Impact of recent changes in river management on maintenance dredging in the Waal river

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Preface

After a long road, I will conclude my master study in hydraulic engineering with this thesis at the Delft University of Technology. The aim of this research was to investigate the maintenance dredging effort at the Waal in different periods where changes have been implemented or new intervention works were planned and to mitigate the dredging problem by proposing new solutions.

The research was carried out at HKV Consultants in Delft and in Lelystad, who have guided me and offered me a workspace. With this thesis project I started experiencing the engineering world. This is not the ‘End’. It is just the beginning of my career. I would like to express my gratitude to HKV Consultants for giving me this opportunity. Furthermore, I would like to thank the members of the graduation committee, namely W.S.J. Uijtewaal, S. van Vuren, A. J. Paarlberg, E. Mosselman and H. Havinga, for their guidance through this research. Finally, I would like to thank my family, friends and everyone for their support during my study and graduation.

J. Kisoensingh

Delft, February 2015
Summary

Over the last centuries, Dutch rivers such as the Rhine have been heavily trained for the purpose of the safe discharge of water, sediment and ice, and navigability. After the notorious flood events of 1993 and 1995 along the Rhine, new large-scale river works were initiated, such as the Room for the River (RfR) programme, to increase flood conveyance capacity. For a better navigation, in 2006 the minimum guaranteed depth on the Waal has been raised from 2.50 m to 2.80 m (relative to the Agreed Low Water level). It is inevitable that the measures of the large-scale works (depending on the type and magnitude of the measure) and changes in the minimum guaranteed depth will influence the morphology of the river and the dredging effort.

Three schematisations are distinguished in this research, namely maintenance dredging in the situation with a minimum guaranteed depth of 2.5 m (‘Ref – 2.5 m’), the situation with a minimum guaranteed depth of 2.8 m (‘Ref – 2.8 m’), and the situation after the implementation of the Room for the River programme (‘RfR’, with a minimum guaranteed depth of 2.8 m). The aim of this research is to determine the impacts of the increase in the minimum guaranteed depth and the Room for the River programme on the maintenance dredging in the river Waal using the deterministic approach (traditional) and a stochastic approach, and to determine the potential of a stochastic approach with respect to the deterministic approach in river management practice.

Currently, morphological calculations are being executed using a deterministic approach. The deterministic approach appears to be an effective tool to provide a quick expression of the physical morphodynamic processes. However, to fully acknowledge these morphodynamic processes and to derive a precise illustration using a deterministic model is very complex. By ignoring the complexity of the morphodynamic processes, the involved uncertainties are not made explicit. Identifying the uncertainty in morphodynamic predictions is necessary in order to come to grips with system behaviour of the Waal. Therefore, it is important not only look at the deterministic calculation, but also to perform stochastic calculations.

In this study, numerical calculations with a 2D depth averaged Delft3D model are performed using a deterministic and stochastic approach to determine the bed level changes, navigability, and dredging effort. For the deterministic approach a representative discharge hydrograph is used and for the stochastic approach 75 different discharge time series.

From the present research it follows that the maintenance dredging volume in the ‘Ref – 2.8 m’ situation is twice as much as in the ‘Ref – 2.5 m’ situation. It increases drastically with 196%. The increase in the maintenance dredging volume in the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation is approximately 10 times lower than the increase in the maintenance dredging volume in the ‘Ref – 2.8 m’ situation (which is related to the dredging effort in the ‘Ref – 2.5 m’ situation). This concludes that the increase of the minimum guaranteed depth has a bigger impact on the maintenance dredging than the impact of the Room for the River measures.

According to the simulations it also follows that the dredging volume in all sharp bends (Millingen (rkm 869-870), Erlecom (rkm 875-876) and Nijmegen (rkm 883-885)) in total is more than the half of the total dredging volume on the Waal. Nijmegen (rkm 883-886) only covers more than one-third of the total maintenance dredging volume on the Waal.

As regards to the deterministic and the stochastic approach, the differences between the mean value of the stochastic approach and the deterministic approach are rather high in the entire
Waal (which lies between 30 and 40%). In the Nijmegen area this difference is negligible. Generally speaking, the mean value of the stochastic approach is not underestimated by the deterministic calculations. The large difference does not imply that the stochastic approach is more promising than the deterministic approach or vice versa. The uncertainty range (90%-confidence band) in the stochastic approach helps the river manager to decide where and how to interfere in the river system and it helps in drawing up performance based contracts with dredging companies. The stochastic approach gives more insight in the range or likelihood of predictions if it comes to dredging. If the river manager wants to employ a dredging company (contractor) for maintenance dredging, he can sign the contract for a lower amount of money, since the mean value of the stochastic approach is lower than the results of the deterministic approach.
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<th>Description</th>
</tr>
</thead>
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<tr>
<td>ALW</td>
<td>Agreed Low Water level</td>
</tr>
<tr>
<td>RFR</td>
<td>Room for the River programme</td>
</tr>
<tr>
<td>WFD</td>
<td>The European Water Framework Directive</td>
</tr>
<tr>
<td>DVR</td>
<td>Sustainable Fairway Rhine Delta (in Dutch: ‘Duurzame Vaardiepte Rijndelta’)</td>
</tr>
<tr>
<td>NURG</td>
<td>Further Elaboration of the River Area (in Dutch: ‘Nadere Uitwerking Rivieren Gebied’)</td>
</tr>
<tr>
<td>IWT</td>
<td>Inland Waterways Transport</td>
</tr>
<tr>
<td>ALD</td>
<td>Agreed Low Discharge (in Dutch: ‘Overeengekomen lage rivierafvoer’)</td>
</tr>
<tr>
<td>Rkm</td>
<td>River Kilometre</td>
</tr>
<tr>
<td>MCS</td>
<td>Monte Carlo Simulation</td>
</tr>
<tr>
<td>FORM</td>
<td>First-Order Reliability Method</td>
</tr>
</tbody>
</table>
Chapter 1

1.1 Background
Over the last centuries, Dutch rivers like the Rhine have been heavily trained for the purpose of safe discharge of water, sediment and ice, and navigability. The river training works consisted of canalization, construction of levees, and bend cut-offs. The Rhine is an important shipping connection between the Port of Rotterdam and Germany. The main Rhine branch, the Waal River, is Europe's busiest river in that respect. Most of the cargo transport to Germany runs via this inland waterway connection. Rapid population growth and economic development of Northwestern Europe have increased the need for river engineering solutions to regulate inland river navigation and better flood management.

After the notorious flood events of 1993 and 1995 along the Rhine, new large-scale river works were initiated, such as the Room for the River (RfR) programme, to increase flood conveyance capacity as well as spatial quality;

In the last decades other large scale projects (programmes) have been initiated, such as:

- The European Water Framework Directive (WFD, in Dutch: Kader Richtlijn Water, KRW), a European Union directive to secure the quality of water bodies;
- Sustainable Fairway Rhine Delta (in Dutch: “Duurzame Vaardiepte Rijndelta”, DVR) to explore sustainable strategies to maintain the enlarged navigation channel.
- Further Elaboration of the River Area (in Dutch: “Nadere Uitwerking Rivieren Gebied,” NURG), to increase ecological areas in the floodplains.

These modern river management and river maintenance works are in full progress at the moment. The works should reconcile several functions, such as protection against floods, floodplain agriculture, navigation, ecology, and recreation. Typical measures of these projects are the lowering of floodplains, groyne lowering, construction of longitudinal dams, side channels, free banks, and the reconnecting of lakes. In 2006, the minimum guaranteed depth on the Waal has also been raised from a 2.50 m depth-criterion to a 2.80 m depth-criterion (with a channel width of 150 m) during Agreed Low Water (ALW) conditions which occur 5% of the time. The other branches of the Rhine maintain a minimum depth of 2.5 m at ALW and varying widths (depending on the local situation) (Schielen et al, 2008). The changes in river management are implemented to create an enlarged navigation channel and make it more sustainable to maintain. However, because of uncertainties in effectiveness of the measures and in order to meet demands for navigation, the Directorate for Public Works and Water Management launched the DVR project. The DVR project aims at defining and evaluating river interventions to keep the Rhine navigable (Mosselman et al, 2007).

1.2 Problem description
One would expect that navigability would have been incorporated in large-scale river works, such as the RfR and WFD schemes, but in fact improving conditions for inland navigation has not been a main design criterion in these programmes (except for DVR). Furthermore, the increase of the minimum water depth of 2.5 m to 2.8 m during Agreed Low Water (ALW) is implemented to make shipping possible. It is inevitable that the measures of the large-scale works (depending on the type and magnitude of the measure) will influence the flow patterns, sediment transport
fields, and may induce larger dynamics of the riverbed. This may negatively influence the river’s navigability and may consequently induce extra maintenance dredging efforts (Van Vuren and Havinga, 2012). This in fact requires a large amount of dredging and a large number of dredging vessels to keep the rivers navigable, which cause increased hindrance to inland navigation, especially in the Waal. The maintenance and dredging costs are expected to rise as a result. The financing of maintenance and dredging is not guaranteed and the risk of accidents may increase, thus lowering the safety of inland navigation. It is therefore important to acknowledge the effect of the increase of the minimum guaranteed depth and the RfR and WFD river intervention works. With this acknowledgement it can be explained what proportion of the increase in dredging effort must be attributed to the increase in depth criterion or by similar measures contained in the RfR. Furthermore, the dredging effort in the ongoing projects has been calculated in a deterministic way. The uncertainty in future river discharges creates uncertainty bands in the development of the riverbed, and thus leads to uncertainty in the derived maintenance dredging. Note that there are also other sources present in river management that creates uncertainty. Because of the use of deterministic calculation methods, there is a lack of understanding of the uncertainty at present. This calls for a stochastic approach. Understanding the uncertainty of required maintenance dredging may aide river managers in better estimating the dredging efforts and thus illuminate the hindrance for inland navigation.

1.3 Research question
Based on the aforementioned issues, the following general research question is formulated:

*What is the impact of recent changes in river management on maintenance dredging in the Waal river?*

Within the scope of this research, the following specific questions are defined:

1. What is the morphological effect of increasing the minimum guaranteed depth with a 2.50 m depth-criterion to a 2.80 m depth-criterion on maintenance dredging in the Waal?
2. What is the morphological effect of the Room for the River project on maintenance dredging in the Waal?
3. What is the added value of a stochastic approach with respect to the deterministic approach in river management practice?

1.4 Research outline
This report starts, in Chapter 2, with providing essential information about the Rhine system, river training evolution in the Rhine and the recent intervention works and their impacts on navigability, especially in the Waal. Chapter 3 focuses on the research methodology. Tools, such as the deterministic method, stochastic method, and the morphodynamic model used in this research are discussed. In chapter 4 three different situations will assessed, namely: the situation with the 2.5 m-depth criterion, the situation with the 2.8 m-depth criterion, and the situation with the 2.8 m-depth criterion plus the Room for the River programme. These situations will be evaluated using the morphodynamic model used in a deterministic and stochastic setting. The potential of a stochastic approach in river management practice has also been investigated. These analyses will be used to answer questions 1 through 3. Chapter 5 is the final chapter and contains the discussion, conclusions, and recommendations. The final chapter also gives the outcome of the thesis and the recommendations for future work on maintenance, based on the findings and assumptions used in the thesis.
Chapter 2 The Rhine in the Netherlands

2.1 Inland Waterways Transport

Inland Waterways Transport (IWT) is of immense importance for national economic wellbeing. The major rivers in the Netherlands play a vital role in navigation. About 40% of international transport arriving from overseas in the Port of Rotterdam is shipped to Germany via the Rhine River (Olierook, 2013). For the time being, the main Rhine branch, the Waal River, is Europe's busiest river in that respect. The attractiveness of Inland Waterways Transport (IWT) is due to low transport costs compared to road or rail transport, and the high level of safety for this type of transport (Hetzer, 2005 and Havinga et al., 2006).

Because of road congestion, policy efforts aim to increase cargo transportation over water. To accomplish this, transport over water must be made more attractive. Reliable navigation conditions require a sufficient draught. Negative changes of the river bathymetry due to bed load transport, suspended load transport, and fast flow velocities should be avoided. For the economic use of waterways, the water depth is important - by contrast, shipping safety requires large channel widths and a smooth riverbed in shallower areas to avoid damage to rudders and ship propellers.

In the next sections the specific topology and training measures on the Rhine system will be discussed.

2.2 The Rhine in the Netherlands

2.2.1 Introduction to the Rhine system

The Rhine is a large and important river in Western Europe with a total length of 1,320 km, of which 800 km is navigable. The river originates in the Alps and flows through Switzerland, France and Germany to the Netherlands. From the source to the mouth, the river consists of the High Rhine, Upper Rhine, Middle Rhine, Lower Rhine and Rhine delta. In the Netherlands there...
are six main branches: Bovenrijn, Waal, Pannerdensch Kanaal, IJssel, Nederrijn, and Lek. From Lobith (km 868), the river flows another 170 km until it empties into the North Sea. At the Pannerdensche Kop, the Rhine divides into the Waal and the Pannerdensch Kanaal, which itself divides into the Nederrijn-Lek and the IJssel at the IJsselkop. At the Pannerdensche Kop bifurcation, approximately 66% of the Rhine discharge is directed to the Waal. The remaining 34% flows into the Pannerdensch Kanaal, and at the IJsselkop bifurcation, two thirds are directed into the Lower-Rhine and one third into the IJssel. Under low and intermediate flow conditions, a weir in the Lower-Rhine controls the water distribution (Van Vuren, 2005).

2.2.2 River training
Over the course of centuries the Dutch rivers have been regulated for inland navigation and flood management. The first so-called regulation structures in the Rhine consisted of river cut-offs, the construction of singular groynes and guide walls to force the flow into a low water bed of limited width, and the closing of secondary channels. These structures were meant to increase the flow velocities in the main channel that prevents the formation of sand bars. The above-mentioned regulation structures, intended for the functions of flood protection and agriculture, appeared to have large advantages for navigation as well: a larger navigable depth and navigable width became available. However, ecological values diminished and biodiversity was reduced.

After the first regulations, the Rhine in the Netherlands became heavily trained in the 19th and early 20th centuries. The large-scale river training consisted of several measures for increased navigability, flood protection and land use (safe discharge of water, sediment, and ice). Fixed planforms, non-permeable groynes, and use of a single main channel are examples of measures to improve navigability. Low levees ‘summer dikes’ protect floodplains and high dikes act as a main flood defence to protect a dense population living in low-lying polders. (Van Vuren, 2005).

Other measures were introduced over time as well. Recent large-scale river works are for example: The Room for the River programme and the Water Framework Directive. The table below gives a summary of most of the river training and river works of the Rhine, especially the Waal (Van Vuren, 2005 and Silva et al., 2001).

Table 1: River training evolution in Rhine, especially the Waal (pictures adapted from: maps.google.nl, www.kanalenin nederland.nl, and Giri, 2011)

<table>
<thead>
<tr>
<th>Period of Intervention</th>
<th>Structural Changes in the Waal</th>
</tr>
</thead>
<tbody>
<tr>
<td>German Rhine branches 1890-1970</td>
<td>Large-scale river regulation works, large-scale effects, and construction of weirs in the German part of the Rhine, leading to a water level reduction and a reduction of sediment load in the Dutch Rhine branches.</td>
</tr>
<tr>
<td>Bovenrijn and Waal 1850 – 1916</td>
<td>Extensive river improvement schemes began around 1850: main channel systematically fixed and narrowed, navigation channels dredged, islands and sandbars removed and the river straightened at various points. Non-permeable groynes, small levees, and high dikes.</td>
</tr>
</tbody>
</table>

Part of the Waal
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1872</td>
<td>Construction of the Nieuwe Waterweg, a new outlet to the sea.</td>
</tr>
<tr>
<td>1885-1904</td>
<td>Separation of the Waal and the Meuse at Heerewaarden, Meuse connected with the Amer.</td>
</tr>
<tr>
<td>1908</td>
<td>Deepening of the Nieuwe Waterweg.</td>
</tr>
<tr>
<td>1927</td>
<td>Construction of the Meuse-Waal canal.</td>
</tr>
<tr>
<td>1969</td>
<td>Construction of the Haringvliet dam, regulation of the river outlets by gates.</td>
</tr>
<tr>
<td>1970</td>
<td>Construction of the Volkerak dam, reducing the downstream storage area and cutting off the tidal influence.</td>
</tr>
<tr>
<td>1985-1988</td>
<td>Construction of a fixed (or armoured) bottom layer in the bend of the Waal near Nijmegen for navigation purposes.</td>
</tr>
<tr>
<td>1996-1998</td>
<td>Construction of a fixed bottom layer in the bend near St. Andries.</td>
</tr>
<tr>
<td>1996-1999</td>
<td>Construction of bendway weirs (to direct the sediment to a preferred site) in the bend near Erlecom.</td>
</tr>
<tr>
<td>2006</td>
<td>Increase of the minimum guaranteed depth from ALW-2.5 m to ALW-2.8 m for navigation.</td>
</tr>
<tr>
<td>2012-2016</td>
<td>NURG: The Heesseltsche floodplains: Lowering of floodplains, building additional channels (<a href="http://www.rijkswaterstaat.nl">www.rijkswaterstaat.nl</a>).</td>
</tr>
</tbody>
</table>

### 2.2.3 Recent changes in river management strategies

After the notorious flood events of 1993 and 1995 along the Rhine, large-scale river works were initiated to raise flood protection standards in the river, like the Room for the River programme. Besides the RfR programme, other large scale projects in the Dutch rivers have started in the last
Impact of recent changes in river management on maintenance dredging in the Waal River

decades to restore nature in the floodplains, and to secure the quality of water bodies. These large-scale works will be discussed in this section.

**Room for the River & NURG programmes**
Flood protection relies on anticipating predictable events, like flooding, and the creation of more space for the rivers. The Room for the River (RfR) and the Further Elaboration of the River Area (NURG) constitute two of these river work programmes. Typical measures are floodplain lowering, groyne lowering, construction of longitudinal dams, side channels, free banks, and reconnection of lakes. In RfR, the discharge capacity of the river is raised, thereby eliminating the need for raising dike heights. Instead of raising dikes, more than 30 site-specific spatial measures were selected to lower flood levels (Van Vuren, 2005 and Silva et al., 2001). Figure 2.2 provides an overview of the interventions in the lower-Rhine, the Waal, and the IJssel for RfR.

![Figure 2.2: River intervention works in the Rhine (by Jayesh Kisoensingh (left)) and an illustration of the intervention works (right), adapted from roomfortheriver.nl](image)

The objective of the NURG programme is to realize seven thousand hectares of new nature in the floodplains of the Rhine branches and the Meuse by 2015. This new nature is part of the realisation of the National Ecological Network for the river. In addition to the creation of new nature, the programme contributes to flood safety and the possible distribution of functions of the large river in terms of shipping and tourism (Van Adrichem, 2013). Some of the NURG measures are lowering of the floodplains, building additional channels, and building water storages.

**Water Framework Directive**
The Water Framework Directive (WFD) was signed by European Union members in the year 2000 to ensure the protection of inland surface waters, transitional waters, coastal waters, and groundwater in such a way that the quality of the surface water and groundwater in Europe would reach the required standard (with respect to ecology and chemical water quality) by the year 2015. The WFD was initiated for a better future of water bodies, and it is implemented through the restoration and (re)design of water systems. Popular measures in this project are river widening, dike relocation, and reconnecting side channels (The European communities, 2000 and Havinga, 2011).
**Expected impacts**

The RfR, WFD and NURG intervention works may influence the flow and sediment transport fields. Depending on the flow stage, a larger part of the discharge will be redirected from the main channel towards the flood plains. Downstream from the river intervention, this discharge will be diverted back into the main channel. This results in larger local gradients in the flow velocity, and subsequently in larger local gradients in sediment transport. Due to these gradients, erosion and accretion waves are initiated and propagate downstream through the river system. These accretion waves may cause a negative influence on the navigability, if they result in a lower navigation depth (Van Vuren, 2005).

**2.2.4 Agreed Low Water**

For the purpose of navigation, the minimum guaranteed depth on the Waal has been raised from 2.50 m to 2.80 m (with a channel width of 150 m) during Agreed Low Water (ALW) in 2006. The ALW reference plane is determined using the ALD (1020 m³/s at Lobith). The ALW plane is used as a reference level for the dredging depth; therefore, changes have a direct influence on the calculated dredging volumes (Van Vuren & Havinga, 2012 and Van Adrichem, 2013).

**2.2.5 The Waal river**

In this research the focus is mainly on the busiest Rhine branch in the scope of Inland Waterways Transport: the Waal. Besides the important role of inland navigation, flood protection is also important. This relates to the morpho- and hydrodynamics of the river. Based on morphological characteristics, the Waal can be subdivided in three parts (Figure 2.2): the Upper-Waal River, the Middle-Waal, and the Lower-Waal River.

![Subdivision of the Waal river (Rijkswaterstaat) with locations of the floodplains](image-url)

List of abbreviations indicating floodplain areas:

<table>
<thead>
<tr>
<th>AD</th>
<th>Afferdensche and Deetsche Waarden</th>
</tr>
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<tbody>
<tr>
<td>BP</td>
<td>Bemmelse Polder</td>
</tr>
<tr>
<td>DO</td>
<td>Dodewaard</td>
</tr>
<tr>
<td>DR</td>
<td>Dreumelse Waard</td>
</tr>
<tr>
<td>DW</td>
<td>Drutense warden</td>
</tr>
<tr>
<td>GE</td>
<td>Gendtse Waarden</td>
</tr>
<tr>
<td>GW</td>
<td>Gamerensche waarden</td>
</tr>
<tr>
<td>HE</td>
<td>Heeselsche uiterwaarden</td>
</tr>
<tr>
<td>HW</td>
<td>Heerewaarden</td>
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<tr>
<td>KL</td>
<td>Klopwenvak</td>
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<tr>
<td>LE</td>
<td>Lent</td>
</tr>
<tr>
<td>LW</td>
<td>Millingerwaard</td>
</tr>
<tr>
<td>MU</td>
<td>Munnekenland</td>
</tr>
<tr>
<td>OP</td>
<td>Ooijpolder</td>
</tr>
<tr>
<td>OW</td>
<td>Ochtensche waarden</td>
</tr>
<tr>
<td>WE</td>
<td>Weur (floodplain)</td>
</tr>
<tr>
<td>WP</td>
<td>Wetlands Pasewaaij</td>
</tr>
<tr>
<td>WW</td>
<td>Winssen warden</td>
</tr>
<tr>
<td>ZA</td>
<td>Zalhommel</td>
</tr>
</tbody>
</table>

Figure 2.3: Subdivision of the Waal river (Rijkswaterstaat) with locations of the floodplains

The Upper-Waal starts at the Pannerdensche Kop and ends downstream from the bend at Nijmegen. This reach contains several relatively sharp bends where stationary morphological phenomena like natural bends, bends with fixed layers or bendway weirs, and crossings between bends play a role. These stationary enforced two-dimensional riverbed shapes are determined by the geometry of the main channel. The relatively straight Middle-Waal starts at Nijmegen and ends at Tiel. In the Middle-Waal non-stationary morphological phenomena are an important factor. Non-stationary phenomena, such as dunes, are freely moving along the river bed. The Lower-Waal starts at Tiel and ends at Woudrichem. This stretch contains one large sharp bend at
Sint Andries and some smaller gently curved bends. In the Lower-Waal both stationary and non-stationary morphological phenomena play an important role (Klaassen & Sloff, 2000). Floodplain areas on the Waal also influence the morphological phenomena during high discharges.

2.2.6 Navigation in the Waal

As stated before, improving conditions for inland navigation has not been a main design criterion in the RfR and WFD programmes. The increase of the minimum guaranteed depth and the river intervention works may have a strong and negative impact on flow and sediment transport fields, and induce larger dynamics of the riverbed. This may negatively influence the river's navigability and cause nautical bottlenecks.

Navigation bottlenecks can be grouped into two types:

1) **Permanent bottlenecks**: these can be found in sharp bends and tend to sustain after high flows recede. The position of these bottlenecks is usually unchanging, because of the large amount of dredging activities in an attempt to maintain a sufficient width and depth (stationary morphological phenomena).

2) **Bottlenecks that occur during floods, as well as, during low and medium flows on a more unstable occurrence. These happen due to retarded scour and large bed forms (non-stationary morphological phenomena).**

The two bottlenecks require different maintenance dredging strategies. The permanent bottlenecks slowly grow in size and only need to be dredged away once or twice a year after a peak discharge. The second type of bottlenecks can change relatively fast in size and location. The non-stationary morphological phenomena can return shortly after dredging. This situation requires a flexible maintenance dredging strategy and should be monitored on a (nearly) day-to-day basis (Van Adrichem, 2013).

These bottlenecks both influence navigation negatively. Currently, additional dredging is required in all remaining and developing nautical bottlenecks. In 2006, the minimum guaranteed depth on the Waal has been raised from 2.5 m to 2.8 m without executing additional structural measures. The maintenance dredging costs, to keep the main channel open, have risen dramatically. Though dredging can reduce the negative impact of shoals (bottlenecks), hindrance to navigation will continue to occur, as it is impossible to remove all shoals after a flood, in time. By its nature, dredging operations cause hindrance for navigation (Van Vuren & Havinga, 2012).
Chapter 3 Research methodology

3.1 Introduction
Keeping in mind that rivers serve many diverse functions (e.g. flood protection, safe and efficient navigation, and ecological value), understanding river morphology is necessary for successful changes in river management, namely intervention works and changes in the minimum depth requirement. Currently, widely implemented tools to calculate the effects of changes in the river system are numerical models. However, the underlying processes of river systems are not fully presumed because they are stochastic and dynamic by their very nature. A wide selection of tools has been adopted as means to fully assess river impacts (Van Vuren, 2005). In this chapter, the tools, namely the morphodynamic model and the stochastic approach, will be discussed. Furthermore, the applicability of these tools to assess the changes in the Waal and the effects on navigability of the Waal will be explained.

3.2 Morphodynamic model
For this research, an existing 2D depth integrated morphological model of the Dutch Rhine branch, the Waal, will be applied. This model has been developed by Mosselman E., Sloff K., Van Vuren S. and Yossef M. (Mosselman et al., 2007; Sloff et al., 2009 (a) (b); Van Vuren et al., 2006). The model is built on the Delft3D modeling software (Deltares, 2014). Two versions of the Delft3D modeling software are used in this study, namely version 3.28.06 and version 4.01.00.

The Delft3D modeling software incorporates a numerical hydrodynamic module called Delft3D-FLOW. This module solves the unsteady shallow water equations in two dimensions (depth averaged). The hydrodynamics are associated with a sediment transport and bed morphology module (Deltares, 2014). For the basis of the model schematisation, the DVR model (Duurzame Vaardiepte Rijndelta programma - 2D morphological model) is used (Sloff et al., 2009 a, b). This model is created as a forecasting mechanism to estimate suggested structural and sediment management measures in the Rhine Delta. Furthermore, the model schematisation contains a representation of the dredging strategy in The Netherlands that is used for the Waal (Van Vuren and Havinga, 2012).

Characteristics of the Delft3D model
The reference situation used in the current 2D depth integrated model is the state of the river before implementation of the RfR programme. The future situation is a schematisation of the river after implementation of the RfR programme. In addition to the RfR projects, all other relevant updates for that year including the WFD-plans are covered by this schematisation. Furthermore, the model schematisation spans the Waal from the bifurcation at the Pannerdensche Kop until Gorinchem, rkm 867 - 953. The resolution of the grid in the main channel is approximately 26 x 80 m (width x length). The main channel in the cross direction is represented by twelve cells. There are fixed layers in the river bends near Emmerich, Nijmegen, and Sint Andries, which cover the outer bends. For the floodplains the sediment layer is nullified. This is done so that the floodplain in the model is not capable of eroding.

The 2D depth integrated model includes also the hydraulic roughness. This allows for variation in roughness for changing flow conditions. To realize this, the hydraulic roughness in the alluvial bed of the main channel is calculated as a function of the local water depth. The hydraulic roughness of the floodplains is characterised by the vegetation type and their spatial distribution. In addition, it is assumed that the bed material is uniform (Van Vuren and Havinga, 2012).
In Delft3D, a dredge and dump module is integrated. A representation of the dredging strategy used for the Waal is contained in the model schematisation. Rijkswaterstaat designates two requirements in the navigability assessment framework for large river projects: one for guaranteed minimum depth and the second for an average depth in the navigation channel. The draught is guaranteed by the minimum depth requirement. This subsequently affects the capacity of the vessels. Vessels experience an abundance of drag in narrow cross sections, which are inducing efficiency losses during sailing. This is greatly reduced by the width-averaged depth requirement. Fortunately, vessel capacity is not affected by this specification. In the dredge and dump module of the Delft3D model, only the requirement for guaranteed minimum depth is included (Yossef et al., 2010). In this module, the ALW plane is used as a reference level for the dredging depth. The ALW is an important parameter in the dredging strategy that triggers the dredging activities. Dredging in the Delft3D model is calculated based upon the water depth below ALW. Changes in the ALW plane therefore have a direct influence on the calculated dredging volumes. In Figure 3.1 the requirements in the navigability assessment framework are defined. To guarantee a minimum depth of 2.8 m during ALW the hatched triangles (parts of the riverbed) should be dredged. To fulfill the second dredging requirement the width-averaged depth in the navigation channel should be at least 4.0 meters below ALW during low discharges.

![Figure 3.1: Requirements in the navigability assessment framework: The requirement of the minimum depth and the width-averaged depth in the navigation channel (not to scale)](image)

In section 2.2.5 the maintenance dredging strategies were presented. Permanent bottlenecks slowly grow in size and need to be dredged only once or twice a year after peak discharges. During high discharges, sedimentation often occurs in the vicinity of sharp bends. Because of the sedimentation the requirement for the minimum depth cannot be fulfilled during low water levels (during low discharges). The dredging is executed mostly at low water levels. The common reason for this is to make shipping possible at low discharges.

Currently, most of the morphodynamic predictions in the on-going projects are based on a deterministic approach. In this approach a yearly representative hydrograph, reflected on discharge measurements between 1999 and 2006, is used. This hydrograph is applied at the upstream boundary of the river Waal (Yossef et al., 2010). The discharge hydrograph, which is repeated each year, is presented in Figure 3.2 for the first two years (Mosselman et al., 2007). Each year is divided into 14 periods. The periods consist of various discharges, which occur for different time periods.
Impact of recent changes in river management on maintenance dredging in the Waal River

Figure 3.2: Representative discharge hydrograph of the first two years used in deterministic runs, showing the Waal River discharge

### 3.3 Stochastic model approach

As previously stated, river systems are dynamic and stochastic by nature. Nevertheless, the underlying morphological processes are not fully acknowledged. In most on-going projects, deterministic models are utilized to assess river systems. A deterministic approach can be defined as a resemblance of the real situation with exact data. In this respect, the representative discharge hydrograph (Figure 3.2) is used. The deterministic approach appears to be an effective tool to provide a quick expression of the physical morphodynamic processes. However, to fully acknowledge these morphodynamic processes and to derive an accurate illustration using a deterministic model is very complex. It is also difficult to precisely evaluate the model inputs and parameters. Ignoring the complexity of the morphodynamic processes may lead to insufficient knowledge of the river system behaviour and the uncertainties involved. These deficiencies in river management practices make the assessment of the involved uncertainty necessary. This involves a stochastic approach that demonstrates a variety of possible morphodynamic states, their probability of occurrence, and the estimation of undesired morphological effects (Van Vuren, 2005). In this thesis, a stochastic approach is used as a synonym for an uncertainty analysis and a probabilistic approach.

When handling uncertainties of large complex system behaviour, a variety of stochastic methods can be applied, for instance: Monte Carlo Simulation (MCS), First-Order Reliability Method (FORM), Numerical Integration, and Stochastic Differential Equations. The applicability of these methods to river morphology is dependent on the exactness of how the methods cope with the strong non-linearity and complexity of river morphodynamics (Van Vuren, 2005). Van der Klis (2003) demonstrated that Monte Carlo Simulation (MCS) with rough sampling is an acceptable, potent, and suitable method to validate uncertainties involved in morphodynamic predictions. Therefore, the Monte Carlo Simulation (MCS) will be used in this research.

In a stochastic calculation, like the MCS, a deterministic model is run continuously. Each time, a different set of model inputs, which are statistically equivalent, are used. Out of the various sources of uncertainty involved in the morphodynamic Rhine model, the uncertainty in the discharge hydrograph imposed at the upstream boundary is only considered. For each model run, a new discharge time series is synthesized. In this research, 75 discharge time series are taken from Van Vuren (2005). According to Van Vuren (2005) several techniques can be used to construct these discharge time series from which the Bootstrap resampling is an appropriate
technique for the Waal discharges. This resampling technique can be used to establish a new time series by resampling from the historical data set.

The fact that while employing the resampling technique the underlying probability distribution of the discharge is not subject to any assumptions, has been considered a beneficial characteristic of resampling. In the Bootstrap technique a situation is used in which data points are not influenced by any correlation structure. Nevertheless, it should be taken into account that the discharge time series of the Waal appears to be strongly dependent on seasonal influences (low discharges in summer and high discharges in winter). In addition, the interaction of discharges occurring in close succession is noteworthy. Therefore, it is advisable to select discharges from short discharge time series (one-year duration), randomly selected form the historical record (including 100 year data), rather than randomly sampling discharges from the entire record. The one-year discharge time series are randomly arranged into new time series of N year duration. In this way, Bootstrapping maintains the periodic dependency of the discharge time series; the interaction of discharges in periods that closely follow each other; and the statistical characteristics of mean, maximum and minimum discharges. The arithmetic mean value of a large number of hydrograph almost converges to the expected value. Therefore, the 75 discharge time series that are generated for a period of 20 years are used. Each year is divided into 36 periods of 10/11 days and the measured daily discharges are averaged over the 10/11-day periods (Van Vuren, 2005). Three randomly chosen discharge time series for the first three years and the statistics of all the 75 discharge time series are presented in Figure 3.3 and Figure 3.4.

Figure 3.3: Discharge time series (hydrographs) for the first 3 years used for the stochastic approach (1 October-1 October)

Figure 3.4: Statistics of all the 75 the discharge time series (1 October - 1 October)
3.4 Methodology
The applicability of the aforementioned tools to assess morphological processes is explained using Figure 3.5.

**Morphodynamic Model**
Three schematisations are considered for this research:
- 2.5 m-depth criterion;
- 2.8 m-depth criterion;
- 2.8 m-depth criterion plus RfR.
These schematisations/situations are simulated using the Delft3D-Flow program (version 3.28.06 and 4.01.00).

- **Deterministic approach**
  A deterministic run using the representative discharge hydrograph in Figure 3.1 is performed.

- **Stochastic Approach**
  For each situation, 75 model runs with different discharge time series are performed.
  Application of MCS to morphodynamic models.

**Deterministic results:**
Bed level changes, navigation and dredging

**Stochastic results:**
Statistic characteristics of bed level changes, navigation and dredging

**Potential of stochastic approach explored**

Figure 3.5: Visualisation of the research methodology

An existing morphodynamic model of the Waal is used to assess the morphological processes per situation. In total there are three situations with 75 different time series each. Thus, there are 75 model iterations (runs) per situation in a 20 year period. With the usage of Delft3D these simulations will be executed. The results from the deterministic approach as well as the results from the stochastic approach will be plotted. For the probabilistic analysis the application of Monte Carlo simulation will follow. Reflecting on the results of all model simulations, the determinism and the stochasticity of the bed level, navigation and dredging will be determined. The morphological response statistics will be evaluated in terms of expected value (this also applies to the deterministic approach), variance, percentile values, and confidence intervals. Finally, a comparison between the deterministic results and the stochastic result will follow to interpret the added value of the stochastic approach to river management practice.
Chapter 4 Results of recent river management changes

4.1 Introduction
As denoted before, the Waal has been trained heavily in the past. In 2006, the minimum guaranteed depth on the Waal has been raised from 2.50 m to 2.80 m (with a channel width of 150 m) during Agreed Low Water (ALW) conditions. Subsequently, the large-scale projects were initiated, for example, the Room for the River programme. These changes and measures may have several impacts on the morphodynamics of the Waal River. Three different situations will be distinguished in this research, namely: the situation with the 2.5 m-depth criterion (referred to as: ‘Ref – 2.5 m’), the situation with the 2.8 m-depth criterion (referred to as: ‘Ref – 2.8 m’) and the situation after the implementation of the Room for the River programme (referred to as: ‘RfR’). The numerical calculations with the 2D depth averaged model of the ‘Ref – 2.8 m’ situation and ‘RfR’ situation are previously executed using version 3.28.06 of the Delft3D modeling system. The numerical calculation of the ‘Ref – 2.5 m’ situation is executed during this research with the current version of Delft3D (version 4.01.00). All three schematisations consist of 75 runs each with a randomly generated time series. Furthermore, the three situations each consists of a separate run that is executed with the representative discharge hydrograph (Figure 3.1). For all the situations the bed level changes, impact on dredging effort, and the navigability will be analysed. The analyses will be performed using both the results of the deterministic and the stochastic approach. The probabilistic calculation using the Monte Carlo Simulation will also be used to quantify uncertainties in morphodynamics, dredging effort and navigability.

4.2 Bed level Changes in the Waal
To analyse the morphodynamics of the Waal, the bed level changes for all three situations after a period of 20 years are calculated using the results of the numerical model calculations. Local gradients in sediment transport are the reason for bed level changes (Annex E). In this research the changes in bed level are calculated as the average of the width of the main channel. This is specified as the width-averaged depth.

The morphological changes of the Upper-Waal, Middle-Waal, and Lower-Waal are separately presented in Annex B. The graphs include the confidence band, the average bed level change after a period of 20 years (T=20 years) with respect to the initial period (T=0 year), and the deterministically calculated bed level change. The reach of the confidence band is an indication for the variation of the response of the bed level changes. According to the graphs in Annex B, the mean response of the bed level changes over time results in a lowered bed level of the main channel.

In addition to the bed level changes after 20 years (Figure B-2, B-4, and B-6), graphs of the bed level changes after 1 year (Figure B-1, B-3, and B-5) are also presented in Annex B. The statistics have been compared with the single model run of the deterministic computation. The results of the deterministic calculation lie roughly within the confidence interval found in the MCS (after 1 year and after 20 years), but after 20 years this is not the case in the Upper-Waal. In the first section of the river trajectory (rkm 867 and rkm 879 (Figure B-2a, B-4a, B-6a)), the deterministically calculated bed level changes fall significantly far from the average bed level changes. As time evolves, the bed level response in the deterministic calculation, as well as in the probabilistic calculation, decreases. However, the bed level lowering in the probabilistic calculation in the trajectory rkm 867-879 (Figure B-2a, B-4a, B-6a)) is relatively larger. It is not unusual that the deterministic realisation lies beyond the 95-percentile value, but the difference
is extreme. As previously stated, the deterministic calculation is performed with one representative discharge series and the probability is calculated using the stochastic approach with 75 different randomly generated discharge series. The mean of the discharge in time of both approaches is equal to each other, but the deterministic approach contains higher discharges. The mean discharge in the representative hydrograph of the Waal is 1,694 m³/s and this matches the mean discharge of the period 1999-2006. This mean discharge of the representative hydrograph is higher than the mean discharge of the 75 discharge time series used in the stochastic approach (input generation of the MCS). It is expected that the deterministic calculation will predict larger morphodynamics. However, it is assumed that instead of the average discharge, the higher discharges (relative to the mean) are dominant in generating a larger mobility of the river bed. However, in the different discharge series generated for the stochastic approach there are much longer periods of medium flow conditions (green dotted line in Figure 3.3 ) than with high flow conditions (Van Adrichem, 2013). This will minimize the deposition during high discharges, which is notable in the graphs in Annex B.

**Bed level differences**
The impacts of the different situations can also be exposed by relating the situations to each other. To obtain this, the bed level changes of each situation will be subtracted. This is done for the deterministic approach as well as for the stochastic approach. For the stochastic approach the graphs with the bed level differences (Figure 4.1) illustrate a confidence band of the bed level change starting from the 5th-percentile value until the 95th-percentile value. The 90% confidence interval, which gives an indication of the variation in bed level change, means that with a probability of 90% the bed level changes are within this range. Furthermore, the mean bed level changes in the Waal are presented in these graphs.

![Figure 4.1](image_url)

a) Difference in width-averaged bed level changes between the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation after a period of 20 years (effect of the increase of the depth criterion)
b) Difference in width-averaged bed level changes between the ‘Ref – 2.8 m’ situation and the ‘RfR’ situation after a period of 20 years (effect of the RfR)

Figure 4.1: Differences in width-averaged bed level changes of the main channel after 20 years with respect to T=0 (initial bed level) for different situations in the Waal with locations of the floodplains using a deterministic approach as well as a the stochastic approach (List with abbreviations, indicating floodplain areas, can be found in Figure 2.3)

In Figure 4.1 the differences in bed level changes of the different situations are presented. A positive bed level change means sedimentation and a negative change means erosion. In Figure 4.1-a it is clear that the increase of the minimum guaranteed depth does not greatly influence the morphodynamics of the riverbed. This is logical because in this situation no structural measures are implemented and extra dredging is executed only in places where the current guaranteed minimum depth (2.8 m) is not met. Due to the characteristics and the non-uniformity in the main channel upstream of the Waal, the river bed experiences more sedimentation than erosion. This leads to an increase of the bed slope upstream.

The ‘RfR’ situation on the other hand displays large variability in bed level change relative to the ‘Ref – 2.8 m’ situation. On almost every part of the Waal, the river is morphodynamically active (sedimentation and erosion). This variability can be derived from the changes made by the schematisation of the Room for the River programme in the Waal. The Room for the River programme consists of measures like floodplain lowering, removal of obstacles, groyne lowering and dike relocation. For example, the lowering of groynes causes alternately sedimentation and erosion. This variation is caused by local differences in the adjustment of the height of the groynes. At times groynes are lowered more frequently than others. Near the lowered groynes sedimentation occurs locally and erosion occurs where groynes have not been lowered. The flow velocity in the navigation channel will be reduced at high discharges due to groyne lowering compared to the situation before groyne lowering. With this reduction in flow velocity, sedimentation will take place. Furthermore, low discharges lead to lower water levels and can have a negative effect on navigation.

Figure 4.1-b shows that the width-averaged bed level will increase up to 0.3 m in many locations and in some locations there might be reduction. This increase is averaged over the cross-section of the main channel (at some part of the cross-section the bed level might experience a decrease). This gives another view of the expected dredging effort. The only factor that triggers the dredging capacity in the Delft3D model is the minimum guaranteed depth. Thus, dredging is triggered by ALW-2.8 m for the ‘Ref – 2.8 m’ situation and the ‘RfR’ situation, and by ALW-2.5 m for ‘Ref – 2.5 m’ situation.
For a good comparison the deterministic and probabilistic calculations are plotted in Figure 4.1. The representative discharge time series that is used in the deterministic calculation is not a part of the 75 discharge time series used in the stochastic approach. It becomes clear that the deterministic approach does not coincide with the mean bed level changes of the stochastic approach. In Figure 4.1-b the deterministic value crosses the mean values at several locations, but lies roughly in the confidence interval. It can be concluded that the deterministic approach does not underestimates the mean morphological response of the stochastic approach.

4.3 Uncertainty bands in the Waal for all three situations
The uncertainty bands of the bed level response after 20 years with respect to T=0 (initial bed level) for the three situations are presented in Figure 4.2. The size of the 90%-confidence band is an indication for the variation of the response. A large confidence band indicates a great variation in possible morphological response, while a small confidence band indicates little variation in this response.
The uncertainty band of the ‘Ref – 2.5 m’ simulation is similar to the ‘Ref – 2.8 m’ simulation (this is logical, because the differences in bed level changes are small), while the uncertainty band of the ‘RfR’ simulation shows a great amount of variability compared to the other two situations. On average the uncertainty band of the the ‘RfR’ simulation shows a great amount of variability compared to the other two simulations. According to the graphs, the ‘RfR’ simulation results in higher peaks in the uncertainty band. As expected these peaks are the result of measures of the RfR programme (which have strong geometrical non-uniformities), especially the lowering of floodplains and side channels. At these locations an increase in the size of the confidence interval is noticed. After the lowering of these floodplains in the ‘RfR’ situation, more water will flow through the floodplains. An increase in floodplain depth results in sedimentation and a decrease leads to erosion (Annex C). At the transition points this results in an increase in bed level variability and hence to a larger size of the confidence band.

Following the analyses of Figure 4.2, it is interesting to know whether the 90%-confidence band is constant during the year or is it different in the high-water (HW) season and the dry (LW) season. One would expect that this phenomenon is stronger after the high-water season than after the dry season. This is also demonstrates in this research. The confidence interval in the dry season (after the high-water season) is larger than in the high-water season (after the dry season). This is clearly illustrated in Figure 4.3 and in Table 2. In Figure 4.3 and in Table 2, the cumulative probability distribution functions for two different locations are presented: one near a place where the geometry strongly varies (rkm 903.7) and one location where the geometry is relatively more uniform (rkm 895.3). For plotting the cumulative probability distribution of the width-averaged bed level changes in the dry and high-water seasons, the period of the dry and high-water seasons is carefully chosen after every season for each of the 75 discharge hydrographs (in the twentieth year). The low and the high discharges vary in the hydrographs that are generated by resampling (see section 3.3). Sometimes the hydrographs end with relatively high discharges or with low discharges. This has a large effect on the morphological response. As expected, more sedimentation occurs after high discharges than after low discharges (directly after high discharges, in the dry season, more sediment settles). This is shown in the probability distribution plots in Figure 4.3. The figure also demonstrates that the uncertainty in bed level change increases after the implementation of the Room for the River project.
a) Location rkm 895.3 (where the channel is more or less prismatic)

b) Location rkm 903.7 (where the geometry strongly varies)

Figure 4.3: Cumulative probability distribution of the width-averaged bed level changes of the main channel at two river locations after 20 years in the dry and high-water season

Table 2: Size of the 90%-confidence interval in the dry and the high-water season

<table>
<thead>
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<th>rkm 903.7 (m)</th>
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<tr>
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<tr>
<td>High – water Season (Ref 2.50 m)</td>
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</tr>
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</tr>
<tr>
<td>Dry Season (RfR)</td>
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</tr>
<tr>
<td>High – water Season (RfR)</td>
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<td>0.42</td>
</tr>
</tbody>
</table>

4.4 Dredging effort

River managers must take care that the riverbed remains at sufficient depth in order to guarantee a navigable river for the Inland Waterways Transport (IWT). Dredging is generally executed during low discharges rather than during high discharges. The common reason is to make shipping possible at low discharges. In 2006, the depth-criterion for the minimum guaranteed depth for the Waal has been increased from 2.5 m to 2.8 m (which are expressed as ALW-2.50 m and ALW-2.80 m). In the Delft3D model these changes are included. Besides the bed level changes, the numerical models also predict the dredging effort. The dredging volume will be calculated using the deterministic approach as well as the stochastic approach. The dredging blocks in the models are 1 km long and have the enacted width of the navigation channel (navigable section), which is 150 m. The dredging calculation is based on the available depth
Impact of recent changes in river management on maintenance dredging in the Waal River

under the ALW plane. Changes in the initial river bed therefore have a direct effect on the expected dredging volumes. With the application of the Monte Carlo Simulation, the statistics of the expected dredging effort per location and the total maintenance dredging volume will be presented in this section.

**Results of the dredging effort per location**

Figure 4.4 shows the results of the dredging effort per river kilometer over the entire Waal for three different situations (*‘Ref – 2.5 m’*, *‘Ref – 2.8 m’* and *‘RfR’* respectively) using the deterministic and stochastic approach. The bars per river kilometer represent the statistics of the yearly dredging effort over a total of 75 model runs. The 5<sup>th</sup> and 95<sup>th</sup> percentile value therefore give a useful view of the uncertainty in dredging per location. For a comparison between the deterministic approach and the stochastic approach, the deterministically calculated dredging volumes per river kilometer are presented as black dots in the figure. For the calculations the average volume per simulation is used over the length of 20 years. All mentioned dredging volumes in this report are volumes as they are in the hopper. Sediment has a higher density in the riverbed and the difference between hopper volume and riverbed volume is in the order 1.4-1.8. All dredge volumes calculated with Delft3D are multiplied with a factor 1.4 to get to hopper volumes (Van Adrichem, 2013). It is important to note that the influence of the planned side channel (*RfR* measure) near Lent is not included for the calculation of the dredging effort.

![Graph showing results of the dredging effort per location](image)

**Figure 4.4**

a) Deterministic and statistical characteristics of the dredging volume per location in different situations averaged over 20 years – rkm 868-888 (from left to right: *‘Ref – 2.5 m’*, *‘Ref – 2.8 m’* and *‘RfR’*)

![Graph showing results of the dredging effort per location](image)

b) Deterministic and statistical characteristics of the dredging volume per location in different situations averaged over 20 years – rkm 889-909 (from left to right: *‘Ref – 2.5 m’*, *‘Ref – 2.8 m’* and *‘RfR’*)
Impact of recent changes in river management on maintenance dredging in the Waal River

**c) Deterministic and statistical characteristics of the dredging volume per location in different situations averaged over 20 years – rkm 910-930 (from left to right: ‘Ref – 2.5 m’, ‘Ref – 2.8 m’ and ‘RfR’)**

**d) Deterministic and statistical characteristics of the dredging volume per location in different situations averaged over 20 years – rkm 931-952 (from left to right: ‘Ref – 2.5 m’, ‘Ref – 2.8 m’ and ‘RfR’)**

Figure 4.4: Statistical characteristics of the dredging volume per location in different situations

The figures show that the changes in the minimum guaranteed depth and river measures have significant effects on the locations of sedimentation and erosion. The mean response of the dredging volume per location is an increase in dredging effort. The mean dredging effort in all runs in the MCS has the same development in time as the dredging volumes in the deterministic calculation. Clearly, the mean dredging volume on most locations is not underestimated by the deterministic calculation overestimates.

The dredging effort in the ‘Ref – 2.8 m’ situation compared to the ‘Ref – 2.5 m’ situation is predicted to increase significantly and this has been the case in the previous years (2005 until 2008, Annex D) (Bardoel, 2010). The ‘RfR’ situation predicts an increase in dredging effort on most locations, but also a decrease on a few locations. The increase can be the effect of lowering of the flow velocity following with a decrease of sediment transport. In reversed situations a decrease of the dredging volume is predicted. This variability in the dredging effort can be derived from the changes made by the schematisation of the Room for the River Project in the Waal. Most dredging takes place upstream of rkm 921 (the Middle- and Upper-Waal) of the Waal. The sedimentation in this region can be the effect of the characteristics of the Waal or measures of the RfR that cause geometrical non-uniformities in the main channel.
In the upper part of the Waal (Upper-Waal) the river consist of several relatively sharp bends. The effect in the bend (see Annex A) is causing sedimentation in the inner bend of the relatively large bends in the Upper-Waal. In the present situation the Millingerwaard (rkm 870), Erlecom (rkm 876), Groenlanden (rkm 880) and Nijmegen (rkm 885) are common dredging locations (Bardoel, 2010). The bends near Erlecom and Nijmegen show the highest predicted dredging quantities in the simulation. Though these bends are protected with bendway weirs and fixed layers (in the outer bend) respectively, erosion and sedimentation occurs downstream of these structures. Although the sections with fixed layers show a considerable reduction in maintenance work, there is a net increase in dredging effort on this river section. Groenlanden and the Millingerwaard are river bends without a fixed bed or bendway weirs. At the bend near Groenlanden relatively less dredging activity is predicted, because the bends have a gentler curve than the other bends on the Upper-Waal (Liefveld et al, 2011).

Besides the bend effect, dike repositioning (Nijmegen), lowering of groynes (Groenlanden), floodplain lowering or removal of obstacles (Erlecom) may contribute to the sedimentation problem.

The nature of dredging downstream of the Waal (the Middle-Waal (rkm 887- rkm915) and Lower-Waal (rkm 915- rkm 953)) is very different from dredging upstream. Downstream, the mean dredging value is much smaller with respect to the 90%-uncertainty interval. In the Upper-Waal this is reversed: the mean here is higher relative to the uncertainty. Locations with a high mean in dredging effort and a small uncertainty band indicate a permanent nautical bottleneck. Hence, dredging should be performed more often at these locations.

4.5 Total maintenance dredging volume

The expected dredging volume in the Waal over a period of 20 years is very useful (for Rijkswaterstaat) in determining the long-term dredging budget. In Figure 4.5 the total amount of yearly maintenance dredging for all the situations in the Waal is presented as a cumulative probability distribution and as a bar plot where the statistical characteristics are shown. In addition, the deterministic values are added in the figures.

From the results of all runs in the MCS it can be concluded that the changes in the minimum guaranteed depth and the measures of the Room for the River project show an increase in the distribution of the yearly dredging effort (averaged over a period of 20 years). For every new situation in the cumulative distribution the mode is shifted to the right (Figure 4.5-a). This indicates that the maintenance dredging volume for a certain probability of occurrence is likely to increase. In the ‘Ref – 2.5 m’ situation the total maintenance dredging is very low compared to the ‘Ref – 2.8 m’ situation and the ‘RfR’ situation. The total maintenance dredging increases drastically. The increase of the minimum depth criterion to 2.8 m leads to a drastic increase of the dredging effort.
The principal purpose of dredging is to maintain the navigability. Bardoel (2010) investigated the dredging records of Rijkswaterstaat in his master thesis report regarding the maintenance of the main channel of the Waal. In Table 7 (Annex D) the dredged quantities from 2005 until 2009 are presented according to the ‘BOS-baggeren’ and the weekly dredging reports. The average amount of dredged sediment from 2006 until 2009 is around 396,000 m³. The mean dredging volume and the deterministic result for the ‘Ref – 2.8 m’ situation obtained in this research (averaged over 20 years) is around 294,000 m³ and 387,000 m³ respectively. These results are comparable to the dredging investigations that Bardoel made in his research, which means that the morphological model results in this research are quite reliable. It is important to note that this comparison is based on available data for 3 years only.

The expectation of the dredging effort in the width-averaged bed level changes is different from the maintenance dredging volume. The reason is that the maintenance dredging is determined over the navigable section and not over the entire width of the main channel. From the comparisons made in Table 3, the increase of the mean value of the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation is around 16%. The increase of the mean value of the ‘Ref – 2.8 m’ situation compared to the ‘Ref – 2.5 m’ situation is around 196%, which is 10 times higher than the ‘RfR’ situation. This large difference in dredging volume can also be seen in Table 10 (Annex D). The ‘RfR’ situation, compared to the ‘Ref – 2.8 m’ situation, brings a relatively smaller change to the yearly dredging effort, with or without the influence of the side channel, in comparison with the changes in the minimum guaranteed depth.
Table 4: Difference between deterministic results and mean value in percentage

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Deterministic result (m³)</th>
<th>Mean value (m³)</th>
<th>Difference Deterministic compared to mean value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ref – 2.5 m’</td>
<td>140,000</td>
<td>99,000</td>
<td>40</td>
</tr>
<tr>
<td>‘Ref – 2.8 m’</td>
<td>387,000</td>
<td>294,000</td>
<td>32</td>
</tr>
<tr>
<td>‘RfR’</td>
<td>445,000</td>
<td>342,000</td>
<td>30</td>
</tr>
</tbody>
</table>

In Figure 4.5-b, it is clear that the deterministic results fall in the confidence interval of the total maintenance dredging volume. However, the deterministic values are higher than the mean dredging volume. According to Figure 4.5-a and Table 4, this is 30 to 40% higher than the arithmetic mean value, but still falls in the 90%-confidence interval. If the dredging effort is calculated using the deterministic approach, this leads to an overestimation in determining the long-term dredging budget (if the approach is correct).

### 4.6 Navigability of the Waal at various draughts

The navigability of the Waal for ships with a draught between 2.0 and 5.5 m is statistically assessed in Figure 4.6 (under the condition that dredging is already taken into account). This assessment is done on the basis of 75 model runs of each an interval of 20 years for three different situations. Each model execution results in one possible future hydraulic and morphological evolution. However, the dredging effort is already taken into account, the most critical water depths for each model execution are estimated along the entire length of the Waal. The statistical properties of the navigability at various draughts can subsequently be determined. In Figure 4.6, the statistical characteristics of the navigable percentage for all 75 model simulations are presented. For a good comparison between the stochastic and the deterministic results, the deterministic values are plotted as white dots.

![Figure 4.6: Deterministic and statistical characteristics of all model runs for the navigability in the Waal for three situations (from left to right: ‘Ref – 2.5 m’, ‘Ref – 2.8 m’ and ‘RfR’ situation)](image)

The figure illustrates the percentage of time the Waal is navigable at a certain draught in a 20-year period. For example, the average percentage of navigable time for the ‘RfR’ situation for ships with a draught of 3 m is 87%. This is one percent less than in the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation. The figure also shows that for a draught of 3 m in the ‘RfR’ situation there is 90% probability that the percentage of navigable time lies between 78% and 93%. The size of the 90% confidence interval can easily be computed as the difference between the 95th percentile and 5th percentile. For a draught of 3 m, the 90%-confidence interval is approximately 15%. The maximum difference in percentage of navigable time for a draught of 3 m over all model simulations, is 95%-71% = 24%. For a draught of 3.5 m the percentage of navigable time
decreases. Relative to other situations in this draught, the maximum difference in the ‘RfR’ situation increases. The mean percentage increases relative to the ‘Ref – 2.5 m’ situation an decreases relative to the ‘Ref – 2.8 m’ situation. Even though an increase in dredging effort is observable in the different schematisations in the probabilistic and deterministic calculation of the navigability, the impairments in navigability at a certain draught is limited. This is due to the regular maintenance dredging.

The navigability decreases significantly for draughts larger than 3.5 m, which is also obvious in the deterministic calculation as well as in the probabilistic calculation. Sharp bends in a river result in a large correction to the draught. This restricts the navigability for ships with larger draughts, which also has negative impacts on the safety of navigation and the economic value. It is obvious that ships with a smaller draught will probably have a larger navigability.

In Figure 4.6, it is clear that the deterministic results are much higher than the results gained by the probabilistic calculation. The difference between the deterministic and stochastic approach in this section and earlier sections arises in the schematisation of the used discharge time series, which is described in Section 3.3. The representative discharge hydrograph, which is used in the deterministic calculation, is not a part of the 75 discharge time series used in the stochastic approach. At some draughts the mean value of the stochastic approach are underestimated by the deterministic approach.

4.7 Detailed investigation Nijmegen

The aforementioned morphological processes are analysed for the entire Waal. Because of the different morphological characteristics of the Waal, it is not possible to explain all processes in detail for every section at once. For better understanding the impacts of the processes, namely the dredging effort and the navigability, one location of the Waal with a high dredging demand (navigation bottlenecks) will be treated in detail. The most interesting, where the dredging effort is high, are: Millingen (rm 869-871), Erlecom (rm 873-876), Nijmegen (rm 883-886) and Willemspolder and Drutense Waard (rm 906-913). Since the maintenance dredging at Nijmegen is relative high, the Nijmegen case will be treated in detail.

The Nijmegen case covers the reach from rm 883 to rm 886 (Figure 4.7). The river Waal bends sharply in this reach and it narrows itself in the form of a bottleneck due to the bend effects (Annex A). The floodplain locally is only 450 m wide whereas the average along the Waal is 1,000 m. The narrowing creates less room for the water flow, which can lead to flooding at high water levels. Therefore, river intervention works have been planned to increase flood conveyance capacity. In this section the aforementioned situations will be treated (the ‘Ref – 2.5 m’ situation, the ‘Ref – 2.8 m’ situation, and the ‘RfR’ situation). The ‘RfR’ situation involves moving the Waal dike at Lent (dike relocation) combined with constructing a side channel in the floodplains (Figure 4.7). The dike will be moved 350 m inland. Relocating a dyke inland widens the floodplain and increases the conveyance capacity of the river. The side channel will have two inlets that are connected with the main channel. This will create an elongated island of about 3 km (Figure 4.7-b). The sill to the side channel is made permeable. For discharges up to 4,000 m³/s there is a continuous flow with a maximum of 1.5% of the Waal discharge through the side channel. For higher discharge the sill is drowned (Van Adrichem, 2013).
According to Van Adrichem (2013) the effect of the discharge distribution over the side and the main channel at Lent was tried to be schematised in the Delft3D model schematisation after RfR by withdrawing extra discharge from the main channel into the side channel at the higher discharge stages. It appeared not to be possible to withdraw water from the main channel directly into the side channel due to the crude grid used in this model. There is no direct influence on the distribution of discharge over the main and the side channel.

4.7.1 Dredging demand
The riverbed in Nijmegen in the outer bend between rkm 883 and rkm 885 (see Figure 4.7) is protected with a fixed layer (bottom protection structure) that has a width of 150 m. This fixed layer designed for navigation purposes, prevents the riverbed from scouring (Annex A). In undisturbed conditions, without a fixed layer, the river bed in the outer bend will erode and deposition will take place in the inner bend. In case there is a fixed layer, the river bed in the outer bend cannot erode anymore. The question that arises is how the morphological process in the inner bend and downstream of the fixed layer will develop in the different situations. For a good explanation the dredging demand for the Nijmegen area will be discussed first. On the basis of the morphological calculations and navigability presented in the previous sections, predictions of the dredging effort are made that meet the requirements for shipping in the Nijmegen area. This section presents the dredging demand per kilometre and total maintenance dredging in Nijmegen for the reach rkm 882-887. In Figure 4.9, the presented dredging volume at a specific river kilometer indicates the dredging of the previous dredging block of 1 kilometre.
Impact of recent changes in river management on maintenance dredging in the Waal River

Figure 4.8: Deterministic and statistical characteristics of the dredging volume per location averaged over 20 years – rkm 882-887 (from left to right: ‘Ref – 2.5 m’, ‘Ref – 2.8 m’ and ‘RfR’)

The effect of the fixed layer on the inner bend between rkm 883 and 885 is noticeable in Figure 4.8. The fixed layer commences at rkm 883 and ends at rkm 885. The dredging volume in-between, compared to the upstream and downstream part of the layer, is relatively less. Due to the non-uniformities (transition from the fixed layer to the alluvial river bed and vice versa) the deposition upstream of the fixed layer is relatively high and erosion occurs downstream. At the beginning of the fixed layer (between rkm 883 and 884) there is less sediment available to settle, but this increases when the end of the fixed layer is nearby (see Annex A). Although the section in-between rkm 883 and 885 shows a considerable reduction in dredging effort, in total there is a net increase on this river section (see Figure 4.9). Thus, dredging is still necessary in this area.

Maintenance dredging at Nijmegen

Figure 4.9: Deterministic and statistical properties of dredging volumes of the Nijmegen case averaged over 20 years for different situations - reach rkm 882-887
Table 5: Total maintenance dredging volume of the Nijmegen case and the increase related to every situation

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Deterministic result</th>
<th>95\textsuperscript{th} percentile value</th>
<th>Mean value</th>
<th>5\textsuperscript{th} percentile value</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ref – 2.5 m’ (m(^3))</td>
<td>61,000</td>
<td>81,000</td>
<td>45,000</td>
<td>18,000</td>
</tr>
<tr>
<td>‘Ref – 2.8 m’ (m(^3))</td>
<td>135,000</td>
<td>192,000</td>
<td>135,000</td>
<td>81,000</td>
</tr>
<tr>
<td>Increase ‘Ref – 2.8 m’ relative to ‘Ref – 2.5 m’ (%)</td>
<td>121</td>
<td>138</td>
<td>200</td>
<td>363</td>
</tr>
<tr>
<td>‘RfR’ (m(^3))</td>
<td>143,000/163,000 (HKV study)</td>
<td>193,000</td>
<td>142,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Increase ‘RfR’ relative to ‘Ref – 2.8 m’ (%)</td>
<td>6/17 (HKV study)</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

The mean total maintenance dredging in the ‘Ref – 2.8 m’ situation increases almost twice as much as the ‘Ref – 2.5 m’ situation and the ‘RfR’ situation for only 6% compared to the ‘Ref – 2.8 m’ situation. It is noteworthy that the dredging on this location, according to the simulations, is more than one-third of the total dredging volume on the Waal. Furthermore, it is remarkable that in this trajectory (rmk 882-887) the mean values of the stochastic approach and the results gained by the deterministic are almost the same. Thus, the mean value of the stochastic approach is not underestimated by the deterministic calculation. It is to be noted that in this research a relatively crude grid is used for estimating the effect of the RfR measures. As a result, the schematization of the RfR measure near Lent (side channel) is very crude. In a HKV study (Barneveld & Paarlberg, 2010), the morphological effect near Lent is studied by applying a more refined grid. The results are presented in Table 5. It can be concluded that the outcome of the morphological effect near Lent in this research is underestimated by the prediction of the HKV study.

### 4.7.2 Morphological processes

The dredging demand that is presented in section 4.7.1 is the result of morphological processes that take place in the Waal due to the fixed layer on the river bed and recent changes in river management. In this section the morphological differences between the different situations over the main channel after a period of 20 years will be analysed in detail over the reach rkm 882-887.

(a) Difference between the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation

(b) Difference between the ‘Ref – 2.8 m’ situation and the ‘RfR’ situation

Figure 4.10: Difference width-averaged bed level change (over the main channel) between the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation and between the ‘Ref – 2.8 m’ situation and the ‘RfR’ situation over the reach rkm 882-887
In Figure 4.10 it is clear that the morphological response after 20 years in the three situations between rkm 883 and rkm 885, reach with fixed layer, is stable and the uncertainty is relatively small. The fixed river bed leads to extra scour and bed level variability immediately downstream the fixed layer. This results in large uncertainties (Figure 4.10-a). In Figure 4.10-b, the uncertainties and the mean value for the ‘RfR’ situation relative to the Ref – 2.8 m’ situation are even higher. This could be the impact of the RfR measures at Lent combined with the effect of the fixed layer in the outer bend of the river bed.

Due to the fixed layer in the outer bend the transport capacity in the inner bend increases (see Annex A). As most of the existing sediment on the fixed layer is transported to the inner bend by the spiral flow, the fixed layer has almost no sediment left at the end of the reach (downstream). If this spiral flow moves from the fixed river bed to the alluvial area (downstream of the fixed layer) sediment can be stirred again and transported by the spiral flow. This is reinforced by the difference in bed roughness between the fixed layer and the alluvial river bed. Due to the different river bed roughnesses, locally different flow velocity occurs. Where these velocities hit each other, vertical vortices and turbulence occur. This enforces the erosion of the river bed downstream of the fixed layer (Van Reen, 2002).

In contrast to the outer bend (downstream of the fixed layer), sediment is still transported in the inner bend. The scour, downstream the fixed layer, has a larger water depth. Therefore, relatively less water flows through the inner bend than in the outer bend, which leads to a decrease in flow velocity in the inner bend. Due to the decrease in transport capacity, the water in the inner bend contains excess sediment. Thus, sedimentation occurs, which can develop into nautical bottlenecks (Van Reen, 2002). This scheme results in an increase of the confidence interval of the morphological response.

**Morphological processes of the navigable section**

The dredging demand is not observable in the plots made for the width-averaged bed level changes and width-averaged bed level differences for the main channel. The reason for this is that cross-sectional profile evolution imposed by the river alignment is considered for the entire width of the main channel and not only for the navigable section. It is impossible to derive from these plots where the sedimentation in the fairway cross section might trigger the dredging capacity in the Delft3D model. Moreover, when maintaining the navigation channel it is not necessary to dredge at high water levels (high discharges). After high discharges most of the sediment is settling. Thus, dredging is mostly executed after the high-water season. To find additional information regarding the morphological processes, plotting the bed level differences along three lines in the main channel (the left side of the main channel, river axis, and the right side of the main channel) is helpful. Furthermore, 2D-plots of the bed level differences are also useful in observing the development of sedimentation areas and erosion pits. In Figure 4.11 the bed level changes along three lines in the main channel are presented and in Figure 4.12 the 2-D morphological changes for the reach rkm 882-886 are presented.
Impact of recent changes in river management on maintenance dredging in the Waal River

Figure 4.11: Differences in bed level changes after 20 years for the different situations directly after high water season (compared to the initial bed level) along three lines in the main channel (left (m=28), river axis (m=27), and right (m=33) - reach rkm 882-887.

(a) Bed level differences between the ‘Ref – 2.8 m’ situation and the ‘Ref – 2.5 m’ situation along three lines in the main channel

(b) Bed level differences between the ‘RfR’ situation and the ‘Ref – 2.8 m’ situation along three lines

(a) Bed level difference after high water season between the ‘Ref – 2.8 m’ situation and the ‘Ref – 2.5 m’ situation

(b) Bed level difference after high water season between the ‘RfR’ situation and the ‘Ref – 2.8 m’ situation
Impact of recent changes in river management on maintenance dredging in the Waal River

(c) 90%-Confidence interval of the bed level difference between the ‘Ref – 2.8 m’ situation and the ‘Ref – 2.5 m’ situation

(d) 90%-Confidence interval of the bed level difference between the ‘RfR’ situation and the ‘Ref – 2.8 m’ situation

Figure 4.1: 2D view of the bed level difference between the different situations after high discharges (compared to the initial bed level) in the twentieth year using the deterministic calculations - reach rkm 882-886

In contrast to the width-averaged bed level changes (in Section 4.2), Figure 4.11 and Figure 4.12 give more detailed information of the ongoing morphological processes in the cross section of the main channel. Figure 4.11 presents the bed level differences along three lines (longitudinal sides) of the bend near Nijmegen. The morphological responses observed in Figure 4.12 is comparable with the differences presented in Figure 4.11. These will be interpreted below.

*Differences between the ‘Ref – 2.8 m’ and the ‘Ref – 2.5 m’ situation:*

Upstream: Upstream of the fixed layer very small differences are observed between the Ref – 2.8 m’ and the ‘Ref – 2.5 m’ situation.

Fixed layer: In this section, very small differences are observed with some deposition at the left side. At the right side (no fixed layer) also very small differences are observed. At the end of this reach sediment settles at the river axis and the right side.

Downstream: Directly downstream of the fixed layer, erosion takes place at the river axis and the right side of the river. Around rkm 886 more sedimentation is observed after which the river stabilizes again.

*Differences between the ‘RfR’ and the ‘Ref – 2.8 m’ situation:*

Upstream: Directly upstream of the inlet of the side channel (in between rkm 882-883) sedimentation is predicted. In the river axis and the left side the sedimentation is less.

Fixed layer: At the beginning of the fixed layer more sedimentation is predicted at the river axis for the ‘RfR’ situation. This continues with some erosion, after which, the situation is equal to the Ref – 2.8 m’ situation. At the right side of the river (no fixed layer) the differences varies with small sedimentation and erosion.

Downstream: Downstream of the fixed layer in the ‘RfR’ situation, more sedimentation is expected at the left side than in the Ref – 2.8 m’ situation. Near rkm 886-887 this sedimentation will increase. Directly downstream, at the river and the right side, more erosion is predicted.
After this reach, some deposition may take place. At the outlet of the side channel (near rkm 886.5) erosion is predicted at the river axis and right side of the river.

As stated before, not the entire cross-section of the main channel is navigable. Only a narrow part of the channel is allocated for shipping. This implies that not the entire cross-section needs to be dredged. To compare the morphological response of the navigable section with the 2D bed level difference in the area of Nijmegen also the differences between ‘Ref – 2.8 m’ situation and the ‘RfR’ situation has been plotted along three lines of the navigable section. The navigable section varies over the Waal river. Sometimes the fairway is located at the left side of the river and sometimes at the right side of the river (due to the bends and non-uniformities). Therefore, the navigation section has varying grid axis. This makes it difficult to plot the bed level response for the entire trajectory. Therefore, in Figure 4.14 the grid axis of rkm 885.5 (see Figure 4.13) is used to plot the differences for a small reach around rkm 885.5.

Figure 4.13: Navigable section (blue) in the main channel and the grid axis of rkm 885.5

(a) Differences between the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation
(b) Differences between ‘Ref – 2.8 m’ situation and the ‘RfR’ situation

Figure 4.14: Local differences in bed level change after high discharges (compared to the initial bed level after 20 years along three lines in the navigation channel (left (m=24), river axis (m=27), and right (m=30)) - reach rkm 885-886

The morphological response in the navigable section of Figure 4.12 (see also Figure 4.13) can be related to the bed level differences in Figure 4.14. The comparison leads to a local resemblance around rkm 885.5. It becomes clear that the width averaged bed level changes can also be plotted for identifying morphological changes in the river. Because of the varying grid axis this becomes difficult for the whole river. For a very small reach this is doable.

Following the morphological analysis it is obvious that the large deposition problem and the dredging demand are not distributed evenly along the river. It is almost permanent at some locations and more sporadic at other locations. This applies to all three situations. From the analysis it is clear that locations with sharp bends have a high probability of sediment deposition. At the Waal, high dredging volumes are found in sharp bend sections, for example downstream of the Pannerdensche Kop bifurcation over the reach rkm 868-885 (Erlecom and Nijmegen). Thus, it is useful to implement structural measures at these locations. On locations with high dredging demand constructive measures as longitudinal dams, sand traps or sills may be implemented.
Chapter 5 Conclusion and recommendations

The objectives of this master thesis are to investigate the effects of the changes in the Waal system (increase of the minimum guaranteed depth and the implementation of the Room for the River measures) and to investigate the potential of a stochastic approach in river management practice. This chapter provides, in summary, an answer to the questions that formed the objectives to the research question that has been formulated in the first chapter. The chapter concludes with recommendations for further research.

5.1 Conclusions

Effect of the changes in the Waal

The effect of increasing the depth criterion from 2.5 m to 2.8 m

Conclusion as to bed level changes

From Section 4.3, it follows that the increase of the depth criterion causes almost no changes in the effect on the morphodynamics of the river bed.

In 2006, the minimum guaranteed depth of the Waal was raised from 2.50 m to 2.80 m to make shipping possible at low discharges. According to the width-averaged bed level changes, the differences in bed level between the two situations are almost zero in the deterministic calculation as well as in the stochastic approach. The reason for this lies in the fact that the morphological responses are averaged over the entire width of the main channel. Furthermore, no structural measures are implemented and extra dredging is executed only in places where the current guaranteed minimum depth (2.8 m) for navigation is not met in the navigable section. Only at the river bends, due to the fixed layer on the river bed, the bed level changes are significant, due to the geometrical non-uniformities.

Conclusion as to dredging effort

The present research has shown that the dredging effort in the 'Ref – 2.8 m' situation is twice as much as in the 'Ref – 2.5 m' situation. It increases drastically with 196%.

More concisely, the mean dredging effort, which has been calculated over the navigable section, is enormously affected due to the increase of the minimum depth requirement. In Table 7 a summary is given of the total maintenance dredging volume and the increase of the dredging volume in percentages for the entire Waal and for the Nijmegen area (rkm 882-887).

Table 7: Summary of maintenance dredging volume of the entire Waal, Nijmegen area and the increase in the 'Ref – 2.8 m' situation compared to 'Ref – 2.5 m' situation (related to Table 3 and Table 5)

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Deterministic result (entire Waal)</th>
<th>Mean value (entire Waal)</th>
<th>Deterministic result (Nijmegen)</th>
<th>Mean value (Nijmegen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Ref – 2.5 m' (m³)</td>
<td>140,000</td>
<td>99,000</td>
<td>61,000</td>
<td>45,000</td>
</tr>
<tr>
<td>'Ref – 2.8 m' (m³)</td>
<td>387,000</td>
<td>294,000</td>
<td>135,000</td>
<td>135,000</td>
</tr>
<tr>
<td>Increase 'Ref – 2.8 m' relative to 'Ref – 2.5 m' (%)</td>
<td>177</td>
<td>196</td>
<td>121</td>
<td>200</td>
</tr>
</tbody>
</table>
The width-averaged bed level changes over the main channel show almost no differences, because all the bed level changes are averaged over the whole width of the main channel. It is likely that in the navigable section (fairway) the minimum depth requirement of 2.8 m is not met. The bed level changes over the navigable section could be immense, which can be the reason for the increase of the maintenance dredging. Around the bends in the Waal the maintenance dredging is the highest. For Nijmegen (rkm 883-886), for instance, the maintenance dredging volume is more than one-third of the total dredging volume on the Waal. According to the simulations, the dredging volume in all sharp bends (Millingen (rkm 869-870), Erlecom (rkm 875-876) and Nijmegen (rkm 883-885)) in total is more than the half of the total dredging volume on the Waal.

Conclusion as to navigability

The above research yields less compelling results where navigability is concerned. This is due to the fact that the dredging is already taken into account, in plotting the navigability. The impairments in navigability at a certain draught in the plot are limited, due to the influence of the dredging effort.

In relation to navigation, the ‘Ref – 2.8 m’ situation shows only an increase in navigation for a draught of 3.5 m. For the other draughts no – or merely a small – increase is observable. The increase of the depth criterion from 2.5 m to 2.8 m makes less sense. It has little influence on the navigability (only at draught 3.5 m). This change has the biggest influence on maintenance dredging effort, which is least accepted for a sustainable navigation strategy. Due to this extra dredging, a large number of dredging vessels is needed for maintenance dredging. Hence, these vessels cause extra hindrance to inland navigation. This results in very high costs for maintenance dredging and economic losses due to the increased hindrance and long waiting time for sailing along the dredging vessels.

**The effect of the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation**

Conclusion as to bed level changes

From the present research it follows that in the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation, an increased variability is predicted in the bed level differences in the deterministic calculation as well as in the stochastic approach. Thus, a larger variability in uncertainty is predicted.

This variability can be derived from the changes made by the schematisations of the Room for the River Project in the Waal, which causes larger gradients in sediment transport. At certain locations there is more sedimentation predicted than other locations. Furthermore, on most locations, a higher uncertainty band (90%-confidence interval) is predicted in the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation.

Conclusion as to dredging effort

Interestingly, this research has shown that the increase in the maintenance dredging volume in the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation is approximately 10 times lower than the increase in the maintenance dredging volume in the ‘Ref – 2.8 m’ situation (which is related to the dredging effort in the ‘Ref – 2.5 m’ situation). In Table 8 a summary is given of the total...
maintenance dredging volume and the increase of the dredging volume in percentages for the entire Waal and for the Nijmegen area (rkm 882-887).

Table 7: Summary of maintenance dredging volume of the entire Waal, Nijmegen area and the increase related to every situation (related to Table 3 and Table 5)

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Deterministic result (entire Waal)</th>
<th>Mean value (entire Waal)</th>
<th>Deterministic result (Nijmegen)</th>
<th>Mean value (Nijmegen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ref – 2.5 m’ (m$^3$)</td>
<td>140,000</td>
<td>99,000</td>
<td>61,000</td>
<td>45,000</td>
</tr>
<tr>
<td>‘Ref – 2.8 m’ (m$^3$)</td>
<td>387,000</td>
<td>294,000</td>
<td>135,000</td>
<td>135,000</td>
</tr>
<tr>
<td>Increase ‘Ref – 2.8 m’ relative to ‘Ref – 2.5 m’ (%)</td>
<td>177</td>
<td>196</td>
<td>121</td>
<td>200</td>
</tr>
<tr>
<td>‘RfR’ (m$^3$)</td>
<td>445,000</td>
<td>342,000</td>
<td>143,000</td>
<td>142,000</td>
</tr>
<tr>
<td>Increase ‘RfR’ relative to ‘Ref – 2.8 m’ (%)</td>
<td>15</td>
<td>16</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

For the mean total maintenance dredging, an increase is predicted of only 16% compared to the ‘Ref – 2.8 m’ situation and an increase of 6% near Nijmegen. In the ‘RfR’ situation the dredging also varies per location. At certain locations the dredging effort increases and at other locations it decreases. The increase can be the effect of lowering of the flow velocity following a decrease of sediment transport due to the RfR measures. In reversed situations a decrease of the dredging volume is predicted.

Another interesting conclusion is that the dredging in locations with bends is more than the half of the total dredging on the Waal. In Nijmegen (rkm 883-886) the total maintenance dredging volume is more than one-third of the total dredging volume on the Waal.

Conclusion as to navigability

The navigability of the ‘RfR’ situation compared to the ‘Ref – 2.8 m’ situation shows almost no difference. This is because of the regular maintenance dredging. At the same time, the increased dredging (16%) and the required vessels to dredge will form more hindrance for the navigation than it is in the ‘Ref – 2.8 m’ situation.

If the Room for the River programme is executed with a 2.5 m depth criterion, the bed level difference is likely to have the same variability as has been predicted with the ‘Ref – 2.8 m’ situation. This is because there is less difference predicted between the ‘Ref – 2.5 m’ situation and the ‘Ref – 2.8 m’ situation. The same holds true for the uncertainty. The dredging of the ‘RfR’ situation, without any doubt, will be much lower than the ‘Ref – 2.8 m’ situation. Nevertheless, compared to the ‘Ref – 2.5 m’ situation there will be still an increase. Deterministically calculated, the navigability would not decrease compared to the ‘Ref – 2.5 m’ situation. However, using the stochastic approach the navigability in the ‘RfR’ situation may experience a small decrease. Of course, this could possibly be different after a new simulation with a new criterion.

The mean dredging effort, which has been calculated over the navigable section, is enormously affected. In Table 7 a summary is given of the total maintenance dredging volume and the increase of the dredging volume in percentages for the entire Waal and for the Nijmegen area (rkm 882-887).
Added value of a stochastic approach in river management practice

In the present research, the bed level changes, navigability, and the dredging effort of the Waal have been analysed using the stochastic and deterministic approach. The stochastic approach consists of statistics such as the 95%-percentile value, the mean value and the 5%-percentile value. With these statistics the 90%-confidence interval can be determined. With this information, the river manager is 90% confident that the bed level changes caused by various human intervention measures, for instance, will be between the 5th and the 95th percentile value at the location of interest. The 2D-plots and the local differences in the bed level along three longitudinal lines in the main channel for the detailed research for Nijmegen show also the 90%-confident interval, specific for a point in the cross-section of the main channel.

For the stochastic approach, 75 discharge time series are used. The larger the number of discharge time series, the guarantee that the mean value almost converges to the expected value is bigger. With the stochastic approach a river manager can be more confident that the mean value of the 75 discharge time series is near the expected value, than by using the deterministic approach. A drawback of the stochastic approach is that the calculations can be rather time-consuming with respect to the deterministic approach, because the models are executed with a large range of resampled discharge series.

Table 8: Difference between deterministic results and mean value in percentage

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Deterministic result (m$^3$)</th>
<th>Mean value (m$^3$)</th>
<th>Difference (%)</th>
<th>Nijmegen Deterministic result (m$^3$)</th>
<th>Nijmegen Mean value (m$^3$)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ref – 2.5 m’</td>
<td>140,000</td>
<td>99,000</td>
<td>40</td>
<td>61,000</td>
<td>45,000</td>
<td>26</td>
</tr>
<tr>
<td>‘Ref – 2.8 m’</td>
<td>387,000</td>
<td>294,000</td>
<td>32</td>
<td>135,000</td>
<td>135,000</td>
<td>0</td>
</tr>
<tr>
<td>‘RfR’</td>
<td>445,000</td>
<td>342,000</td>
<td>30</td>
<td>143,000</td>
<td>142,000</td>
<td>0</td>
</tr>
</tbody>
</table>

In current river management practice the deterministic approach is used instead of the stochastic approach. Most of the times, the deterministic calculations fall within the 90%-confidence interval and are higher than the mean value. In Table 9 the differences in dredging volume between the deterministic and the mean value of the stochastic approach are represented. Although the differences between the deterministic and stochastic analyses, the mean value of the stochastic approach, on most of the analyses, is not underestimated by the deterministic calculations. This applies also to the total maintenance dredging volume. The mean value of the stochastic approach and the results gained by the deterministic calculation of the total maintenance dredging volume in Nijmegen (reach rkm 882-887) show almost no differences.

With the help of a stochastic calculation the uncertainties in the morphological response of the river system can be identified. This results in a better understanding of the river behaviour. The stochastic approach shows that at one location the uncertainty can be more pronounced than at other locations. There are locations with high mean values and low uncertainty and vice versa. This can help river managers to assess impacts of engineering works and further to provide insight into the range of possible morphological responses to different design alternatives, their occurrence, and the maintenance costs.

For the dredging, the statistics (derived from the stochastic approach) can give insight into the locations where the dredging demand is the highest (where structural measures can be applied).
Impact of recent changes in river management on maintenance dredging in the Waal River

and where permanent dredging is necessary. Locations where the dredging demand is the highest are locations that can potentially develop into nautical bottlenecks associated with high maintenance costs. In the stochastic approach, these locations can be recognized by a high mean value and a small 90%-confidence interval in dredging effort. Locations with a low mean and high uncertainty in dredging are locations where the dredging should be continued. The mean dredging effort is very useful for Rijkswaterstaat to determine the long-term dredging budget.

As seen in Table 9 the difference in dredging volumes between the deterministic and the stochastic approach of the dredging volume are rather high in the entire Waal (which lies between 30 and 40%). In the Nijmegen area this difference is negligible. The high difference does not imply that the stochastic approach is more promising than the deterministic approach or vice versa. The uncertainty range (90%-confidence band) helps the river manager to decide where and how to interfere in the river system and it helps in drawing up performance based contracts with dredging companies. The stochastic approach gives more insight in the range or likelihood of predictions if it comes to dredging. If the river manager wants to employ a dredging company (contractor) for maintenance dredging, he can sign the contract for a lower amount of money, since the mean value of the stochastic approach is lower than the results of the deterministic approach.

5.2 Recommendations and discussion

Maintenance dredging

From Section 4.5 and 4.7.1 it follows that the increase of the mean dredging effort of the ‘Ref – 2.8 m’ situation is twice as much as the dredging effort in the ‘Ref – 2.5 m’ situation. The increase of the mean dredging effort of the ‘RfR’ situation compared to the dredging effort in the ‘Ref – 2.8m’ situation is 16% for the entire Waal and 6% for Nijmegen.

It is to be noted that in this research a relatively crude model is used for estimating the effect of the RfR measures. In a HKV study (Barneveld & Paarlberg, 2010), the morphological effect near Lent is also studied by using the actual planned RfR measure near Lent with a more refined model. The result is that near Nijmegen (rkm 882- 887) the expected dredging volume is 14% (20.000 m³) bigger than the calculated dredging volume in this research. Related to the dredging effort in the ‘Ref – 2.8 m’ situation the calculated dredging volume in the ‘RfR’ situation in the HKV study differs 11% that the calculated dredging volume in this research (Table 5).

It is also remarkable that the dredging in Nijmegen, according to the simulations in the present research, is more than one-third of the total dredging volume on the Waal. By using the crude model the morphological effect in this study is underestimated. For better results and a good estimation of the morphological response, it is recommended to use a more refined grid for an optimal function of the planned RfR measure. Extraction of water with sediment and reconnecting of the side channels with the main channel may affect the discharge flow and sediment transport and can have an influence on the erosion and sedimentation locations.
Validating the morphological model and its result

The Delft3D model for predicting the morphological response of river systems works fine for researchers, but still the predictions are not always 100% correct. Moreover, these predictions are very sensitive towards the water level and bed level. A sensitivity analysis of the Delft3D calculation is recommended towards the water level and bed level variety. This can be done by analysing the data from the current dredging activities or water/bed level measurements and comparing it with the predicted morphological response.

Navigability

In section 4.6, the navigability of the Waal at various draughts is presented. Prior to plotting the navigability, the dredging is already taken into account. The impairments in navigability at a certain draught in the plot are limited, because of the influence of the maintenance dredging. For a better view of the navigability it is suggested to create a plot without any maintenance dredging.

Deterministic approach versus stochastic approach

For the prediction of the bed level changes the deterministic approach and the stochastic approach are used. The prediction is made over a 20 year period. Most of the times, the deterministic calculations fall within the 90%-confidence interval and are higher than the mean value. However, on some locations the deterministic value falls significantly far from the mean value or 95th – percentile value, for example in the width-averaged bed level changes (Annex B). In the first section of the river trajectory (rmk 867 and rkm 879), the deterministically calculated bed level change falls significantly far from the average bed level change. As time evolves the bed level response in the deterministic calculation, as well as in the probabilistic calculation, decreases. However, the bed level lowering in the probabilistic calculation in the trajectory rkm 867-879 (Figure B-2a, B-4a, B-6a)) is relatively larger. It is not unusual that the deterministic realisation lies beyond the 95-percentile value, but the difference is extreme. The differences may be the result of less or no dumping upstream of rkm 870. It is recommended to investigate what aspects lead to this extreme difference.

As known, the deterministic approach is more often used the river management practice. In the stochastic approach as such as has been used in this research 75 discharge time series were used. According to the law of large numbers the arithmetic mean of the values almost surely converges to the expected value as the number of repetitions goes to infinity. Thus, the more time series are used for determining the morphological response of the Waal the more reliable the result. It is suggested that in this expertise the stochastic approach should be used more often to get results that almost surely converge to the expected value for the river management.

Uncertainty

With the uncertainty analyses river engineers can assess the impacts of engineering works better and can get a further insight into the range of possible morphological responses to different design alternatives, and their occurrence. This can help them with finding solutions to mitigate the sedimentation problem and the dredging demand. On the other hand finding ways to positively influence the uncertainty in the morphological processes, dredging effort and navigation can lead to a promising prediction for the future. The topic of influencing the uncertainty should be addressed further.
Furthermore, in this research only the uncertainty in the discharge hydrograph is taken into account. There are other sources of uncertainty in the river system. It is recommended to take more sources into account in further studies.

**River intervention works**

River intervention works can change the nature (distribution) of the deposition problem or dredging demand from permanent to more sporadic and vice versa. Structural measures to reduce the maintenance dredging are expensive and the funds are not easily allocated. It is therefore illogical to prevent all the maintenance dredging work since models show that the dredging can occur pretty much on any location. However, maintenance dredging itself is a threat for navigation, measures should be assessed to mitigate excessive maintenance dredging. The locations that show sporadic dredging (a low mean and high uncertainty in dredging) should continue to be dredged. The locations that show a high mean and low uncertainty in dredging are interesting locations for structural mitigation measures. These locations are predominantly found on the large river bends, namely near Millingen, Erlecom and Nijmegen. Not all the dredging might be prevented, but a considerable improvement is acceptable. The management principles should be combined with intervention works in a (innovative) way so that the dredging amounts will not increase as much as the models have predicted. Below some recommendations for possible innovative intervention works will be given for a further research.

**Increase the flow velocity:**

- By locally narrowing the channel width, the flow velocity can be increased. This will result in a higher sediment transport capacity (Annex C) and the inner bend will start eroding. Locally narrowing of the river can be initiated, for example, by constructing of longitudinal dams. This strategy will increase flushing flow to remove the accumulated sediments on the river bed and to scour the bed frequently enough. The drawback here is that the river will not have enough room in the high-water season. This problem can be solved by placing permeable longitudinal dams or by longitudinal dams with inlets to narrow the river. For higher discharges these permeable dams or inlets will be drown. With trial and error the height of the dams and sills at the inlet can be determined and what discharge is good enough to keep the river flushing.

**Sediment control**

- Other solutions to the current problems are implementing of small flow-training structures designed to modify the near-bed flow pattern and redistribute flow and sediment transport within the channel cross section, such as vanes, sills, sediment traps, vegetation areas or structures that divert the flow to shallow locations.

**Vanes**

The vanes function by generating secondary circulation in the flow. The circulation alters magnitude and direction of the bed shear stress and causes a reduction in velocity and sediment transport in the vane controlled area. As a result, the river bed aggrades in the vane controlled area and degrades outside. The vanes can be laid out to make the water and sediment move through a river curve as if it were straight.
Sediment trap
If a waterway's cross-section is suddenly increased by increased depth or width such as when the stage goes above bankfull, the flow velocity drops and the capacity to transport sediment falls even faster, so sediment will tend to deposit. This effect is a common cause of shoaling in navigation channels and ports, and is sometimes used to force sediment deposition in a particular location, such as sediment trap
References


Appendices

Annex A. Sedimentation

Bend Effect

In natural bends the geometry of the riverbed of the main channel causes secondary flow and spiral flow. In the upper part of the river water column the radial velocity is directed towards the outer bend and towards the inner bend in the lower part. This circulation is usually weak as compared to the downstream velocity.

The centripetal acceleration, together with the vertical structure of the downstream velocity, gives rise to a cross-stream circulation, often named secondary flow. When combined with the main (downstream) flow, this leads to a spiraling flow field, often called spiral flow.

The spiral flow leads to a transverse gradient in the sediment transport directed towards the inner bend, which causes erosion in the outer bed and sedimentation in the inner bend resulting in a transverse bed slope. This process is stopped when equilibrium is reached between the gravitational force and shear stresses induced by the spiral flow. Since the river discharge changes continuously and because the equilibrium responds rapidly to the new discharge situation, changes in the enforced two-dimensional riverbed shapes of the bends occur continuously (Van Adrichem, 2013 and De Vriend et al, 2011).

Bend effect with a fixed layer

In undisturbed conditions, without a fixed layer, the river bed in the outer bend will erode and deposition will take place in the inner bend. In case there is a fixed layer, the river bed in the outer bend cannot erode anymore. The fixed height in the outer bend (due to the fixed layer)
results in a decrease of the hydraulic profile, resulting in a higher flow velocity. Because of the higher velocity more erosion will occur, but this is not possible in the outer bed, where the fixed layer is situated. Thus, erosion will occur in the inner bend (because it is still possible there). Besides this, the bed roughness is increased in the outer bend after protecting the river bed (due to the dumped stones). This results in less water flow in the outer bend and more water flow in the inner bend (with a higher flow velocity and thus more erosion). Near the fixed layer, almost no sediment is available for transport. Thus, the secondary flows are unsaturated with sediment. This flow cannot drag sediment from the outer bend. Therefore, sediment will be dragged on locations where sediment is available for transport (the inner bend). Thus, erosion of the inner bend occurs (Van Reen, 2002).

In the fixed river bed the spiral flow cannot drag sediment, because there is no sediment available to be stirred. If this spiral flow moves from the fixed river bed to the alluvial area (downstream of the fixed layer) sediment can be stirred again and transported by the spiral flow. This is reinforced by the difference in bed roughness between the fixed layer and the alluvial river bed. Due to the different river bed roughnesses, locally different flow velocity occurs. Where these velocities hit each other vertical vortices and turbulence occur. This enforced the erosion of the river bed in the outer bend.

As most of the existing sediment on the fixed layer is transported to the inner bend by the spiral flow, the fixed layer has almost no sediment left at the end of the reach (downstream). Directly downstream of the fixed layer (on the alluvial river bed) sediment is again available, which will cause erosion in this area.

In contrast to the outer bend, sediment is still transported in the inner bend. The erosion scour in the outer bend has a larger water depth. Therefore, less water flows through the inner bend, which leads to a decrease in flow velocity. Thus, sedimentation occurs, which can develop into nautical bottlenecks (Van Reen, 2002).
Annex B: Bed level changes and sediment transport

Bed level changes for the ‘Ref – 2.5 m’ situation

Figure B-1: Bed level change after 1 year with respect to T= 0 for the ‘Ref – 2.8 m’ situation in the Upper-Waal

a) Upper-Waal

b) Middel-Waal
c) Lower-Waal

Figure B-2: Bed level change after 20 years with respect to T= 0 for the ‘Ref – 2.8 m’ situation in the Waal (Upper-Waal, Middle-Waal and Lower-Waal)

Bed level changes for the ‘Ref – 2.8 m’ situation

Figure B-3: Bed level change after 1 year with respect to T= 0 for the ‘Ref – 2.8 m’ situation in the Upper-Waal

a) Upper-Waal
Impact of recent changes in river management on maintenance dredging in the Waal River

Figure B-4: Bed level change after 20 years with respect to T= 0 for the ‘Ref – 2.8 m’ situation in the Waal (Upper-Waal, Middle-Waal and Lower-Waal)

Bed level changes for the ‘RfR’ Situation

Figure B-5: Bed level change after 1 year with respect to T= 0 for the ‘RfR’ situation in the Upper-Waal
Impact of recent changes in river management on maintenance dredging in the Waal River

Figure B-6: Bed level change after 20 years with respect to $T=0$ for the ‘RfR’ situation in the Waal (Upper-Waal, Middle-Waal and Lower-Waal)
Annex C: Morphodynamic responses to human interventions

In this section the development of the river bed due to human intervention are explained (Crosato, 2014)

Sediment Extraction

Figure C-1: Development of the river bed after sediment extraction

In Figure C-1 the development of the river bed is presented in the case of continuous sediment extraction. After a long while a new equilibrium is found when the sediment transport capacity downstream of the extraction point equals the reduced sediment load. Characteristic long-term consequences of continuous sediment extraction are: overall degradation of the riverbed and drop of the water level. Downstream of the extraction point the decrease of the longitudinal slope causes the increase in water depth.
Excavation of a side channel

Figure C-2: Short-term and long-term development of a river bed after excavating a side channel

In the situation presented in Figure C-2 a side channel is excavated. The presence of a side channel can be schematised as water withdrawal from the main channel. Where the side channel reconnects with the main channel there will be water input into the river. The withdrawn and returned quantities are the same and equal to ΔQ. The short-term and long-term responses to the excavation of a side channel are illustrated in Figure C-2. On the short term erosion is to be expected upstream of the intake (point M2) and downstream of the outflow (point M1). Sedimentation is expected downstream of the intake and upstream of the outflow. On the long term, the excavation of a side channel has implications for the water and bed levels in main channel in-between the inlet and the outlet of the side channel and upstream of the inlet. The bar that is formed can result in a bottleneck for navigation and induces extra dredging volumes.
River narrowing

In Figure C-3 the river has been narrowed. On the long-term river narrowing causes bed degradation. Upstream of the narrowed part experiences also bed degradation. The upstream degradation depends on the length of the narrowed part. The erosion at the narrowed stretch creates extra navigational depth and reduces the dredging effort.
Impact of recent changes in river management on maintenance dredging in the Waal River

**River Widening or Floodplain lowering**

![Diagram of river widening or floodplain lowering](image)

In Figure C-4 the river is widened or the floodplain is being lowered. For both situations more or less the same development holds. River widening causes bed rising in the long-term, also upstream of the narrowed part. The amount of upstream aggradation depends on the length of the narrowed part. The bar that is formed can be a bottleneck for navigation and induces extra dredging volumes.
Annex D: Dredging Quantities

Bardoel (2010) used for his research the database ‘BOS-baggeren’ as the main source of information. The data from the ‘BOS-baggeren’ system are inserted on the dredging ships and contain information about the dredging locations, ship routes and dump locations. In the table below the dredged volume is presented according to the ‘BOS-baggeren’ and according to the week reports. The information from the week reports only contains the weekly dredged reports. As can be seen in the table below the differences between the two data sources can be rather large. The reason for the differences between the data is under investigation. According to Bardoel (2010) the information of the ‘BOS-baggeren’ is much more detailed and easy to track.

Table 9: Differences between two data sources for the dredged quantities (Bardoel, 2010)

<table>
<thead>
<tr>
<th>Year</th>
<th>Dredged according to BOS-baggeren [10^3 m³]</th>
<th>Dredged according to week reports [10^3 m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>57</td>
<td>63</td>
</tr>
<tr>
<td>2006</td>
<td>225</td>
<td>363</td>
</tr>
<tr>
<td>2007</td>
<td>526</td>
<td>587</td>
</tr>
<tr>
<td>2008</td>
<td>435</td>
<td>809</td>
</tr>
<tr>
<td>2009</td>
<td>398</td>
<td>733</td>
</tr>
<tr>
<td>Total</td>
<td>1.641</td>
<td>2.555</td>
</tr>
</tbody>
</table>
Annex E: Sediment transport

Morphodynamic effects due to human interferences such as the Room for the River program can be defined as bed changes caused by changes in local gradients in the sediment transport. According to van Adrichem (2013), the overall increase in transport in the longitudinal direction of the river indicates net erosion and subsidence of the main channel.

![Figure E-1: Sediment transport volume after 20 years along the Waal as a result of the probabilistic (mean) and deterministic calculation for all the situations](image.png)

The results of the deterministic and stochastic approach show some variation in sediment transport in the longitudinal direction of the river, which indicates that the initial bed level is not in equilibrium with the used schematisation.

The overall transport gradient in the ‘RfR’ situation becomes less than the gradient in the ‘Ref-2.80 m’ situation. This indicates that less net erosion takes place and an improvement for the large-scale bed degradation on the Waal. In particular upstream of Lent the bed experiences less degradation and the degradation is also tempered downstream of Lent on some notable locations. Although the degradation of the Waal takes place on a much larger timescale than simulated with the model and erosion is not stopped in the ‘RfR’ schematisation after 20 years, the observed tempering of erosion is not a temporary effect. The process of bed degradation on the Waal is not stopped, but the eventual equilibrium water depth on the Waal becomes smaller by the river measures included in the ‘RfR’ schematisation.

In the probabilistic calculations the sediment transport rate in a year depends on the yearly hydrograph and the initial bed level position in that year. During low yearly averaged discharges, low transport rates are found and the graphs indicate that the transport rate decreases in the longitudinal direction of the river during low discharges. During high discharges this effect reverses (Van Ardichem, 2013).