represents the time. The cumulative change of the mean bed level relative to the initial bed level is visualised in the left subfigures. The right subfigures show cumulative change of the mean bed level relative to the reference simulation without dredging.

figure 4.11. Effect of dredging on the mean bed level relative to the reference simulation without dredging, based on Engelund and Hansen 1967



The effect of dredging appears to be larger than the effect of the type of sea boundary conditions. Dredging in the Boven and Nieuwe Merwede causes a decrease of the sedimentation in the Merwedes. Because of dredging in the Boven Merwede, less sediment flows into the Beneden Merwede and gives a decrease of sedimentation in the Beneden Merwede. The relative effect of the dredging in the Boven and Nieuwe Merwede on bed level changes, based on morphological simulations with the adjusted model, is summarised in table 4.7. The main characteristics of the simulation with dredging can be found Appendix V.

table 4.7. Relative effect of dredging on bed level

	relative effect on mean z_{bed} Boven Merwede [m / 5 years]	**relative effect on mean z_{bed} Beneden Merwede [m / 5 years]**	**relative effect on mean z_{bed} Nieuwe Merwede [m / 5 years]**
dredging in Boven and Nieuwe Merwede	-0.112	-0.050	-0.137

It is recommended to include dredging in morphological simulations of the Merwedes. In addition, it is recommended to investigate the location and time of the dredging activities and the composition of the dredged volumes.

4.6. Conclusions

The morphological simulations give insight in the relevant aspects of the modelling of bed level changes in the Merwedes. The following conclusions can be drawn based on the analysis of morphological simulations.

Accuracy of morphological simulations

Only qualitative conclusions can be drawn from this analysis of bed level changes, because the accuracy of the morphological simulations is limited. The sensitivity analysis shows that the results are strongly influenced by the simulated bed level:

- The differences of the mean sediment transport (Engelund and Hansen) relative to the initial bed level are between - 92 % and + 314 %.
- Using the simulated bed level gives differences in the sedimentation per river branch from - 77 % up to + 78 %.

Tidal influence

Based on the morphological simulations, it could be concluded that the type of the sea boundary condition has a small effect on bed level changes in the Boven and Nieuwe Merwede. The tidal influence on morphology seems to be a factor 3 larger in the Beneden Merwede than in the Boven Merwede and Nieuwe Merwede. From the sensitivity analysis, it follows that using the simulated bed level gives an underestimation of the effect of a sea boundary condition on the expected sedimentation.

Influence of choice of sediment transport model

The results of morphological simulations are very sensitive to the choice of a transport model.

Influence of dredging

Dredging has a significant effect on the morphological development of the Merwedes. The effect of dredging appears to be larger than the effect of the type of sea boundary conditions.

Influence of salt intrusion

The process salt intrusion cannot be included in morphological simulations with the adjusted model, because SOBEK-RE cannot simulate both salt intrusion and morphology. The influence of salt intrusion on morphology is unknown, but could be serious based on analysis of sediment transport (section 3.4).

Ranking of modelling aspects

The following ranking has been determined with respect to the relevance for one-dimensional morphological modelling of the Merwedes which is based on the analysis of simulated sediment transport (chapter 3) and simulated bed level changes (this chapter):

1. Including variations in river discharges
2. The choice of a accurate sediment transport model
3. Including the tidal influence in the Waal and Merwedes
4. Including salt intrusion in the Rhine-Meuse Delta
5. Using a spring-neap cycle instead of a schematised tidal cycle as sea boundary condition

This ranking applies to the yearly sediment transport (or the expected value). These adjustments improve the simulation of the autonomous development of the bed level of the Merwedes.

The ranking of modelling aspects varies between the Merwedes at specific discharges. The influence of the tide on the mean sediment transport in the Beneden Merwede is much larger than the choice of a sediment transport model (see figure 3.11). This is relevant to determination of morphological effects of a measure at a specific river discharge.

5. CASE STUDY AVELINGEN

5.1. Introduction

In this chapter, the obtained knowledge has been applied to floodplain excavation Avelingen. Section 5.2 describes the background of this case study. The approach of this case study is described in section 5.3. The relative effects of the preferred alternative on flow are presented in section 5.4. The relative effects on sediment transport in section 5.5. Section 5.6 gives the relative effects on morphology. The discussion of the results of this case study is described in section 5.7. The conclusions with respect to Avelingen are summarised in section 5.8.

5.2. Background

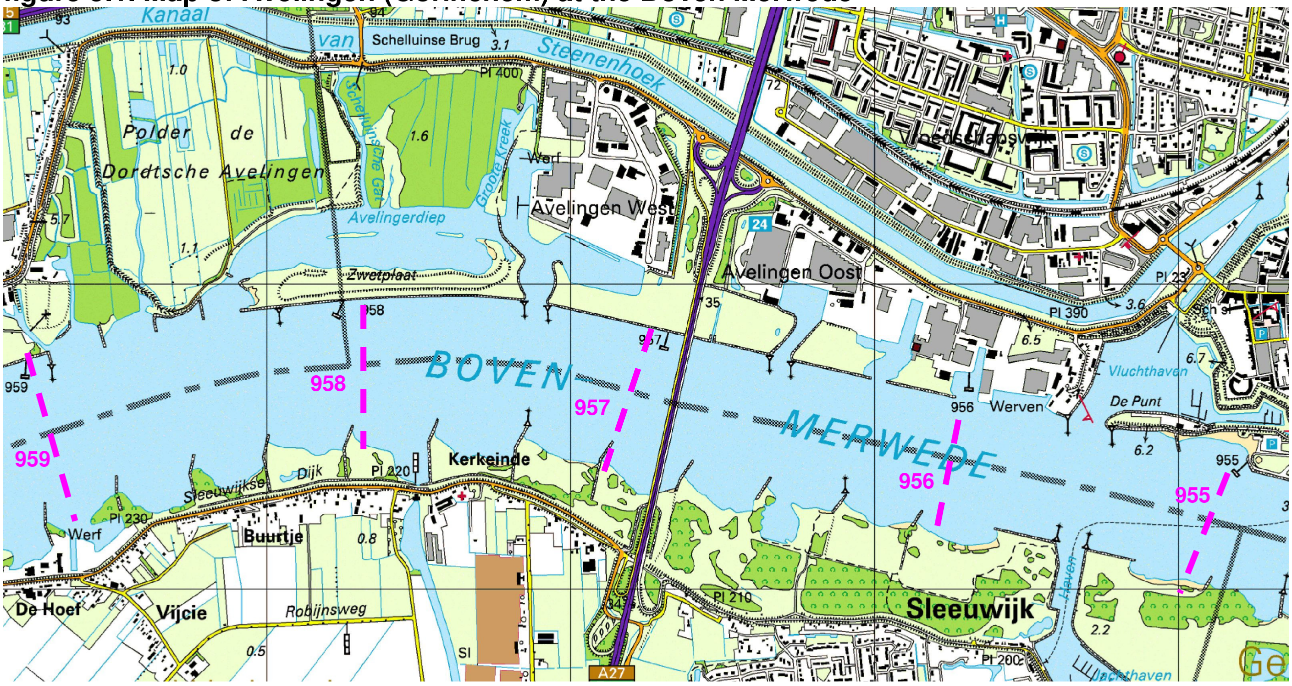
5.2.1. Framework

The policy of the Dutch government with respect to river management is directed to give rivers more space to improve safety against flooding. The additional purpose is to improve the environmental quality of the river basin. The government has point out some locations where measures will be taken by means of PKB Room for the River.

Floodplain excavation Avelingen at Gorinchem is one of the measures within the frame work of Room for the River. The buildings of industrial zone Avelingen cause a local narrowing of the river Boven Merwede. This increases the water level in case of extreme discharges. To give the river more space, the floodplain near the industrial zone Avelingen will be excavated and a side channel will be dug under the bridge.

The location of Avelingen is visualised in figure 5.1. The distance along the river Boven Merwede is marked in this map.

figure 5.1. Map of Avelingen (Gorinchem) at the Boven Merwede



The local authority of Gorinchem gave order to Witteveen+Bos to make a plan study for the rearrangement of Avelingen. Relevant part of this plan study is the determination of the hydraulic and morphological effects of floodplain excavation Avelingen (Witteveen+Bos, 2008).

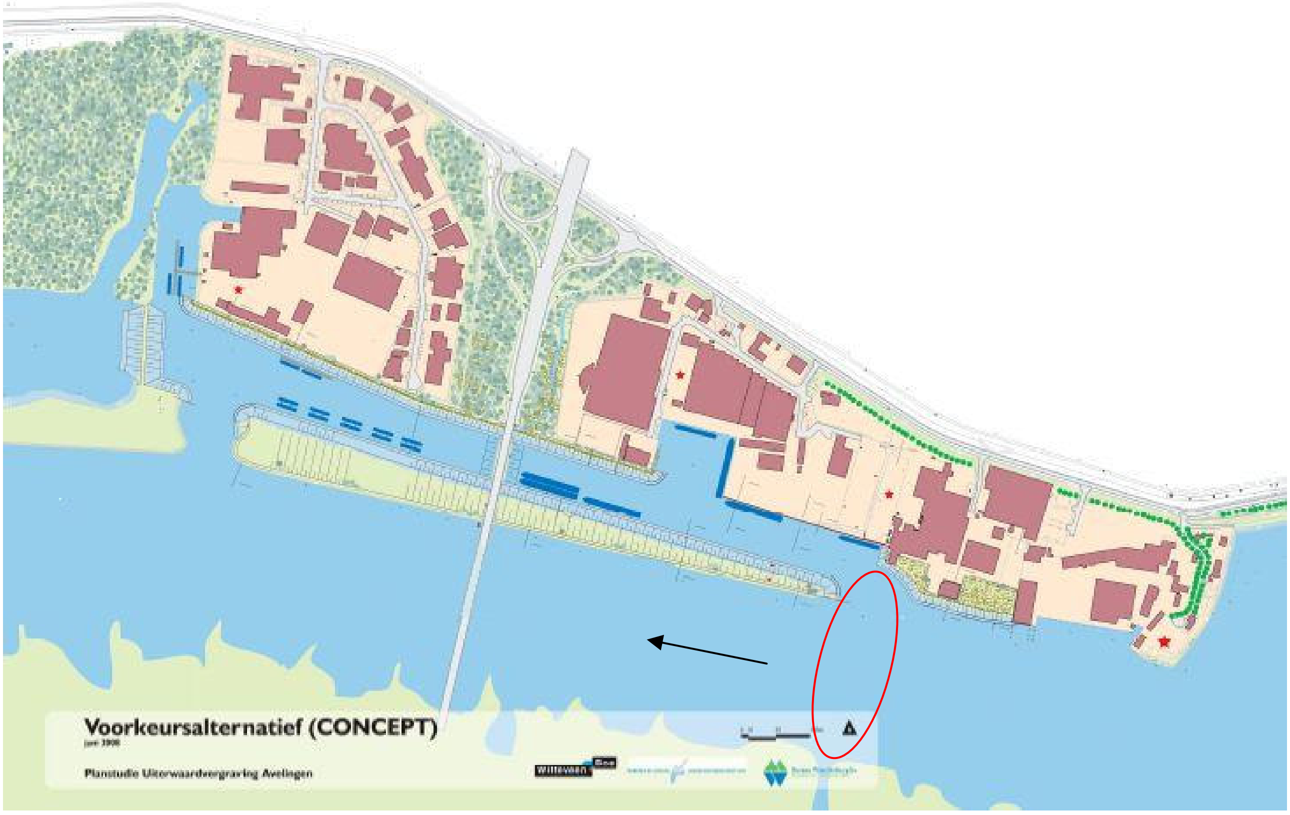
5.2.2. Description of preferred alternative

The preferred alternative of floodplain excavation Avelingen contains a channel in the foreland of industrial zone Avelingen with a width of 100 m at the inflow opening and a width of 140 m at the downstream side. In addition, the preferred alternative contains the following parts (Witteveen+Bos, 2008, p. 20):

- Removing the storage area of MERCON and replacing the crane railway on piles
- Filling up of a small and larger harbour
- Constructing a sill under the existing bridge on a level of 2 m + NAP and maintaining the existing sill in the scenic area.
- Removing the Damen headland
- Constructing a guide dam

Figure 5.2 gives an overview of the preferred alternative of floodplain excavation Avelingen. The inflow opening of the side channel is marked with a red oval. The flow direction of the Boven Merwede is represented by an black arrow.

figure 5.2. Overview of preferred alternative of floodplain excavation Avelingen



5.3. Approach

The preferred alternative of floodplain excavation Avelingen has been compared to the reference situation. The effects of floodplain excavation Avelingen have been studied by analysing flow, sediment transport and morphology. Finally, the relevance of the conclusions of the analyses of flow, sediment transport and bed level changes for the analysis of the morphological effects of floodplain excavation Avelingen has been examined.

Flow

The effect of floodplain excavation Avelingen on flow in the Waal and Merwedes has been investigated by means of a Fourier analysis of simulated flow. This analysis is restricted to the combination of 9 stationary discharges at the upstream boundaries and a spring-neap cycle at the sea boundaries. The approach of the one-dimensional flow analysis is described in section 2.2.

Sediment transport
The effect of floodplain excavation Avelingen on the mean sediment transport in the Waal and Merwedes has been analysed by post-processing of flow simulations. The applied method corresponds to the one-dimensional analysis of sediment transport which is described in section 3.2.

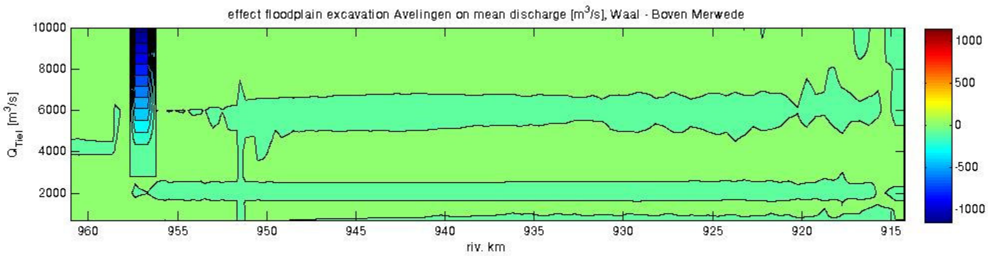
Morphology
The morphological effects of the floodplain excavation have been determined with the adapted model of the Rhine-Meuse Delta. It is not possible to restart the simulation with an adjusted schematisation, because of the fact that the grid of the preferred alternative is different from the reference situation. Therefore, the simulation with the floodplain excavation starts at t = 0.

The implementation of the preferred alternative in the SOBEK model of the Rhine-Meuse Delta is described in Witteveen+Bos (2008, bijlage III).

5.4. Effects on flow

Floodplain excavation Avelingen influences the flow in the Boven Merwede and Waal. Figure 5.3 shows the effect of the side channel at Avelingen on the mean discharge in the main channel of the Waal – Boven Merwede. The distance along the river is on the horizontal axis.[13] The vertical axis represents the upstream discharge. The side channel withdraws water from the main channel of the Boven Merwede at 956.18 km and the discharge of the side channel confluences with the main channel at 957.38 km. When the discharge of the Waal is larger than about 2800 - 4000 m^3/s, the side channel flows. The discharge in the side channel is 1146 m^3/s in case of an upstream discharge of 10.000 m^3/s. The flow distribution at the bifurcation Merwedekop remains almost unaltered compared to the reference situation (not visualised).

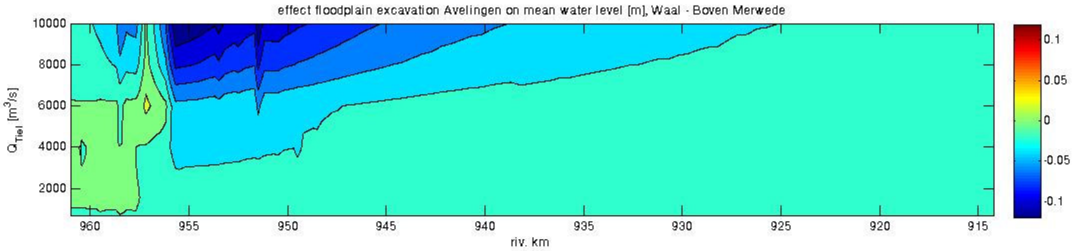
figure 5.3. Effect of floodplain excavation Avelingen on mean discharge in Waal and Merwedes



The effect of floodplain excavation Avelingen on the mean water level in the Waal –Boven Merwede is visualised in figure 5.4. The horizontal axis represents again the location along the river. The side channel causes a lowering of the mean water level in the Waal - Boven Merwede. This effect is known as a backwater curve effect. The largest lowering of the mean water level is located direct upstream of the side channel. The lowering of the mean water level decreases in upstream direction. When the upstream discharge is 10.000 m^3/s, the lowering of the mean water level at 955 km is 0.114 m in SOBEK.

[13] In the figures in this report, the upstream side is at the right side.

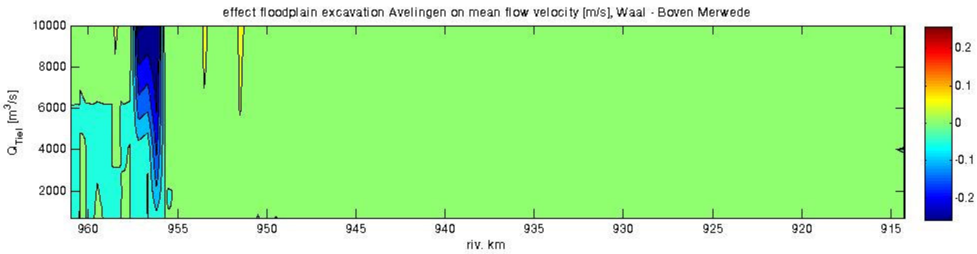
figure 5.4. Effect of floodplain excavation Avelingen on mean water level in Waal and Merwedes



Floodplain excavation Avelingen causes a decrease of the flow velocity in the main channel of the Boven Merwede. This is visible in figure 5.5. Figure 5.5 shows the effect of floodplain excavation Avelingen on the mean flow velocity as function of the location (horizontal axis) and the discharge (vertical axis).

- The floodplain excavation causes a lowering of the flow velocity in the main channel at the inflow opening of the side channel under all circumstances. At this location the cross-section is wider than in the reference situation.
- When the side channel flows, the flow velocities in the main channel are smaller than in the reference situation due to the reduction of the discharge in the main channel.
- The maximum effect is a lowering of the mean flow velocity of 0.25 m/s.
- The local increases of the flow velocity at 951.5, 953.5 and 958.5 km are caused by differences in the grid size of the simulations of reference situation and the situation with the preferred alternative Avelingen.

figure 5.5. Effect of floodplain excavation Avelingen on mean flow velocity in Waal and Merwedes



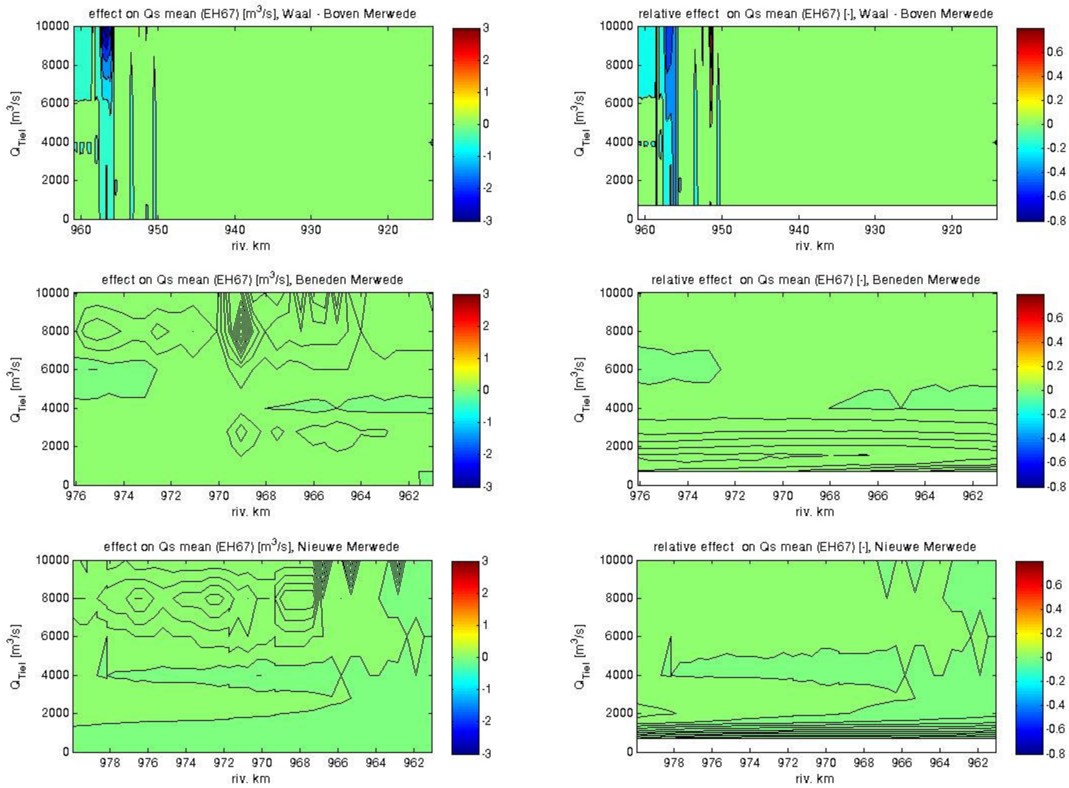
5.5. Effects on sediment transport

The effects of floodplain excavation Avelingen on the mean sediment transport are visualised in figure 5.6. The left subfigures show the difference in mean sediment transport relative to the reference situation. The right subfigures show the relative difference expressed in a percentage relative to the reference situation.

The presence of the side channel causes a reduction of the sediment transport capacity up to 51 % in the main channel near the side channel and the inflow opening of the side channel. This reduction of 51 % takes place as 11.5 % of the upstream discharge flows in the side channel (at a Waal discharge of 10000 m^3/s). This is visible in the top subfigures of figure 5.6 in the Boven Merwede at 956.18 km.

The presence of the side channel has no influence on the sediment transport capacity of the Beneden Merwede (middle subfigures) and Nieuwe Merwede (bottom subfigures).

figure 5.6. Effect of floodplain excavation Avelingen on mean sediment transport (Engelund and Hansen 1967) in Waal and Merwedes

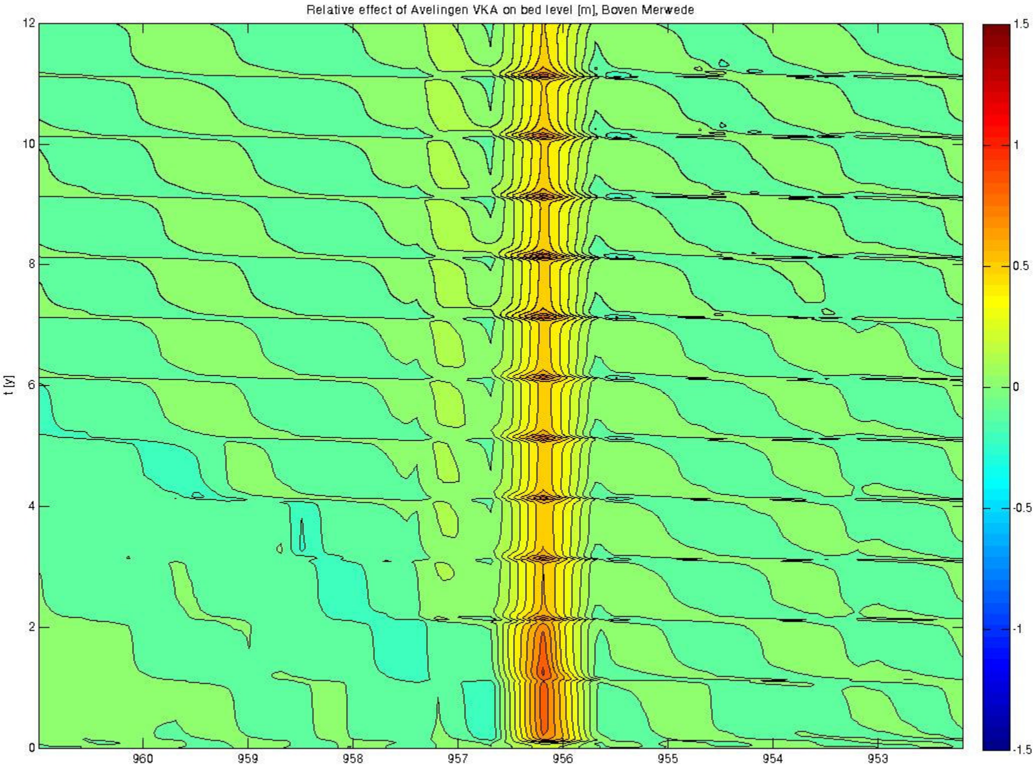


5.6. Morphological effects

Local effect at Avelingen

Sedimentation of the main channel takes place at the inflow opening of the side channel (956.18 km) in the first months after the start of the simulation. This is visible in figure 5.7. This figure shows the differences in mean bed level of the main channel between the case with floodplain excavation Avelingen and the reference situation for the Boven Merwede. The distance along the river is on the horizontal axis. The vertical axis represents the simulation time in years. Widening of the cross-section of the main channel at the inflow opening causes a bed level increase with an order of magnitude of 0.2 m up to 0.6 m. These simulated morphological effects can be attributed to widening of the main channel at the inflow opening of the side channel.

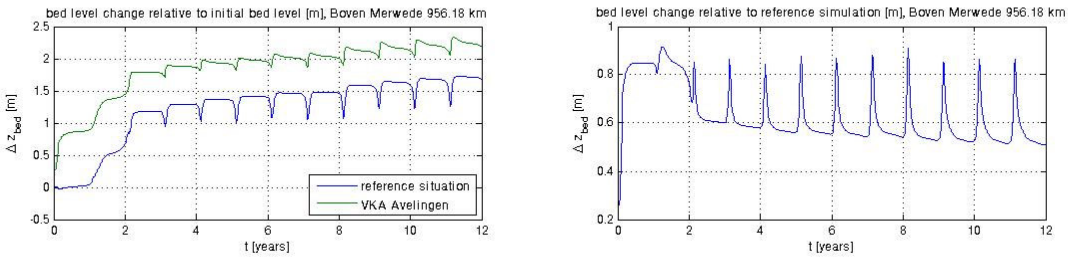
figure 5.7. Relative effect of floodplain excavation Avelingen on bed level of Boven Merwede



The development of the bed level of the main channel at the inflow opening of the side channel is visualised in detail in figure 5.8. The left subfigure shows the cumulative bed level change at 956.18 km during both the reference simulation and the simulation with the preferred alternative (VKA) Avelingen. The right subfigure shows the effect of floodplain excavation Avelingen on the cumulative bed level change at 956.18 km relative to the reference simulation.

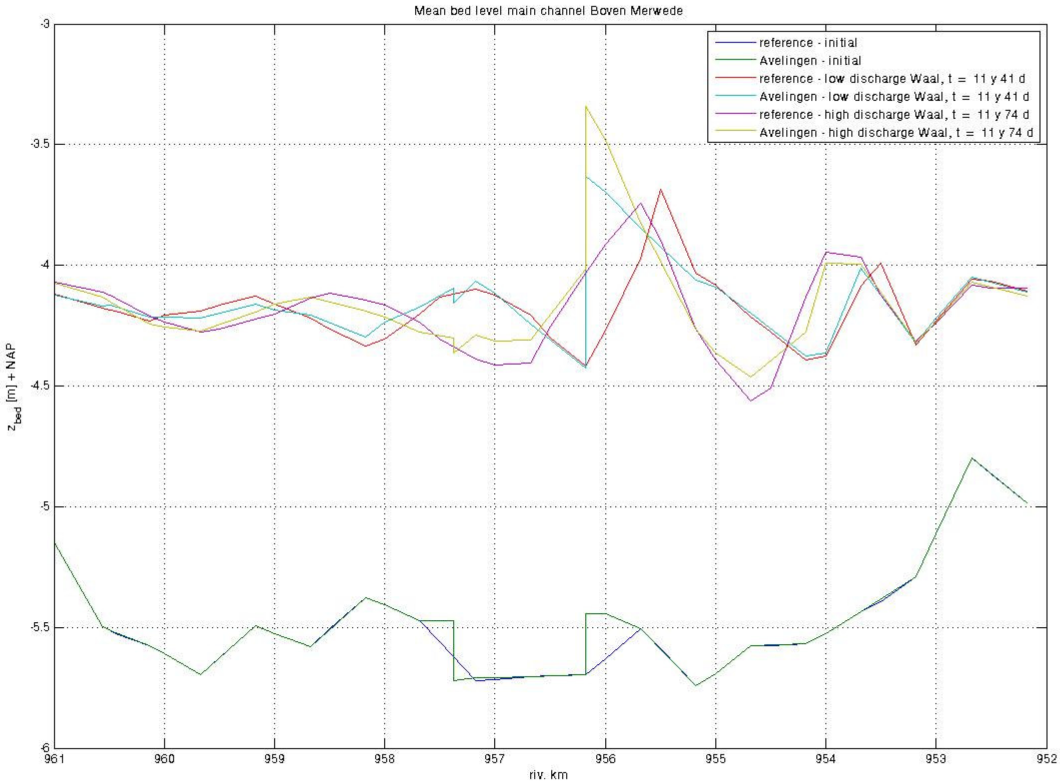
- The results of the first 3 years show a warming up of the model.
- In the remaining simulation period, the periodicity of the applied hydrograph is visible: short periods with a high discharge and long periods with lower discharges.
- The difference between the bed level of the preferred alternative Avelingen and the reference situation has an order of magnitude of 0.6 m.

figure 5.8. Effect of floodplain excavation Avelingen on bed level Boven Merwede 956.18 km at the inflow opening of the side channel



The bed level of the whole Boven Merwede increases about 1 m during the simulation. Therefore, it is dubious whether the adjusted model is representative for the real situation of the Boven Merwede after 12 years of simulation. These large bed level changes are clearly visible in figure 5.9. The bed level of the whole main channel of the Boven Merwede is visualised in figure 5.9. This figure shows the bed level for the reference situation and for the preferred alternative Avelingen on 3 moments: the initial situation at the beginning of the simulation, the situation when the discharge of the Waal is small (after 11 years and 41 days) and the situation when the discharge of the Waal is large (after 11 years and 74 days).

figure 5.9. Effect of floodplain excavation Avelingen on bed level of Boven Merwede

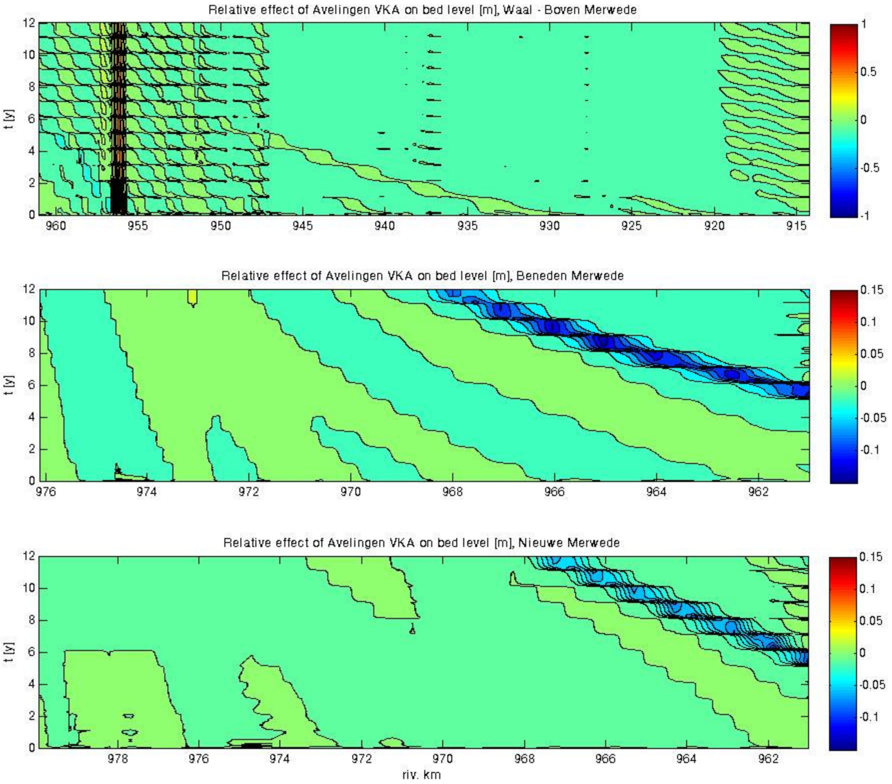


Temporary downstream effects

Figure 5.10 shows the differences in mean bed level of the main channel between the case with floodplain excavation Avelingen and the reference situation during the simulation. Simulation time is represented on the vertical axis and distance on the horizontal axis.

There is less sediment available for the downstream branches during the sedimentation at the inflow opening. This gives that an erosion front travels in downstream direction. No further sedimentation takes place and sediment flows in downstream direction when the sediment transport capacity of the main channel near the inflow opening is equal to the upstream sediment transport capacity. The erosion pit will be filled up in downstream direction by this sedimentation front. When the erosion front and sedimentation front are passed, the situation is unaltered compared to the reference situation. The pit in the bed of the main channel which travels in downstream direction, has a depth of 0.1 m. The erosion and sedimentation front are visible in the top subfigure of figure 5.10 for the Boven Merwede (between 956 and 961 km, first 6 years). After 5 years, the erosion front and sedimentation front pass the Merwedekop. This is visible in the middle subfigure for the Beneden Merwede (at 961km) and in the bottom subfigure for the Nieuwe Merwede (at 961 km).

figure 5.10. Relative effect of floodplain excavation Avelingen on bed level of Waal and Merwedes



5.7. Discussion

The results of this case study have been compared with Witteveen+Bos (2008) in section 5.7.1 and the limitations of this case study are described in section 5.7.2.

5.7.1. Comparison with Witteveen+Bos (2008)

The approximation of the effect of floodplain excavation Avelingen on the mean water level corresponds reasonably well with the assessment by Witteveen+Bos (2008, p. 21). According to Witteveen+Bos the effect is a lowering of 0.107 m at 955 km under normative conditions. The estimation in this case study is 0.114 m.

According to Witteveen+Bos (2008, p. 15), the morphological effect of Avelingen is sedimentation during high river discharges in the main channel with a order of magnitude of decimetres. Morphological simulations in these case study results in sedimentation with an order of magnitude of 0.2 up to 0.6 m in the main channel near the inflow opening of the side channel.

5.7.2. Limitations

The value of the results of this case study is limited:

- The morphological effects have been simulated with a unverified, uncalibrated morphological model.
- The grid size is large compared to the measure floodplain excavation Avelingen. The length of the side channel is just a few grid cells.
- While three-dimensional effects can be expected, an one-dimensional analysis is applied.
- The influence of extreme river discharges on morphology has not been included. The maximum discharge in the applied hydrograph is about 3500 m^3/s.
- The influence of salt intrusion has been neglected in the simulation of the morphological effects.

This case study shows qualitative effects of floodplain excavation Avelingen on flow, sediment transport and morphology. The effects on sediment transport and morphology cannot be determined accurately with the applied method. To determine the quantitative effects of floodplain excavation Avelingen on sediment transport and morphology, a detailed simulation should be done with a two-dimensional model.

5.8. Conclusions

Based on this one-dimensional analysis of flow, sediment transport and morphological changes, the following conclusions can be drawn with respect to the effect of the preferred alternative of floodplain excavation Avelingen.

5.8.1. Effects of floodplain excavation Avelingen

Effects on flow

- The side channel flows if the discharge of the Waal is larger than about 2800 - 4000 m^3/s.
- The effects of the side channel increases for increasing river discharge. When the upstream discharge is 10.000 m^3/s,
  - 1146 m^3/s flows through the side channel,
  - the lowering of the mean water level is 0.114 m at 955 km,
  - the reduction of the mean flow velocity is 0.25 m/s in the main channel at the inflow opening of the side channel.
- The floodplain excavation causes a lowering of the flow velocity in the main channel at the inflow opening of the side channel under all circumstances. At this location the cross-section is wider than in the reference situation.
- The side channel causes a lowering of the mean water level in the Waal - Boven Merwede. This effect is known as a backwater curve effect. The largest lowering of the mean water level is located direct upstream of the side channel. The lowering of the mean water level decreases in upstream direction.
- When the side channel flows, the flow velocities in the main channel are smaller than in the reference situation due to the reduction of the discharge in the main channel.
- The flow distribution at the bifurcation Merwedekop remains almost unaltered compared to the reference situation.

Effects on mean sediment transport

- The presence of the side channel causes a reduction of the sediment transport capacity up to 51 % (at a Waal discharge of 10000 m^3/s) in the main channel near the side channel and the inflow opening of the side channel.

Morphological effects

- Sedimentation of the main channel takes place at the inflow opening of the side channel (956.18 km) in the first months after the start of the simulation. The difference between the bed level of the preferred alternative Avelingen and the reference situation has an order of magnitude of 0.2 up to 0.6 m at 956.18 km. This estimation is based on a one-dimensional morphological simulation with an uncalibrated, unverified model.
- During the sedimentation at the inflow opening, there is less sediment available for the downstream branches. This caused that an erosion front travels in downstream direction. When the sediment transport capacity of the main channel near the inflow opening is equal to the upstream sediment transport capacity, no further sedimentation takes place and sediment flows in downstream direction. The erosion pit will be filled up in downstream direction by this sedimentation front. When the erosion front and sedimentation front are passed, the situation is unaltered compared to the reference situation. The pit in the bed of the main channel which travels in downstream direction, has a depth of 0.1 m.

5.8.2. Sensitivity of result

The following aspects are relevant for the determination of the effect of floodplain excavation Avelingen:

1. Including variations in river discharges
2. The choice of a accurate sediment transport model
3. Including the tidal influence in the Waal and Merwedes
4. Including salt intrusion in the Rhine-Meuse Delta

Including variations in river discharges
When extreme discharges will be included in the morphological simulations, the prediction of sedimentation could cause an (temporary) increase of sedimentation.

Choice of sediment transport model
The sediment transport model of Engelund and Hansen 1967 has been used to estimate the morphological effect of floodplain excavation Avelingen. However, this model overestimates the expected sedimentation in the Boven Merwede with 283 % (see table 3.17). Van Rijn 2007 gives much better results: an overestimation of 45 %. This means that the choice of Van Rijn 2007 could reduce the simulated morphological effect by about 60 %.

Including the tide
The influence of neglecting the tide on the simulated expected sedimentation in the Boven Merwede is much smaller: the increase of the sedimentation in the Boven Merwede has a value of 6 – 11 % (see table 3.8). In this case study, a spring-neap cycle is used as sea boundary condition.

Including salt intrusion
Neglecting salt intrusion in the Rhine-Meuse Delta results in an increase of the simulated expected sedimentation in the Boven Merwede of 3 – 5 % (see tables 3.14 and 3.15). In this case study, the effect of salt intrusion on the morphological effect of floodplain excavation Avelingen has been neglected. The effect of this choice is very small compared to the effect of the choice of a sediment transport model.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

A brief overview of the conclusions of this study is given in this section. Section 6.1.1 summarizes the general conclusions. Section 6.1.2 contains the main conclusions of case study Avelingen.

6.1.1. General conclusions

Tidal influence

- The presence of the tide has a significant effect on the flow, sediment transport and morphology of the Merwedes. The tidal influence in the Merwedes cannot be neglected, because of the following reasons:
  - Neglecting the tide has a significant effect on the discharge distribution at the Merwedekop. The averaged inflow in the Beneden Merwede will then be overestimated by 12.2 %. Further, the tidal motion causes a flow circulation from the Beneden Merwede via the Merwedekop into the Nieuwe Merwede. In addition, the tide has a significant influence on sediment transport up to Sint Andries (Waal, 926 km).
  - The tide decreases the mean sediment transport in the Boven Merwede and increases the mean sediment transport in the Beneden and Nieuwe Merwede.
  - The tide decreases the effective (Waal) discharge of the Beneden Merwede with 850 m^3/s and decreases the effective (Waal) discharge of the Nieuwe Merwede with 150 m^3/s. The tide has no influence on the effective discharge of the Boven Merwede.
- The flow circumstances of the Merwedes are outside the scope of Van de Kreeke and Robaczewska (1993). The influence of the river discharge on the flow in the Merwedes is too large. Therefore, the long-term mean sediment transport in the Merwedes cannot be estimated by the approximation of Van de Kreeke and Robaczewska.

Influence of river discharge

- The influence of the river discharge on mean sediment transport in the Merwedes is much larger than the tidal influence.
- The tidal influence depends on the magnitude of the upstream river discharge.
- The way in which the river discharge is schematised, has a large influence on simulations of flow, sediment transport and morphology.

Influence of salt intrusion

- Salt intrusion in the Rhine-Meuse Delta has a significant effect on flow and sediment transport in the Merwedes.
  - Salt intrusion causes a increase of the mean water level in the Merwedes which leads to a decrease in mean flow velocity and mean sediment transport in the Merwedes.
  - Neglecting salt intrusion gives deviations in mean sediment transport with the same order of magnitude as neglecting the tide in the Merwedes.
  - The presence of salt in the Rhine-Meuse Delta leads to a decrease of sedimentation in the Boven Merwede and Beneden Merwede and an increase of sedimentation in the Nieuwe Merwede.
- The influence of salt intrusion on morphology is unknown, but could be serious.

Influence of choice of sediment transport model

- The choice of a sediment transport model has a larger influence on sediment transport than the sea boundary conditions. The sediment transport model of Van Rijn 2007 gives the best approximation of the measured sedimentation in the Boven and Beneden Merwede. This is based on post-processing of flow simulations. It is unknown which sediment transport model gives the best result for the Nieuwe Merwede, because of incomplete measurements.
- The adaptation time and length scales of the sediment transport are such that the actual transport can be taken equal to the sediment transport capacity. This justifies the use of a sediment transport model.

- The sediment transport in the Merwedes can be computed with a transport model for total load which includes both suspended load and bed load.
- The results of morphological simulations are very sensitive to the choice of a transport model.
- The influence of the presence of mud on sedimentation in the Merwedes is small.

Influence of human intervention

- Flow in the Nieuwe Merwede is influenced by the management of discharging via the Haringvliet sluices into the North Sea.
- Dredging has a significant effect on the morphological development of the Merwedes. The effect of dredging appears to be larger than the effect of the type of sea boundary conditions.

Sediment balance

- Based on the analysis of the results of the one-dimensional flow model of the Rhine-Meuse Delta, the general trend in the Merwedes is sedimentation.

Ranking of modelling aspects

The following ranking has been determined with respect to the relevance for one-dimensional morphological modelling of the Merwedes which is based on the analysis of simulated sediment transport and simulated bed level changes:

1. Including variations in river discharges
2. The choice of a accurate sediment transport model
3. Including the tidal influence in the Waal and Merwedes
4. Including salt intrusion in the Rhine-Meuse Delta
5. Using a spring-neap cycle instead of a schematised tidal cycle as sea boundary condition

This ranking applies to the yearly sediment transport (or the expected value). These adjustments improve the simulation of the autonomous development of the bed level of the Merwedes.

The ranking of modelling aspects varies between the Merwedes at specific discharges. The influence of the tide on the mean sediment transport in the Beneden Merwede is much larger than the choice of a sediment transport model. This is relevant to determination of morphological effects of a measure at a specific river discharge.

6.1.2. Conclusions case study Avelingen

Based on one-dimensional modelling, the following conclusions can be drawn with respect to the effects of the preferred alternative of floodplain excavation Avelingen on sediment transport and morphology.

- The presence of the side channel will cause a reduction of the mean sediment transport capacity up to 51 % in the main channel near the side channel and the inflow opening of the side channel at an extreme upstream (Waal) discharge of 10000 m^3/s.
- The morphological effects could be restricted to sedimentation of the main channel at the inflow opening of the side channel (Boven Merwede, 956.18 km) with an order of magnitude of 0.2 up to 0.6 m. This estimation is based on a one-dimensional morphological simulation with an uncalibrated, unverified model.

These effects correspond reasonably well with the assessment by Witteveen+Bos (2008).

The results of the one-dimensional modelling of the effects of floodplain excavation Avelingen are sensitive for the following choices:

1. Including variations in river discharges
   When extreme discharges are included in the morphological simulations, the prediction of sedimentation could cause an (temporary) increase of sedimentation.
2. The choice of a accurate sediment transport model.
   Using Van Rijn 2007 instead of Engelund and Hansen 1967 reduces the prediction of sedimentation with 60 %.

3. Including the tidal influence in the Waal and Merwedes
   When the tide is neglected, the prediction of sedimentation in the Boven Merwede increases 6 – 11 %.
4. Including salt intrusion in the Rhine-Meuse Delta
   If salt intrusion is neglected, the prediction of sedimentation increases 3 – 5 %.

6.2. Recommendations

Based on this study, the following recommendations are proposed.

River-tide interaction
Both variations in river discharge and the tidal influence should be included in morphological studies of the Merwedes, because of interaction between river flow and tidal flow.

Tide
The influence of the tide on sediment transport in the Merwedes can best be represented by a spring-neap cycle. However, a less detailed tidal cycle is a reasonable approximation of the tidal influence on sediment transport in the Merwedes. Using a tidal cycle instead of a spring-neap cycle gives a small underestimation of the expected value of sediment transport and the expected value of sedimentation.

Mean sediment transport
It is recommended to extend the theory of Van de Kreeke and Robaczewska (1993) about mean sediment transport for cases in which flow is dominated by residual flow. This adjusted approximation could be applied in the Merwedes when residual flow is stronger than tidal flow.

Sediment transport mechanisms
The occurring sediment transport mechanisms in the Merwedes should be studied in more detail to reduce the uncertainty in the simulated sediment transport.

Bed composition
It is highly recommended to investigate the effects of the schematisation of the bed composition on the simulated sediment transport.

Usability of one-dimensional analysis
A two-dimensional analysis of the tidal influence on sediment transport and bed level changes could give insight in the usability of a one-dimensional analysis. So, it can be assessed whether cross-section averaged parameters are representative for a two-dimensional situation.

One-dimensional morphological modelling
It is recommended to make a one-dimensional model of the Rhine-Meuse Delta which includes the following processes: flow, salt intrusion, sediment transport and morphology. The model should be suitable to simulate the influence of tidal fluctuations, times series of upstream discharges and dredging activities.

Morphological effect Avelingen
The morphological effect of floodplain excavation Avelingen should be studied in more detail by a two-dimensional model. This could be combined with the study of other planned measures within the framework of Room for the River.

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APPENDIX I Sediment transport models

1. INTRODUCTION

In this appendix the applied sediment transport models are reproduced. The original models are not suitable for the situation with reversal of flow. For that reason, these models are rewritten. Also, there are made some modifications and simplifications to the bed load and suspend load model of Van Rijn 2007. The following sediment transport models are described:

- Total sediment transport model of Engelund and Hansen 1967 (chapter 2)
- Bed load and suspended load model of Van Rijn 1984 (chapter 3)
- Simplified bed load and suspended load model of Van Rijn 1993 (chapter 4)
- Bed load and suspended load model of Van Rijn 2007 (chapter 5)

This appendix also contains an overview of the used parameters (chapter 6). This overview describes the meaning of the used symbols and the units of these parameters.

2. ENGELUND AND HANSEN 1967

The sediment transport model of Engelund and Hansen (1967) describes the total transport (Van Rijn 1993, p. 7.93):

$$q_{s;total} = \frac{1}{1-\varepsilon_p} \frac{0.05 \cdot U^5}{\Delta^2 \cdot g^{0.5} \cdot D_{50} \cdot C^3}$$

Additional explanation of Chezy value

The Chezy value from SOBEK has been be used as total roughness in the sediment transport models instead of a roughness predictor. This value has been used because it is assumed that the flow is accurately described by the SOBEK TMR 2006 model, although the calibrated hydraulic roughness contains shortcomings of the model schematisation. This aspect of uncertainty has not been studied in this research project. This total roughness has been used in the sediment transport model of Engelund and Hansen (De Vriend, 2007, p. 4.13).

3. VAN RIJN 1984

The full equations of Van Rijn 1984 describe both bed load and suspended load.

Dimensionless particle diameter (Van Rijn 1993, p. 7.72):

$$D_* = D_{50}\left(\frac{\Delta \cdot g}{\nu^2}\right)^{1/3}$$

Critical shields parameter (Van Rijn 1993, p. 4.4):

If 1 < D_* ≤ 4

$$\theta_{cr} = 0.24 \cdot D_*^{-1}$$

If 4 < D_* ≤ 10

$$\theta_{cr} = 0.14 \cdot D_*^{-0.64}$$

If 10 < D_* ≤ 20

$$\theta_{cr} = 0.04 \cdot D_*^{-0.1}$$

If 20 < D_* ≤ 150

$$\theta_{cr} = 0.013 \cdot D_*^{0.29}$$

If D_* > 150

$$\theta_{cr} = 0.055$$

Critical bed-shear stress according Shields (Van Rijn 1993, p. 4.5):

$$\tau_{b;cr} = (\rho_s - \rho_w) \cdot g \cdot D_{50} \cdot \theta_{cr}$$

Grain-related Chezy-coefficient, roughness height based on 3·D_{90} (Van Rijn 1993, p. 7.26):

$$C' = 18 \cdot {}^{10}\log\left(\frac{12 \cdot d_w}{3 \cdot D_{90}}\right)$$

Effective bed-shear stress (Van Rijn 1993, p. 7.26):

$$\tau_b' = \frac{\rho_w \cdot g \cdot U \cdot |U|}{(C')^2}$$

Dimensionless bed-shear parameter (Van Rijn 1993, p. 7.26):

If τ_b' ≤ $\tau_{b;cr}$

T = 0

If τ_b' > $\tau_{b;cr}$

$$T = \frac{\tau_b' - \tau_{b;cr}}{\tau_{b;cr}}$$

Direction of sediment transport

If U ≥ 0

dir_s = 1

If U < 0

dir_s = -1

Bed load per unit width (Van Rijn 1993, p. 7.25):

If T < 3

$$q_{s;bed} = dir_s \cdot \frac{1}{1-\varepsilon_p} 0.053 \cdot \left(g \cdot \Delta \cdot D_{50}^{\ 3}\right)^{0.5} \cdot T^{2.1} \cdot D_*^{-0.3}$$

If T ≥ 3

$$q_{s;bed} = dir_s \cdot \frac{1}{1-\varepsilon_p} 0.1 \cdot \left(g \cdot \Delta \cdot D_{50}^{\ 3}\right)^{0.5} \cdot T^{1.5} \cdot D_*^{-0.3}$$

Bed form height (Van Rijn 1993, p. 7.72), derived from Chezy coefficient (total roughness):

$$k_s = \frac{12 \cdot d_w}{10^{\frac{C}{18}}}.$$

Reference level (Van Rijn 1984b, p. 1628):

$a = 0.5 \cdot k_s$ with $a_{\min} = 0.01 \cdot d_w$

Reference concentration (Van Rijn 1993, p. 7.72):

$$c_a = 0.015 \frac{D_{50}}{a} \cdot T^{1.5} \cdot D_*^{-0.3}$$

Representative particle size of suspended sediment (Van Rijn 1993, p. 7.73):

$$D_s = \left[1 + 0.011 \cdot (\sigma_g - 1) \cdot (T - 25)\right] \cdot D_{50}$$

Fall velocity of suspended sediment based on D_s (Van Rijn 1993, p. 3.13):

If $1 \cdot 10^{-6}$ m < D_s ≤ $100 \cdot 10^{-6}$ m

$$w_s = \frac{\Delta \cdot g \cdot D_s}{18 \cdot \nu}$$

If $100 \cdot 10^{-6}$ m < D_s < $1 \cdot 10^{-3}$ m

$$w_s = \frac{10 \cdot \nu}{D_s} \left[\left(1 + \frac{0.01 \cdot \Delta \cdot g \cdot D_s^{\,3}}{\nu^2} \right)^{0.5} - 1 \right]$$

If D_s ≥ $1 \cdot 10^{-3}$ m

$$w_s = 1.1 \cdot (\Delta \cdot g \cdot D_s)^{0.5}$$

Bed-shear velocity (Van Rijn 1993, p. 7.72) based on total roughness:

$$u_* = \frac{g^{0.5}}{C} \cdot |U|$$

Ratio of sediment and fluid mixing coefficient (Van Rijn 1993, p. 7.72):

$\beta = 1 + 2 \cdot \left(\frac{w_s}{u_*} \right)^2$ with $\beta_{\max} = 2$

Stratification correction (Van Rijn 1993, p. 7.72):

$$\psi = 2.5 \cdot \left(\frac{w_s}{u_*} \right)^{0.8} \cdot \left(\frac{c_a}{c_0} \right)^{0.4}$$

Suspension number (Van Rijn 1993, p. 7.72):

$$Z' = \frac{w_s}{\beta \cdot \kappa \cdot u_*} + \psi$$

Integration factor (Van Rijn 1993, p. 7.72):

$$F = \frac{\left(\frac{a}{d_w} \right)^{Z'} - \left(\frac{a}{d_w} \right)^{1.2}}{\left(1 - \frac{a}{d_w} \right)^{Z'} \cdot (1.2 - Z')}$$

Suspended load (Van Rijn 1993, p. 7.72):

$$q_{s;sus} = \frac{1}{1 - \varepsilon_p} F \cdot U \cdot d_w \cdot c_a$$

Total transport:

$$q_{s;total} = q_{s;bed} + q_{s;sus}$$

4. VAN RIJN 1993

The simplified equations of Van Rijn 1993 describe both bed load and suspended load.

Dimensionless particle diameter (Van Rijn 1993, p. 7.72):

$$D_* = D_{50}\left(\frac{\Delta \cdot g}{\nu^2}\right)^{1/3}$$

Critical flow velocity (Van Rijn 1993, p. 7.27):

If $100 \cdot 10^{-6}$ m ≤ D_{50} ≤ $500 \cdot 10^{-6}$ m

$$U_{cr} = 0.19 \cdot D_{50}{}^{0.1} \cdot {}^{10}\log\left(\frac{12 \cdot d_w}{3 \cdot D_{90}}\right)$$

If $500 \cdot 10^{-6}$ m < D_{50} < $2 \cdot 10^{-3}$ m

$$U_{cr} = 8.50 \cdot D_{50}{}^{0.6} \cdot {}^{10}\log\left(\frac{12 \cdot d_w}{3 \cdot D_{90}}\right)$$

Mobility parameter (Van Rijn 1993, p. 7.27):

If $|U| \le U_{cr}$:

$M_e = 0$

If $|U| > U_{cr}$:

$$M_e = \frac{|U| - U_{cr}}{\sqrt{\Delta \cdot g \cdot D_{50}}}$$

Bed load (Van Rijn 1993, p. 7.27):

$$q_{s;bed} = \frac{1}{1-\varepsilon_p} 0.005 \cdot U \cdot d_w \cdot M_e{}^{2.4} \cdot \left(\frac{D_{50}}{d_w}\right)^{1.2}$$

Suspended load (Van Rijn 1993, p. 7.73):

$$q_{s;sus} = \frac{1}{1-\varepsilon_p} 0.012 \cdot U \cdot d_w \cdot M_e{}^{2.4} \cdot \left(\frac{D_{50}}{d_w}\right) \cdot D_*{}^{-0.6}$$

Total transport:

$$q_{s;total} = q_{s;bed} + q_{s;sus}$$

5. VAN RIJN 2007

The influence of the presence of mud in parts of the Beneden Merwede and Nieuwe Merwede is included in the sediment transport model of Van Rijn 2007. The effect of the presence of mud is not included in the other sediment transport models. However, the sediment transport model of Van Rijn 1984 gives better results in river areas than Van Rijn 2007. Van Rijn 2007 had been formulated to improve the influence of wind waves on sediment transport. It is desirable that the sediment transport capacities calculated by Van Rijn 1984 and Van Rijn 2007 are of the same order of magnitude when the presence of mud is neglected. It has been decided to apply Van Rijn 2007 with the settings of Van Rijn 1984 to study the effect of the presence of mud:[14]

- Grain-related roughness:
  Instead of $1 \cdot D_{90}$ (Van Rijn 2007a, p. 658), $3 \cdot D_{90}$ (Van Rijn 1993, p. 7.26) is used for the grain-related roughness. According to Van Rijn (oral recommendation via Z.B. Wang, March 17 2010), $3 \cdot D_{90}$ applies to finer sediment and $1 \cdot D_{90}$ applies to much coarser sediment.
- Reference level:
  Instead of a minimum value of the reference level of 0.01 m (Van Rijn 2007b, p. 673), a value of $0.01 \cdot d_w$ (Van Rijn 1984b, p. 1628) is used.
- Particle size of suspended sediment:
  Instead of the model of 2007 for the particle size of suspended sediment (Van Rijn 2007b, 9. 674), the model of 1984 (Van Rijn 1993, p. 7.73) is used.

The main remaining differences between Van Rijn 1984 and Van Rijn 2007 are:

- The maximum value of β, the ratio of sediment and fluid mixing coefficient: 2.0 in Van Rijn 1984 (Van Rijn 1993, p. 7.72) versus 1.5 in Van Rijn 2007 (Van Rijn 2007b, p. 671).
- A recalibration of coefficients and exponents in the bed load model (Van Rijn 2007a, p. 658).
- The addition of the influence of the presence of mud in Van Rijn 2007.

Since the mean particle diameter of the bed material is larger than the sand-mud transition (62 μm), flocculation is not included in the models. For the influence of hindered settling and turbulence damping on the concentration and velocity profile the simplified method of Van Rijn (1984b, p. 1625) is used instead of a hindered settling factor and a damping function.

The full equations of Van Rijn 2007 describe both bed load and suspended load. The original models are valid for the combination of currents and waves. These equations are rewritten for the situation with currents only and contain the influence of the presence of mud in the bed material.

Dimensionless particle diameter (Van Rijn 1993, p. 7.72):

$$D_* = D_{50}\left(\frac{\Delta \cdot g}{\nu^2}\right)^{1/3}$$

Critical shields parameter (Van Rijn 1993, p. 4.4):

If $1 < D_* \leq 4$

$$\theta_{cr} = 0.24 \cdot D_*^{-1}$$

If $4 < D_* \leq 10$

$$\theta_{cr} = 0.14 \cdot D_*^{-0.64}$$

If $10 < D_* \leq 20$

$$\theta_{cr} = 0.04 \cdot D_*^{-0.1}$$

If $20 < D_* \leq 150$

$$\theta_{cr} = 0.013 \cdot D_*^{0.29}$$

[14] According to prof. dr. ir. L.C. van Rijn, via a personal comment of dr. ir. Z.B. Wang on March 17, 2010.

If $D_* > 150$

$$\theta_{cr} = 0.055$$

Critical bed-shear stress according Shields (Van Rijn 1993, p. 4.5):

$$\tau_{b;cr} = (\rho_s - \rho_w) \cdot g \cdot D_{50} \cdot \theta_{cr}$$

Proportion of clay (D_i < 8 μm) in bed material, based on a clay-silt ratio of 0.50 (Van Rijn 2007a, p. 650)

$$p_{cs} = \frac{1}{3} \cdot p_{mud}$$

Critical bed-shear stress of sand-mud mixture (Van Rijn 2007a, p. 652):

$$\tau_{b;cr;sand-mud} = (1 + p_{cs})^3 \cdot \tau_{b;cr}$$

Grain-related Chezy-coefficient, roughness height based on $3 \cdot D_{90}$ (Van Rijn 1993, p. 7.26) instead of $1 \cdot D_{90}$ (Van Rijn 2007a, p. 658):

$$C' = 18 \cdot {}^{10}\log\left(\frac{12 \cdot d_w}{3 \cdot D_{90}}\right)$$

Effective bed-shear stress (Van Rijn 2007a, p. 658) based on grain-related roughness:

$$\tau_b' = \frac{\rho_w \cdot g \cdot U \cdot |U|}{(C')^2}$$

Dimensionless bed-shear parameter (Van Rijn 2007a, p. 658):

If $\tau_b' \leq \tau_{b;cr;sand-mud}$

$$T = 0$$

If $\tau_b' > \tau_{b;cr;sand-mud}$

$$T = \frac{\tau_b' - \tau_{b;cr;sand-mud}}{\tau_{b;cr;sand-mud}}$$

Direction of sediment transport

If U ≥ 0

$dir_s = 1$

If U < 0

$dir_s = -1$

Bed load per unit width (Van Rijn 2007a, p. 658):

$$q_{s;bed} = dir_s \cdot \frac{1}{1 - \varepsilon_p} \cdot (1 - p_{cs}) \cdot 0.5 \cdot D_{50} \cdot D_*^{-0.3} \cdot \left(\frac{|\tau_b'|}{\rho_w}\right)^{0.5} \cdot T$$

Bed form height (Van Rijn 1993, p. 7.72), derived from Chezy coefficient (total roughness):

$$k_s = \frac{12 \cdot d_w}{10^{\frac{C}{18}}}$$

Reference level (Van Rijn 1984b, p. 1628):

$a = 0.5 \cdot k_s$ with $a_{min} = 0.01 \cdot d_w$, instead of $a_{min} = 0.01$ m (Van Rijn 2007b, p. 673)

Reference concentration (Van Rijn 2007b, p. 673):

$$c_a = 0.015(1 - p_{cs})\frac{D_{50}}{a} \cdot T^{1.5} \cdot D_*^{-0.3} \text{ with } c_{a;max} = 0.05$$

Mobility parameter (Van Rijn 2007b, p. 674):

$$\psi_u = \frac{U^2}{\Delta \cdot g \cdot D_{50}}$$

Representative particle size of suspended sediment (Van Rijn 1993, p. 7.73)

$$D_s = \left[1 + 0.011 \cdot (\sigma_g - 1) \cdot (T - 25)\right] \cdot D_{50}$$

Fall velocity of suspended sediment based on D_s (Van Rijn 1993, p. 3.13):

If $1 \cdot 10^{-6}$ m < D_s ≤ $100 \cdot 10^{-6}$ m

$$w_s = \frac{\Delta \cdot g \cdot D_s}{18 \cdot \nu}$$

If $100 \cdot 10^{-6}$ m < D_s < $1 \cdot 10^{-3}$ m

$$w_s = \frac{10 \cdot \nu}{D_s} \left[\left(1 + \frac{0.01 \cdot \Delta \cdot g \cdot D_s^{\ 3}}{\nu^2} \right)^{0.5} - 1 \right]$$

If D_s ≥ $1 \cdot 10^{-3}$ m

$$w_s = 1.1 \cdot (\Delta \cdot g \cdot D_s)^{0.5}$$

Bed-shear velocity (Van Rijn 1993, p. 7.72) based on total roughness:

$$u_* = \frac{g^{0.5}}{C} \cdot |U|$$

Ratio of sediment and fluid mixing coefficient (Van Rijn 2007b, p. 671):

$$\beta = 1 + 2 \cdot \left(\frac{w_s}{u_*} \right)^2 \text{ with } \beta_{\max} = 1.5$$

Overall correction factor representing all additional effects (volume occupied by particles, reduction of particle fall velocity and damping of turbulence), (Van Rijn 1984b, p. 1625):

$$\psi = 2.5 \cdot \left(\frac{w_s}{u_*} \right)^{0.8} \cdot \left(\frac{c_a}{c_0} \right)^{0.4}$$

Suspension number (Van Rijn 1993, p. 7.72):

$$Z' = \frac{w_s}{\beta \cdot \kappa \cdot u_*} + \psi$$

Integration factor (Van Rijn 1993, p. 7.72):

$$F = \frac{\left(\frac{a}{d_w} \right)^{Z'} - \left(\frac{a}{d_w} \right)^{1.2}}{\left(1 - \frac{a}{d_w} \right)^{Z'} \cdot (1.2 - Z')}$$

Suspended load (Van Rijn 1993, p. 7.72):

$$q_{s;sus} = \frac{1}{1 - \varepsilon_p} F \cdot U \cdot d_w \cdot c_a$$

Total transport:

$$q_{s;total} = q_{s;bed} + q_{s;sus}$$

6. OVERVIEW OF PARAMETERS IN SEDIMENT TRANSPORT MODELS

a	[m]	reference level
C	[$m^{0.5}$/s]	Chezy coefficient main channel
C’	[$m^{0.5}$/s]	grain-related Chezy coefficient
c_a	[-]	reference concentration
c_0	[-]	maximum concentration, 0.65
D_{50}	[m]	median particle diameter of bed material
D_{50}/D_{10}	[-]	ratio, 1.501
D_{90}	[m]	characteristic particle diameter of bed material
D_s	[m]	representative particle size of suspended sediment
D_*	[-]	dimensionless particle diameter
d_w	[m]	water depth (averaged over width main channel)
dir_s	[-]	direction of sediment transport
F	[-]	integration factor
g	[m/s^2]	gravitational acceleration
k_s	[m]	bed form height
p_{cs}	[-]	proportion of clay in bed material
p_{mud}	[-]	proportion of mud in bed material
$q_{s;bed}$	[m^3/s/m]	bed load per unit width
$q_{s;sus}$	[m^3/s/m]	suspended load per unit width
$q_{s;total}$	[m^3/s/m]	total sediment transport per unit width
M_e	[-]	mobility parameter
T	[-]	dimensionless bed-shear parameter
U	[m/s]	averaged flow velocity main channel
U_{cr}	[m/s]	depth averaged critical flow velocity
u_*	[m/s]	bed-shear velocity
w_s	[m/s]	fall velocity of suspended sediment
Z’	[-]	suspension number
β	[-]	ratio of sediment and fluid mixing coefficient
Δ	[-]	relative density of bed material, $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$
ε_p	[-]	porosity of bed material, 0.40
κ	[-]	constant of Von Karman, 0.4
ν	[m^2/s]	kinematic viscosity of water, $1 \cdot 10^{-6}$ m^2/s
θ_{cr}	[-]	critical Shields parameter
ρ_w	[kg/m^3]	water density, 1000 kg/m^3
ρ_s	[kg/m^3]	density of bed material, 2650 kg/m^3
σ_g	[-]	geometric standard deviation of bed material, 2.938
τ_b'	[N/m^2]	effective bed-shear stress
$\tau_{b;cr}$	[N/m^2]	critical bed-shear stress according Shields
$\tau_{b;cr;sand-mud}$	[N/m^2]	critical bed-shear stress of sand-mud mixture
ψ	[-]	stratification correction
ψ_u	[-]	mobility parameter

APPENDIX II Approximation of mean sediment transport by Van de Kreeke and Robaczewska (1993)

1. INTRODUCTION

Chapter 2 describes the methodology of the comparison of the mean sediment transport with the analytical expression of the net sediment transport of Van de Kreeke and Robaczewska (1993). The theory of this analytical approximation is briefly described in chapter 3. Chapter 4 contains a comparison of this approximation by the mean sediment transport.

2. METHODOLOGY

2.1. Comparison

In the theory of Van de Kreeke and Robaczewska, sediment transport is proportional to the power of the flow velocity: $q_s = f|U|^n sign(U)$. This corresponds with the sediment transport model of Engelund and Hansen (1967) which has been used in the sediment transport analysis. Therefore, the first-order analytical expression of the net sediment transport for n = 5 has been applied in this analysis (Sivakholundu, 2009, p. 316).

2.2. Flow

The flow results of simulations with the one-dimensional SOBEK TMR 2006 model of the Rhine-Meuse delta have been used for the comparison of the net sediment transport. The flow has been computed for different stationary river discharges. The seaward boundary condition in this model is a spring-neap cycle which has been derived from predictions of the tide for April 7 until May 6, 2008 (Rijkswaterstaat, 2010).

2.3. Mean sediment transport based on time series of the sediment transport

Time series of the local sediment transport capacity have been calculated with Matlab, using time series of local flow parameters. Then, the mean sediment transport has been determined by means of a Fourier analysis of local time series of the sediment transport.[15]

2.4. Mean sediment transport based on approximation of Van de Kreeke and Robaczewska

The amplitudes and phases of the flow velocity components are the input of the analytical expression of the net sediment transport of Van de Kreeke and Robaczewska. Therefore, the flow is analysed by means of a Fourier transformation with a discretization along the frequency axis. The length of the time series is 30 days and 13 hours which corresponds to the analysis of the Ems estuary by Van de Kreeke and Robaczewska (1993, p. 215). The corresponding frequency resolution is $3.72 \cdot 10^{-7}$ Hz. This length is long enough to distinguish M_2 and S_2. According to the Rayleigh criterion the length of the time series must be at least 14.8 days (Deltares, 2009, p. 76). The time step of 10 minutes gives a Nyquist frequency of $8.33 \cdot 10^{-4}$ Hz. The theory of Van de Kreeke and Robaczewska is described in the following chapter.

3. THEORY

Van de Kreeke and Robaczewska (1993) have derived an approximate analytical expression for the net sediment transport, averaged over a tidal period. The main issues of this approach are briefly described in this chapter.

3.1. Assumption

- The tidal current is dominated by the M_2 tidal current.[16]

[15] See section 3.2.2 of the main report.

[16] According to section 3.3.2 (main report), this assumption is not valid in the Merwedes.

3.2. Flow velocity

Time series of the local flow velocity can be decomposed in terms of Fourier series. This gives the following expression of the flow velocity, which includes the components of tidal current M_2, M_4, M_6 and S_2 (Van de Kreeke and Robaczewska, 1993, p. 212):

$$u(t) = \hat{U}_{mean} + \hat{U}_{M2}\cos(\sigma \cdot t) + \hat{U}_{M4}\cos(2\sigma \cdot t - \beta) + \hat{U}_{M6}\cos(3\sigma \cdot t - \gamma) + \hat{U}_{S2}\cos(\sigma_1 \cdot t - \alpha_1)$$

with

$\hat{U}_{mean}$	residual flow velocity
$\hat{U}_{M2}$	amplitude of the M_2 tidal current
$\hat{U}_{M4}$	amplitude of the M_4 tidal current
$\hat{U}_{M6}$	amplitude of the M_6 tidal current
$\hat{U}_{S2}$	amplitude of the S_2 tidal current
σ	angular frequency of the M_2 tidal current
σ_1	angular frequency of the S_2 tidal current
β	phase of the M_4 tidal current relative to the M_2 tidal current
γ	phase of the M_6 tidal current relative to the M_2 tidal current
α_1	phase of the S_2 tidal current relative to the M_2 tidal current

Normalizing the expression for the flow velocity by the amplitude of the M_2 tidal current gives:

$$u(t) = \varepsilon_0 + \cos(\sigma \cdot t) + \varepsilon_4 \cos(2\sigma \cdot t - \beta) + \varepsilon_6 \cos(3\sigma \cdot t - \gamma) + \varepsilon_2 \cos(\sigma_1 \cdot t - \alpha_1)$$

with $\varepsilon_0 = \frac{\hat{U}_{mean}}{\hat{U}_{M2}}$, $\varepsilon_4 = \frac{\hat{U}_{M4}}{\hat{U}_{M2}}$, $\varepsilon_6 = \frac{\hat{U}_{M6}}{\hat{U}_{M2}}$ and $\varepsilon_2 = \frac{\hat{U}_{S2}}{\hat{U}_{M2}}$

and $\varepsilon_0 << 1$, $\varepsilon_4 << 1$, $\varepsilon_6 << 1$ and $\varepsilon_2 << 1$.

3.3. Sediment transport

In the theory of Van de Kreeke and Robaczewska, sediment transport is proportional to the power of the flow velocity: $q_s = f|U|^n sign(U)$. Using this equation for the sediment transport with n =5 and substituting the expression, gives the following expression of the first-order long-term mean sediment transport, neglecting terms with of O(ε^2) and higher:

$$\frac{\overline{q_s}}{\hat{U}_{M2}^{\ 5} \cdot f} = \frac{15}{8}\varepsilon_0 + \frac{5}{4}\varepsilon_4 \cos\beta$$

with

$\beta = \varphi_{M4} - 2\varphi_{M2}$ phase of the M_4 tidal current relative to the M_2 tidal current.

The first term of the right-hand side represents the interaction of the residual flow with the lunar semidiurnal tide M_2. The second term contains the interaction between the lunar semidiurnal tide M_2 and its higher harmonic M_4.

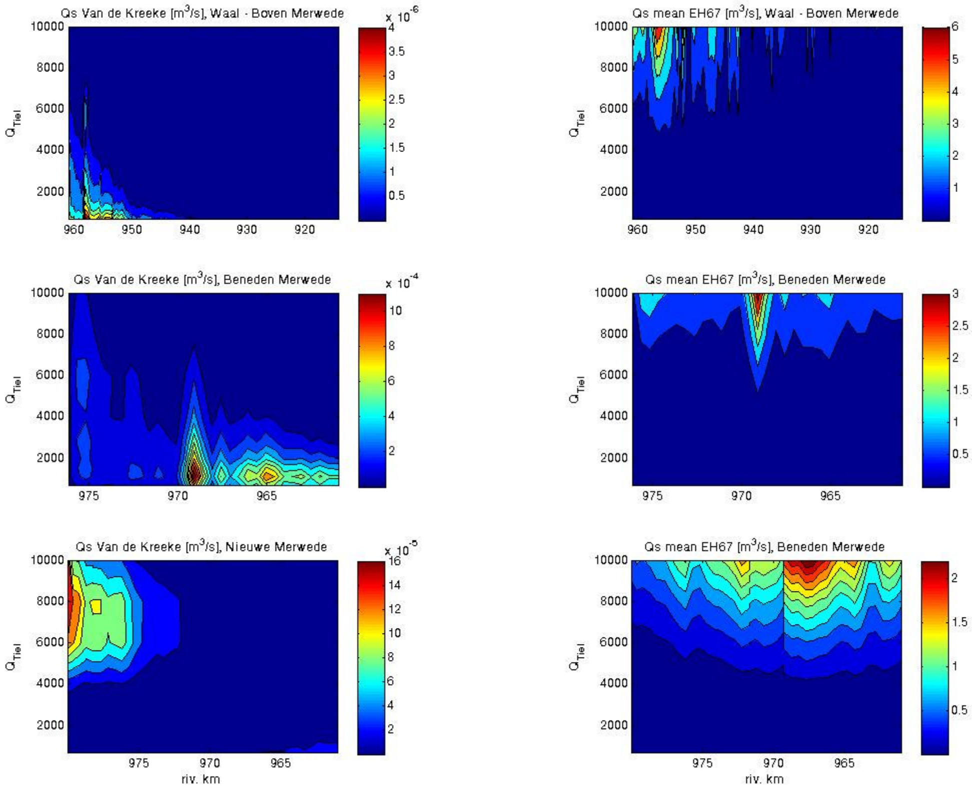
The total sediment transport capacity can be quantified using Engelund and Hansen (1967): $q_{s;total} = \frac{1}{1-\varepsilon_p}\frac{0.05 \cdot U^5}{\Delta^2 \cdot g^{0.5} \cdot D_{50} \cdot C^3}$. The general approximation for the net sediment transport can be rewritten to an expression according to Engelund and Hansen with $f = \frac{1}{1-\varepsilon_p}\frac{0.05}{\Delta^2 \cdot g^{0.5} \cdot D_{50} \cdot C^3}$. This results in:

$$\overline{q_s} = f \cdot \hat{U}_{M2}{}^5 \cdot \left(\frac{15}{8} \varepsilon_0 + \frac{5}{4} \varepsilon_4 \cos \beta \right) = \frac{1}{1-\varepsilon_p} \frac{0.05}{\Delta^2 \cdot g^{0.5} \cdot D_{50} \cdot C^3} \cdot \hat{U}_{M2}{}^5 \cdot \left(\frac{15}{8} \varepsilon_0 + \frac{5}{4} \varepsilon_4 \cos \beta \right).$$

4. COMPARISON OF MEAN SEDIMENT TRANSPORT WITH APPROXIMATOIN

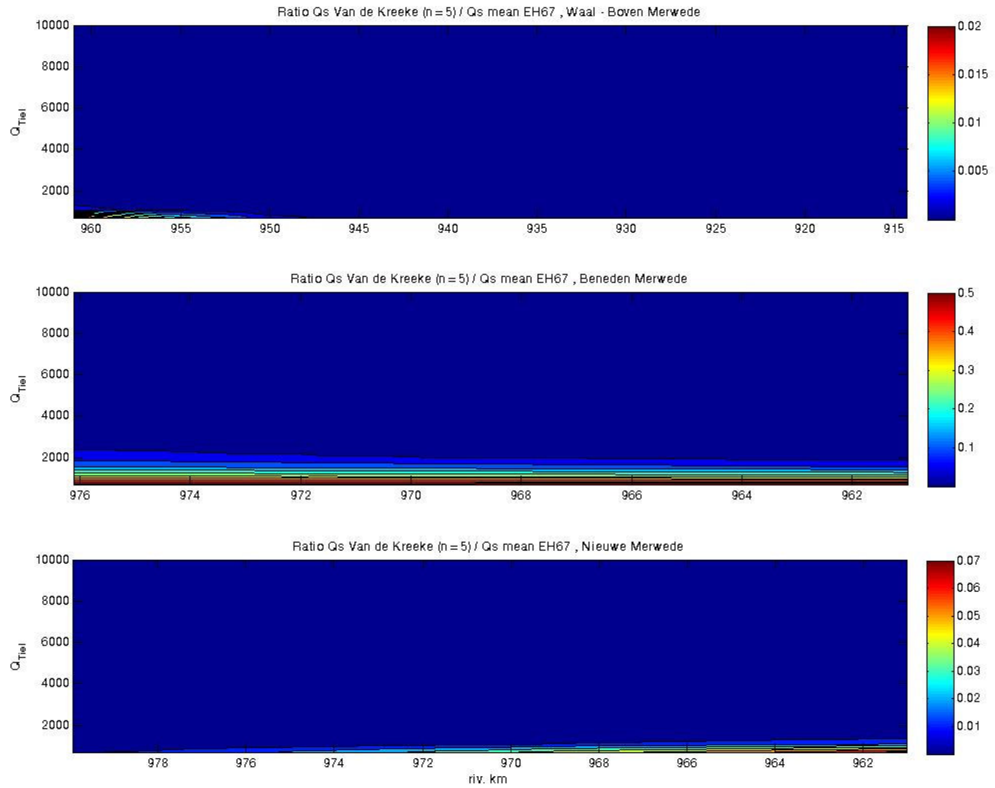
Figure II.1 contains the results of the first-order approximation of Van de Kreeke and Robaczewska (left subfigures) and the mean sediment transport based on time series of the sediment transport (right subfigures). The horizontal axis represents the location along the river and the vertical axis represents the upstream river discharge.

figure II.1. Mean sediment transport as function of location and upstream river discharge in the Waal - Boven Merwede, Beneden Merwede and Nieuwe Merwede; at the left side the first-order approximation of Van de Kreeke; at the right side the mean sediment transport based on time series of the sediment transport.



The ratio of the first-order approximation of Van de Kreeke and the mean sediment transport based on time series of the sediment transport is visualised in figure II.2. The horizontal axis represents the location along the river and the vertical axis represents the upstream river discharge.

figure II.2. Ratio of the first-order approximation of Van de Kreeke and the mean sediment transport based on time series of the sediment transport; as function of location along the river and upstream river discharge in the Waal - Boven Merwede, Beneden Merwede and Nieuwe Merwede.



The net sediment transport of Van de Kreeke is much smaller than the mean sediment transport based on time series of the sediment transport. Only in the Beneden Merwede at small river discharges, the net sediment transport of Van de Kreeke has approximately the same order of magnitude as the mean sediment transport based on time series of the sediment transport. The net sediment transport of Van de Kreeke decreases with increasing river discharge in the Waal - Boven Merwede and Beneden Merwede. However, the mean sediment transport based on time series of the sediment transport increases with increasing river discharge. Therefore the net sediment transport in the Merwedes can not be estimated by the approximation of Van de Kreeke and Robaczewska.

APPENDIX III Expected value of sediment transport

1. INTRODUCTION

An indication of the expected value of the sediment transport (or the yearly sediment transport) can be obtained by including the probability of a certain upstream river discharge. The expected value of sediment transport is the yearly sediment load or the sum of the contributions of all discharges to the yearly sediment transport. In the sediment transport analysis, flow simulations with different stationary river discharges have been used. To determine the expected value of the sediment transport, a weighed average of the simulations should be used. This note contains an explanation of two different methods to determine the expected value of the sediment transport. A simple method is described is chapter 2. Chapter 3 describes a improved method. This improved method has been applied in this study.

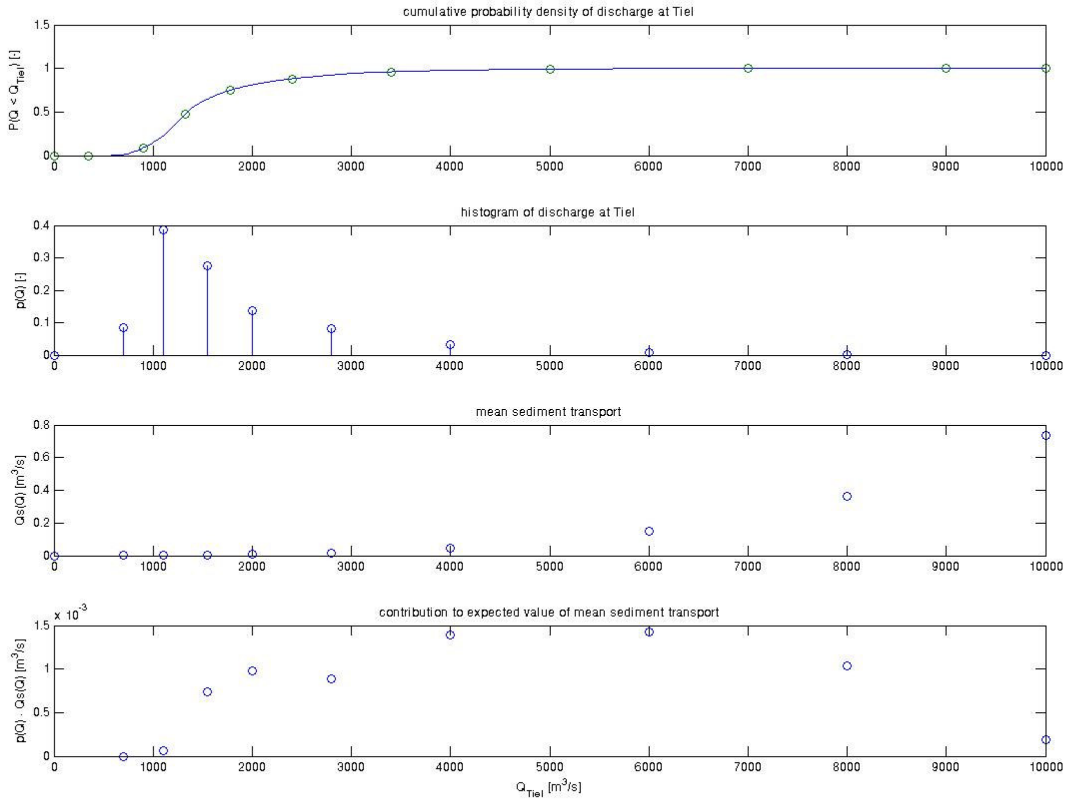
2. SIMPLE METHOD

The expected value of the sediment transport can be calculated with the following approximation:

1. Flow has been simulated for 9 cases with different stationary discharges
2. The probability of the occurrence of the upstream stationary discharge has been determined for each case:
   - At first, the discharge domain is divided in 9 parts. The boundaries of these parts are the average discharge of the neighbouring cases.
   - The probability of occurrence has been determined by: $P(Q < Q_{upper\_boundary}) - P(Q < Q_{lower\_boundary})$ for each part. See figure III.1a and III.1b.
3. For each case, the contribution to the expected value of the sediment transport (figure III.1d) is determined by the product of the mean sediment transport (figure III.1c) and the probability of occurrence (figure III.1b) of these case: $Qs(Q) \cdot p(Q)$.
4. The expected value of the sediment transport is the sum of contributions of the cases: $\Sigma\ Qs(Q) \cdot p(Q)$.

A important disadvantage of the simple method is the large difference in discharge of successive cases. Therefore an improved method has been applied to determine the expected value of sediment transport.

figure III.1. Example of the simple method to determine the expected value of sediment transport

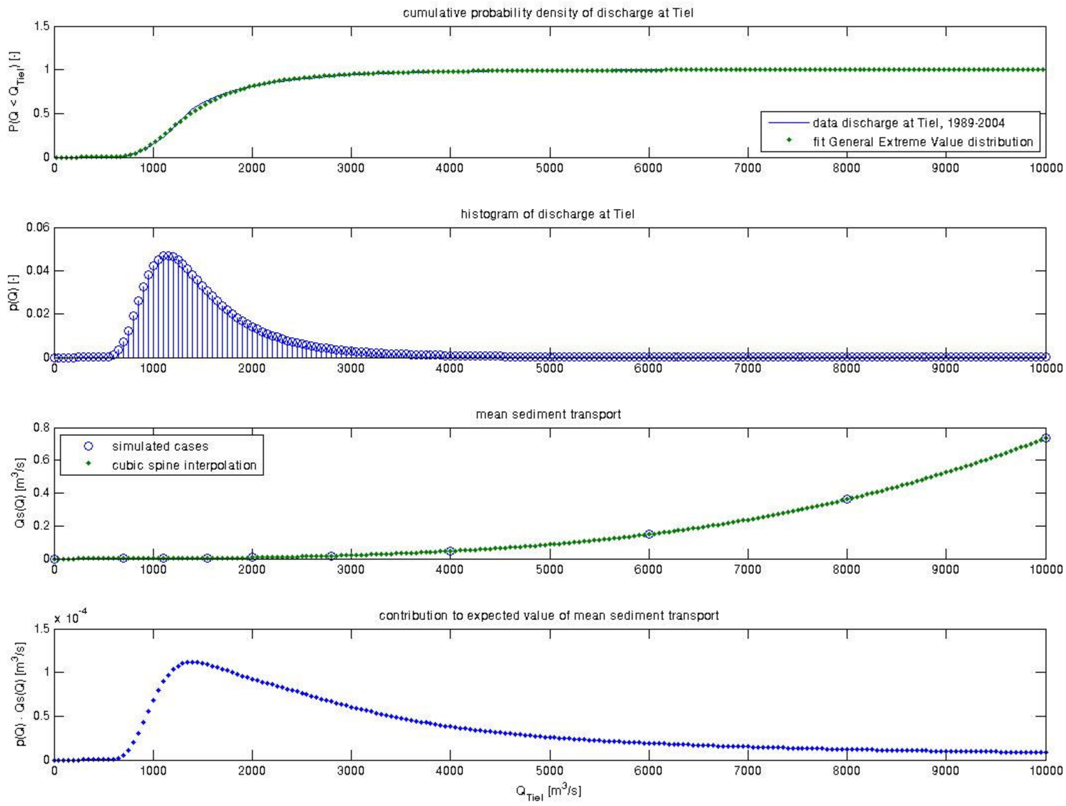


3. IMPROVED METHOD

The simple method has been improved to get an accurate description of the expected value of the sediment transport (Doyle, 2007):

1. Flow has been simulated for 9 cases with different stationary discharges
2. A cumulative distribution function has been fitted through the data of the discharge at Tiel (1989 - 2004). See figure III.2a. The applied cumulative distribution function is a Generalized Extreme Value distribution with the following characteristics:
   - Location parameter $\mu = 1226$
   - Scale parameter $\sigma = 403.2$
   - Shape parameter $\xi = 0.2524$
3. The discharge domain has been discretized with a constant interval of 50 m^3/s. It is recommended to refine this discretization in future studies.
4. For each part the probability of occurrence is determined by the fitted cumulative probability density function: $P(Q < Q_{upper\_boundary}) - P(Q < Q_{lower\_boundary})$. See figure III.2b.
5. The mean sediment transport is interpolated over the discharge domain by means of cubic spline interpolation. See figure III.2c.
6. For each case, the contribution to the expected value of the sediment transport (figure III.2d) is determined by the product of the mean sediment transport (figure III.2c) and the probability of occurrence (figure III.2b) of these case: $Qs(Q) \cdot p(Q)$.
7. The expected value of the sediment transport is the sum of discrete contributions of the cases: $\Sigma\ Qs(Q) \cdot p(Q)$.

figure III.2. Example of the improved method to determine the expected value of sediment transport



The use of the improved method has the following implications for the results relative to the simple method:

- The expected value of the mean sediment transport increases slightly with about 1 %.
- The main contribution comes from lower discharges relative to the simple method.

APPENDIX IV Overview of bed composition and calibration factors in adjusted SOBEK model

1. INTRODUCTION
An overview is given of the bed composition and calibration factor in the adjusted (morphological) SOBEK model of the Rhine-Meuse Delta in respectively chapter 2 and chapter 3.

2. BED COMPOSITION
The bed composition of the branches of the Rhine-Meuse Delta will be approximated by a constant bed composition per river branch (D_{50} and D_{90}) based on averaging of Fugro data (2002). The mean bed composition per river branch is presented in table IV.1. The schematisation of the bed composition of the whole Rhine-Meuse Delta is based on these data and is presented for all branches is table IV.2. The schematisation of bed composition of the Waal, Boven Merwede, Beneden Merwede and Nieuwe Merwede is not included in table IV.2, because the linear schematisation of these branches is included in section 4.3. The schematisation of the bed composition of these branches is marked with *.

3. CALIBRATION FACTORS
The calibration factor of the sediment transport model is set to 0 for the following areas to improve the performance of the adjusted model:
- A part of the Haringvliet, westerly of the Spui,
- All harbours and branches with dead ends, except the braches with dead ends near the Waal, Merwedes, Biesbosch and Meuse.

In this way, only flow will be computed in these branches and it is assumed that sediment transport is negligible small in these river branches and estuaries. An overview of calibration factors of the sediment transport of all river branches can be found in table IV.2.

table IV.1. Mean bed composition per river branch

River branch	D50 [µm]	D90 [µm]
Amer	258	408
Beneden Merwede	550	2273
Bergse Maas	516	966
Dordtsche Kil	245	3110
Haringvliet	142	313
Hollandsch Diep	86	200
Lek	436	1168
Maas	556	1511
Nieuwe Maas	282	5264
Nieuwe Merwede	341	506
Nieuwe Waterweg	346	679
Noord	402	2589
Oude Maas	302	1875
Spui	251	1959
Waal - Boven Merwede	797	3554

table IV.2. Bed composition and calibration factors in adjusted SOBEK model

River	Name river branch in SOBEK	calibration factor sediment transport [-]	D50 [µm]	D90 [µm]
Amer	aakv_001a	1	258	408
Amer	aakv_001b	1	258	408
Amer	aakv_002	1	258	408
Amer	AMER1	1	258	408
Amer	AMER2	1	258	408
Amer	AMER3	1	258	408

River	Name river branch in SOBEK	calibration factor sediment transport [-]	D50 [µm]	D90 [µm]
Amer	Kerksloot	0	258	408
Amer	overlaat_aakv	1	258	408
Amer	Spijkerboor_B	1	258	408
Amer	Spijkerboor-A	1	258	408
Amer	Steurgat	1	258	408
Beneden Merwede	BEME	1	*	*
Beneden Merwede	WANTIJ	0	550	2273
Bergse Maas	Andelms1	0	516	966
Bergse Maas	Andelms2	0	516	966
Bergse Maas	Andelms3	0	516	966
Bergse Maas	BEMA_A	1	516	966
Bergse Maas	BEMA_B	1	516	966
Bergse Maas	BEMA063	0	516	966
Bergse Maas	Getijms3	1	516	966
Bergse Maas	Getijms4	1	516	966
Dordtsche Kil	DOKI073	1	245	3110
Haringvliet	HAVL042	0	142	313
Haringvliet	HAVL043	0	142	313
Haringvliet	HAVL044	1	142	313
Haringvliet	HAVL045	1	142	313
Haringvliet	HAVL046	1	142	313
Haringvliet	HAVL047	1	142	313
Haringvliet	HAVL048	1	142	313
Haringvliet	HAVL049	1	142	313
Haringvliet	HAVL050	1	142	313
Haringvliet	HAVL051	1	142	313
Haringvliet	HAVL052	1	142	313
Haringvliet	HAVL053	1	142	313
Haringvliet	ZEHV097	0	142	313
Haringvliet	ZEHV098	0	142	313
Haringvliet	ZEHV099	0	142	313
Haringvliet	ZEHV100	0	142	313
Haringvliet	ZEHV101	0	142	313
Haringvliet	ZEHV102	0	142	313
Haringvliet	ZEHV103	0	142	313
Haringvliet	ZEHV104	0	142	313
Hollandsch Diep	HODI_bo1	1	86	200
Hollandsch Diep	HODI_bo2	1	86	200
Hollandsch Diep	HODI055	1	86	200
Hollandsch Diep	HODI056	1	86	200
Hollandsch Diep	HODI057	1	86	200
Hollandsch Diep	HODI058	1	86	200
Hollandsch Diep	HODI059	0	86	200
Hollandsch Diep	Z_MAAR_GAT	0	86	200
Lek	Lek____2	1	436	1168
Lek	VAK159	1	436	1168
Maas	Getijms1	1	556	1511
Maas	Getijms2	1	556	1511

River	Name river branch in SOBEK	calibration factor sediment transport [-]	D50 [µm]	D90 [µm]
Nieuwe Maas	BAKI027	1	282	5264
Nieuwe Maas	EMHA015	0	282	5264
Nieuwe Maas	HOIJ028	1	282	5264
Nieuwe Maas	HOIJ029	0	282	5264
Nieuwe Maas	MAHA019	0	282	5264
Nieuwe Maas	NIMA_Rotterdam	1	282	5264
Nieuwe Maas	NIMA010	1	282	5264
Nieuwe Maas	NIMA012	1	282	5264
Nieuwe Maas	NIMA014	1	282	5264
Nieuwe Maas	NIMA016	1	282	5264
Nieuwe Maas	NIMA018	1	282	5264
Nieuwe Maas	NIMA020	1	282	5264
Nieuwe Maas	NIMA022	1	282	5264
Nieuwe Maas	NIMA023	1	282	5264
Nieuwe Maas	NIMA025	1	282	5264
Nieuwe Maas	NIMA026	1	282	5264
Nieuwe Maas	NIMA083	1	282	5264
Nieuwe Maas	PET1011	0	282	5264
Nieuwe Maas	PET2013	0	282	5264
Nieuwe Maas	PET3008	0	282	5264
Nieuwe Maas	RIHA021	0	282	5264
Nieuwe Maas	WAHA017	0	282	5264
Nieuwe Merwede	Gatvdhil	1	341	506
Nieuwe Merwede	Gatvdkampen_1	1	341	506
Nieuwe Merwede	Gatvdkampen_2	1	341	506
Nieuwe Merwede	GatvdV_2	1	341	506
Nieuwe Merwede	Gatvdvisschen	1	341	506
Nieuwe Merwede	GvdV_1	1	341	506
Nieuwe Merwede	GvdV_2	1	341	506
Nieuwe Merwede	NIME	1	*	*
Nieuwe Merwede	NIME_1	1	*	*
Nieuwe Merwede	NIME_2	1	*	*
Nieuwe Merwede	nime_overl1	1	*	*
Nieuwe Merwede	nime_overl2	1	*	*
Nieuwe Merwede	nime_overl3	1	*	*
Nieuwe Merwede	NIME-BIBO1	1	341	506
Nieuwe Merwede	NIME-BIBO2	1	341	506
Nieuwe Merwede	NIME-BIBO3	1	341	506
Nieuwe Merwede	NOWA110	1	341	506
Nieuwe Merwede	NOWA111	1	341	506
Nieuwe Merwede	NOWA112	1	341	506
Nieuwe Merwede	NOWA113	1	341	506
Nieuwe Merwede	NOWA114	1	341	506
Nieuwe Merwede	NOWA115	1	341	506
Nieuwe Merwede	NOWA116	1	341	506
Nieuwe Merwede	NOWA117	1	341	506
Nieuwe Waterweg	BEHA096	0	346	679
Nieuwe Waterweg	BEKA093	1	346	679

River	Name river branch in SOBEK	calibration factor sediment transport [-]	D50 [µm]	D90 [µm]
Nieuwe Waterweg	BEKA095	0	346	679
Nieuwe Waterweg	BOLE005	0	346	679
Nieuwe Waterweg	BOLE006	0	346	679
Nieuwe Waterweg	BOLE007	0	346	679
Nieuwe Waterweg	BRED086	1	346	679
Nieuwe Waterweg	CAKA087	1	346	679
Nieuwe Waterweg	CAKA088	1	346	679
Nieuwe Waterweg	CAKA089	0	346	679
Nieuwe Waterweg	CAKA090	0	346	679
Nieuwe Waterweg	CAKA091	0	346	679
Nieuwe Waterweg	CAKA092	0	346	679
Nieuwe Waterweg	DIHA080	0	346	679
Nieuwe Waterweg	GEHA009	0	346	679
Nieuwe Waterweg	HAKA_078a	1	346	679
Nieuwe Waterweg	HAKA_078b	1	346	679
Nieuwe Waterweg	HAKA_SVKH	1	346	679
Nieuwe Waterweg	HAKA079	1	346	679
Nieuwe Waterweg	HAKA99	1	346	679
Nieuwe Waterweg	MAMO001	1	346	679
Nieuwe Waterweg	MAMO002	1	346	679
Nieuwe Waterweg	MAMO097	0	346	679
Nieuwe Waterweg	MIHA094	1	346	679
Nieuwe Waterweg	MISSISSIPI	1	346	679
Nieuwe Waterweg	NIWA_SVKW	1	346	679
Nieuwe Waterweg	NIWA003	1	346	679
Nieuwe Waterweg	openbdam	1	346	679
Nieuwe Waterweg	openhartelhvn	1	346	679
Nieuwe Waterweg	SEHA082	0	346	679
Noord	NOOR075	1	402	2589
Noord	NOOR076	1	402	2589
Noord	NOOR098	1	402	2589
Noord	RIET077	1	402	2589
Oude Maas	KRAB036	0	302	1875
Oude Maas	OUMA_Dordrecht	1	302	1875
Oude Maas	OUMA_Spijkenisse	1	302	1875
Oude Maas	OUMA033	1	302	1875
Oude Maas	OUMA035	1	302	1875
Oude Maas	OUMA037	1	302	1875
Spui	SPUI084	1	251	1959
Waal - Boven Merwede	Waal___2	1	*	*

APPENDIX V Characteristics of morphological simulations

1. INTRODUCTION

This appendix contains the characteristics of morphological simulations of the Merwedes with the adjusted SOBEK model. The following characteristics have been quantified for each river branch:

- the mean bed level of the main channel (mean z_{bed} [m] + NAP),
- the cumulative bed level change of the main channel relative to the initial bed level (Δz_{bed} [m]),
- the standard deviation of the bed level of the main channel (σz_{bed} [m]).
  The standard deviation of the bed level of the main channel gives an indication of the spatial variation of the bed level of a river branch.

Chapter 2 contains the characteristics of the reference simulation. The characteristics of simulations with other sea boundary conditions are included in chapter 3. Chapter 4 contains the characteristics of a simulation with another sediment transport model. The characteristics of a simulation with dredging are included in chapter 5.

2. CHARACTERISTICS OF REFERENCE SIMULATION

The characteristics of the reference simulation are summarised in table V.1 for the Boven Merwede, in table V.2 for the Beneden Merwede and in table V.3 for the Nieuwe Merwede.

table V.1. Characteristics of the Boven Merwede of reference simulation

time [years]	mean z_{bed} [m] + NAP	Δz_{bed} [m]	σz_{bed} [m]
0	-5.486	0.000	0.226
1	-5.303	0.183	0.359
2	-5.113	0.372	0.428
3	-4.918	0.568	0.434
4	-4.750	0.736	0.384
5	-4.583	0.903	0.279
6	-4.443	1.043	0.087
7	-4.404	1.081	0.087
8	-4.340	1.146	0.100
9	-4.285	1.201	0.108
10	-4.231	1.255	0.092
11	-4.184	1.302	0.090
12	-4.157	1.329	0.091

table V.2. Characteristics of the Beneden Merwede of reference simulation

time [years]	mean z_{bed} [m] + NAP	Δz_{bed} [m]	σz_{bed} [m]
0	-6.047	0.000	0.528
1	-6.016	0.032	0.572
2	-5.987	0.060	0.627
3	-5.953	0.094	0.663
4	-5.910	0.137	0.692
5	-5.871	0.176	0.720
6	-5.820	0.227	0.754
7	-5.704	0.343	0.841
8	-5.584	0.463	0.904
9	-5.462	0.585	0.917
10	-5.342	0.705	0.912
11	-5.227	0.820	0.911
12	-5.115	0.932	0.944

table V.3. Characteristics of the Nieuwe Merwede of reference simulation

time [years]	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	σ z_{bed} [m]
0	-4.117	0.000	0.245
1	-4.098	0.019	0.252
2	-4.080	0.037	0.262
3	-4.061	0.056	0.271
4	-4.038	0.079	0.277
5	-4.017	0.100	0.285
6	-3.991	0.126	0.288
7	-3.933	0.184	0.282
8	-3.873	0.244	0.284
9	-3.812	0.305	0.267
10	-3.753	0.364	0.270
11	-3.695	0.422	0.275
12	-3.631	0.486	0.263

3. CHARACTERISTICS OF SIMULATIONS WITH OTHER SEA BOUNDARY CONDITIONS

The characteristics of simulations with several sea boundary conditions are summarised in table V.4 for the Boven Merwede, in table V.2 for the Beneden Merwede and in table V.6 for the Nieuwe Merwede. The following sea boundary conditions have been applied:

- s.n.c. spring-neap cycle
- t.c. schematised tidal cycle
- c.w.l. constant water level

A spring-neap cycle has been applied in the reference simulation.

The first row of the tables corresponds to 7 years, because the simulations have been restarted after 7 years.

table V.4. Characteristics of simulations of the effect of sea boundary conditions on the Boven Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	s.n.c	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**
7	-4.404	-4.404	-4.404	1.082	1.082	1.082	0.087	0.087	0.087
8	-4.340	-4.339	-4.334	1.146	1.147	1.152	0.100	0.103	0.097
9	-4.285	-4.282	-4.273	1.201	1.204	1.212	0.108	0.110	0.105
10	-4.231	-4.227	-4.215	1.255	1.259	1.271	0.092	0.095	0.090
11	-4.184	-4.177	-4.166	1.302	1.308	1.320	0.090	0.092	0.088
12	-4.157	-4.148	-4.138	1.329	1.338	1.347	0.091	0.093	0.091

table V.5. Characteristics of simulations of the effect of sea boundary conditions on the Beneden Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	s.n.c	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**
7	-5.704	-5.704	-5.704	0.344	0.344	0.344	0.841	0.841	0.841
8	-5.584	-5.589	-5.573	0.463	0.458	0.474	0.904	0.903	0.940
9	-5.462	-5.472	-5.445	0.585	0.576	0.603	0.917	0.921	1.001

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
10	-5.342	-5.355	-5.317	0.705	0.692	0.730	0.912	0.919	1.021
11	-5.227	-5.243	-5.193	0.820	0.804	0.854	0.911	0.916	1.028
12	-5.115	-5.132	-5.069	0.932	0.915	0.979	0.944	0.945	1.051

table V.6. Characteristics of simulations of the effect of sea boundary conditions on the Nieuwe Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	s.n.c	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**	**s.n.c**	**t.c.**	**c.w.l.**
7	-3.933	-3.933	-3.933	0.184	0.184	0.184	0.282	0.282	0.282
8	-3.873	-3.874	-3.870	0.244	0.242	0.247	0.284	0.284	0.295
9	-3.812	-3.814	-3.806	0.305	0.302	0.311	0.267	0.269	0.289
10	-3.753	-3.756	-3.744	0.364	0.361	0.373	0.270	0.270	0.287
11	-3.695	-3.699	-3.683	0.422	0.418	0.434	0.275	0.276	0.296
12	-3.631	-3.636	-3.616	0.486	0.481	0.500	0.263	0.269	0.289

4. CHARACTERISTICS OF A SIMULATION WITH ANOTHER SEDIMENT TRANSPORT MODEL

The characteristics of simulations with several sediment transport models are summarised in table V.7 for the Boven Merwede, in table V.8 for the Beneden Merwede and in table V.9 for the Nieuwe Merwede. The following sediment transport models have been applied:

- EH67 Engelund and Hansen 1967
- VR93 Van Rijn 1993

The sediment transport model of Engelund and Hansen has been applied in the reference simulation.

The first row of the tables corresponds to 7 years, because the simulations have been restarted after 7 years.

table V.7. Characteristics of simulations of the effect of the choice of a sediment transport model on the Boven Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	EH67	**VR93**	**EH67**	**VR93**	**EH67**	**VR93**
7	-4.404	-4.404	1.082	1.082	0.087	0.087
8	-4.340	-4.461	1.146	1.024	0.100	0.114
9	-4.285	-4.509	1.201	0.977	0.108	0.110
10	-4.231	-4.536	1.255	0.949	0.092	0.089
11	-4.184	-4.543	1.302	0.942	0.090	0.079
12	-4.157	-4.548	1.329	0.938	0.091	0.089

table V.8. Characteristics of simulations of the effect of the choice of a sediment transport model on the Beneden Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	EH67	**VR93**	**EH67**	**VR93**	**EH67**	**VR93**
7	-5.704	-5.703	0.344	0.344	0.841	0.842
8	-5.584	-5.482	0.463	0.565	0.904	0.985
9	-5.462	-5.273	0.585	0.774	0.917	1.000

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
10	-5.342	-5.091	0.705	0.956	0.912	1.002
11	-5.227	-4.956	0.820	1.092	0.911	1.035
12	-5.115	-4.829	0.932	1.218	0.944	1.043

table V.9. Characteristics of simulations of the effect of the choice of a sediment transport model on the Nieuwe Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	EH67	**VR93**	**EH67**	**VR93**	**EH67**	**VR93**
7	-3.933	-3.933	0.184	0.184	0.282	0.282
8	-3.873	-3.836	0.244	0.281	0.284	0.260
9	-3.812	-3.746	0.305	0.371	0.267	0.265
10	-3.753	-3.661	0.364	0.455	0.270	0.242
11	-3.695	-3.591	0.422	0.526	0.275	0.265
12	-3.631	-3.526	0.486	0.591	0.263	0.284

5. CHARACTERISTICS OF A SIMULATION WITH DREDGING

The characteristics of simulations without dredging and with dredging in the Boven and Nieuwe Merwede are summarised in table V.10 for the Boven Merwede, in table V.11 for the Beneden Merwede and in table V.12 for the Nieuwe Merwede. The reference simulation is without dredging.

The first row of the tables corresponds to 7 years, because the simulations have been restarted after 7 years.

table V.10. Characteristics of simulations of the effect dredging on the Boven Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	without dredging	**with dredging**	**without dredging**	**with dredging**	**without dredging**	**with dredging**
7	-4.404	-4.404	1.082	1.082	0.087	0.087
8	-4.340	-4.383	1.146	1.103	0.100	0.103
9	-4.285	-4.359	1.201	1.127	0.108	0.119
10	-4.231	-4.325	1.255	1.161	0.092	0.113
11	-4.184	-4.290	1.302	1.195	0.090	0.105
12	-4.157	-4.269	1.329	1.217	0.091	0.097

table V.11. Characteristics of simulations of the effect dredging on the Beneden Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	without dredging	**with dredging**	**without dredging**	**with dredging**	**without dredging**	**with dredging**
7	-5.704	-5.704	0.344	0.344	0.841	0.841
8	-5.584	-5.586	0.463	0.462	0.904	0.903
9	-5.462	-5.469	0.585	0.578	0.917	0.911
10	-5.342	-5.360	0.705	0.687	0.912	0.901
11	-5.227	-5.259	0.820	0.788	0.911	0.891
12	-5.115	-5.165	0.932	0.882	0.944	0.912

table V.12. Characteristics of simulations of the effect dredging on the Nieuwe Merwede

time [years]	mean z_{bed} [m] + NAP	mean z_{bed} [m] + NAP	Δ z_{bed} [m]	Δ z_{bed} [m]	σ z_{bed} [m]	σ z_{bed} [m]
	without dredging	with dredging	without dredging	with dredging	without dredging	with dredging
7	-3.933	-3.933	0.184	0.184	0.282	0.282
8	-3.873	-3.897	0.244	0.220	0.284	0.286
9	-3.812	-3.861	0.305	0.255	0.267	0.269
10	-3.753	-3.829	0.364	0.287	0.270	0.271
11	-3.695	-3.800	0.422	0.317	0.275	0.275
12	-3.631	-3.767	0.486	0.349	0.263	0.265