Effect of climate change on the hindrance of navigation by river dune development

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Preface

This M.Sc. thesis forms the completion of my study Civil Engineering, section Water Engineering and Management at the Faculty of Engineering Technology at the University of Twente. The process of this research was very interesting and educational. First of all, I would like to thank my graduation committee prof.dr. Suzanne Hulscher, dr.ir. Marjolein Dohmen-Janssen and dr.ir. Astrid Blom, for their enthusiastic support and supervision. During the first stage of the research, Mr. van Deursen and Mr. Middelkoop were very helpful in searching information on climate change. Mr. Buijsrogge supported me with the simulations in Sobek. Mr. Havinga and Mr. Van Toorenburg provided the method calculating the restriction of the loading capacity of navigation. I would like to thank Antoine Wilbers for inviting me to Utrecht and explaining everything about his method.

Finally, I would also like to thank my parents for the opportunity to study and for their ever-lasting support and confidence. I am grateful to my Peer for being there and always taking care of my self-esteem. Last but not least I would like to thank my friends and Zwicked! Het Huisch for their support and the fun times we cherished.

Laura Haitel
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Summary

Navigation on the River Rhine is of great economic importance for the Netherlands. Small water depths due to low discharges can restrict the loading capacity of vessels. This effect may be enhanced by the presence of river dunes on the riverbed. The height of the river dunes depends on the flow conditions, which are expected to change in the future as a result of climate changes. It is to be expected that the temperature in Europe will rise, and high discharges will occur more often due to this. River dunes could restrict the depth for navigation if the dune height increases. Three main issues are: (1) the effect of climate change on discharges in the Rhine, (2) the effect of these changing flow conditions on the development of river dunes and (3) the effect of river dunes on the hindrance of navigation.

The effect of climate change on flow conditions is determined by multiplying three sets of actual data with factors that result from climate change scenarios for Europe. These scenarios result from the prediction of an increasing global temperature of 2°C in 2100, forecasted by the Intergovernmental Panel on Climate Change (IPCC). Several scenarios that were used to predict the consequences of climate change for the discharge of the Rhine resulted in an increase of the discharge in winter and a decrease of the discharge in summer. A drought scenario gives a different perception of climate change and results in decreasing discharges for the entire year, with a maximum decrease of 20% in summer. The water depth in the Rhine increases with increasing discharges and vice versa.

The effect of changing flow conditions on river dune development is calculated with the method of Wilbers (2004), which is a method for unsteady flow conditions, based on the ideas of Allen (1976). River dunes develop as a result of an interaction between flow conditions and sediment transport. In the Rhine, between Lobith and the Pannerdensche Kop, river dunes of about 1.6 m high were measured during the flood of 1995, when the peak discharge was 12000 m³/s [Wilbers & Ten Brinke, 2003]. The maximum dune height is reached a few days after the peak of the discharge. This means that there is a time lag in the development of river dunes. Several methods for predicting the dune dimensions were developed; most of them are equilibrium dune height predictions, based on steady flow conditions. However, steady flow conditions hardly occur in the Rhine. The method of Wilbers (2004) follows an adaptive approach, based on the former dune height and equilibrium dune height. The bed shear stress determines which equilibrium height to use. For the Rhine between Lobith and the Pannerdensche Kop, the equilibrium predictors are the Van Rijn (1982) method and a predictor of Wilbers, which is an adaptation of the method of Tsuchiya (1967). The effect of climate change on the height of river dunes is clearly perceptible. The maximum dune height increases with increasing discharge. The magnitude of this increase depends on the proportion of the dune height in relation to the equilibrium height that corresponds to the peak discharge. Next to that, the growth rate of the dune height is fast for initial growth and slow when the maximum dune height is closer to the equilibrium height. This explains the fact that the maximum
dune height that reaches only 40% of the equilibrium height increases more in the climate change scenarios than the maximum dune height the reaches 80% of the equilibrium height. In addition, the time lag of the dune development also increases with increasing dune height and is larger for a longer growth period.

The hindrance of navigation is determined by the restriction of the loading capacity. The ship depth at maximum loading capacity varies for different types of vessels. Class V vessels are supposed to be normative on the Rhine. The ship depth at maximum loading capacity of these vessels is 4 m. Restricted water depth hinders navigation, as ships cannot use their maximum loading capacity. Climate change causes more problems in the future with restricted water depths for navigation, especially during summer. The loading capacity turns out to be restricted by about 20% to 50%. It is concluded that the effect of river dunes on the restriction of the water depth is insignificant, with a restriction of about 1%. This means that the changing height of river dunes, as a result of climate change, does not hinder navigation.
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List of symbols

\( a \) = constant by Yalin (1985) \\
\( A \) = adaptation constant by Allen (1979) \\
\( A_f \) = flow area in Sobek [m\(^2\)] \\
\( \alpha \) = adapted constant by Wilbers for Tsuchiya method [-] \\
\( b \) = constant by Yalin (1985) [-] \\
\( B \) = channel width [m] \\
\( \beta \) = roughness parameter by Tsuchiya (1967) [-] \\
\( C \) = Chézy coefficient [m\(^{1/2}\)/s] \\
\( C_{90} \) = Chézy coefficient for 90% of the grain size [m\(^{1/2}\)/s] \\
\( c_b \) = bed form migration celerity [m/s] \\
\( D_* \) = dimensionless particle diameter by Van Rijn [-] \\
\( D_{50} \) = the median grain size [m] \\
\( D_{min} \) = minimum depth of an empty class V vessel [m] \\
\( D_{max} \) = maximum depth of a maximum loaded Class V vessel [m] \\
\( \Delta \) = specific density [-] \\
\( dP \) = change of amount of precipitation [%] \\
\( dT \) = changing temperature [°C] \\
\( \varepsilon \) = porosity [-] \\
\( F \) = friction factor by Fredsoe (1979) [-] \\
\( \Phi \) = transport parameter [-] \\
\( Fr \) = Froude number [-] \\
\( g \) = gravitational acceleration [m/s\(^2\)] \\
\( h \) = water depth [m] \\
\( H \) = dune height [m] \\
\( H(t) \) = dune height at time t [m] \\
\( H_e \) = equilibrium dune height [m] \\
\( H_t \) = dune height at time step t [m] \\
\( H_{t-1} \) = dune height at previous time step [m] \\
\( \eta \) = dune length coefficient [-] \\
\( i_{b} \) = bed slope [-] \\
\( k \) = wave number [m\(^{-1}\)] \\
\( k_x \) = roughness height, dependent of grain size [m] \\
\( k_s \) = roughness height, dependent of bed forms [m] \\
\( K \) = wake depth [m] \\
\( L \) = dune length [m] \\
\( L_{mn} \) = restriction of the loading capacity [-] \\
\( L_{prof} \) = length of the profile of a primary dune [m] \\
\( L_s \) = length of secondary dune [m] \\
\( \mu \) = ripple factor [-] \\
\( N_s \) = number of secondary dunes on top of primary dunes [-] \\
\( Q \) = discharge [m\(^3\)/s] \\
\( \theta \) = Shields parameter [-] \\
\( \theta_{cr} \) = critical Shields parameter [-] \\
\( R \) = hydraulic radius [-]
\( r = \) loading rate \([\text{[-]}]\)
\( \rho = \) density of water \([\text{kg/m}^3]\)
\( s = \) sediment transport \([\text{m}^3/\text{s}]\)
\( s_b = \) bed load transport \([\text{m}^3/\text{s}]\)
\( T = \) transport parameter by Van Rijn \([-]\)
\( T_i = \) depth of an empty ship \([\text{m}]\)
\( T_m = \) maximum ship depth for navigation \([\text{m}]\)
\( T_n = \) actual water depth \([\text{m}]\)
\( T_v = \) minimum water depth for maximum loading capacity \([\text{m}]\)
\( t = \) time \([\text{days}]\)
\( \Delta t = \) time step of calculation model \([\text{day}]\)
\( \tau_b = \) bed shear stress \([\text{N/m}^2]\)
\( u = \) flow velocity \([\text{m/s}]\)
\( u_* = \) shear velocity \([\text{m/s}]\)
\( u_{cr} = \) critical shear velocity \([\text{m/s}]\)
\( u_b = \) bed load velocity \([\text{m/s}]\)
\( u_d = \) velocity of bed forms \([\text{m/s}]\)
\( \nu = \) kinematic viscosity \([\text{m}^2/\text{s}]\)
\( W_t = \) storage depth in Sobek \([\text{m}]\)
\( \omega_f = \) fall velocity \([\text{m/s}]\)
\( \xi = \) dune height coefficient \([-]\)
\( \psi = \) flow parameter \([-]\)
1 Introduction

1.1 Background
Navigation on the River Rhine is of great economic importance for the Netherlands. Small water depths due to low discharges can restrict the loading capacity of vessels. This effect may be enhanced by the presence of river dunes on the riverbed. The height of the river dunes depends on the flow conditions, which are expected to change in the future as a result of climate change.

In 1992, scientists from several countries predicted a global average temperature increase of 2 °C for the year 2100 [Buisman et al., 2000]. For Europe, this climate change leads to an increase in temperature, and subsequently an increase of precipitation amounts in winter and a decreasing amount of precipitation in summer. Due to these changing precipitation patterns, the discharges in the Rhine increase in winter and decrease in summer [Kwadijk, 1993, Middelkoop, 2000]. The development of river dunes can be influenced by these changing flow conditions, as river dunes develop as a result of flow conditions and sediment transport.

Higher discharges in the Rhine cause larger river dunes (Figure 1.1) that develop with a time lag to the flow conditions [Van Rijn, 1982, Julien & Klaassen, 1995, Wijbenga, 1990]. The maximum dune height is reached a few days after the peak of the discharge, when water levels are already decreasing. The water depth for navigation can be restricted when river dunes are still present at decreasing water levels. In the Rhine in the Netherlands, river dunes of about 1 m high, develop at discharges from approximately 7000 m$^3$/s.

This research gives insight in one of the effects of climate change on navigation on the Rhine in the Netherlands. In order to determine the influence of river dunes on the water depth, the changes of the dune dimensions as a result of climate change are quantified.

1.2 River dunes in the Rhine
The part of the Rhine that is considered in this study is the Bovenrijn in the Netherlands. It is the river branch between Lobith and the Pannerdensche Kop, which is the bifurcation of the Waal and the Pannerdensch Kanaal. The Netherlands cover the lower part of the river catchment. The Rhine originates in the Alpine area in Switzerland and in Germany there are a lot of tributaries (Figure 1.1): River dunes in the Rhine at bifurcation the Pannerdensch Kop (source: Wilbers 2004).
1.2). The Bovenrijn has embankments and groynes constructed along the entire length (Figure 1.1). Groynes extend 40 to 80 m into the main channel and are spaced 150 to 200 m apart. The yearly average discharge of the Rhine at Lobith is 2300 m$^3$/s. The water depth at average discharge is about 5 m and the width between the groynes is about 340 m [Wilbers & Ten Brinke, 2003].

A recent extreme peak discharge of about 12000 m$^3$/s occurred in January 1995. The water depth was about 13 m and large dunes developed. During this flood, echo-soundings were made of the riverbed. The maximum dune height was about 1.5 m and occurred a few days after the peak discharge. Specific measurements in the Rhine River branches during the February-March 1997 flood of about 7000 m$^3$/s also documented the growth, decay and migration rates of dunes. It was concluded that the primary dunes of about 1 m high developed, with smaller dunes superimposed on them [Julien et al, 2002].

At the beginning of the floods, the entire bed was covered with small dunes. During rising discharge, the bed was covered with large dunes with more or less straight fronts. During the falling discharge the dunes increased in length, but decreased in height. They were also covered with smaller secondary dunes [Wilbers & Ten Brinke, 2003].

Many methods for calculating dune dimensions give equilibrium dimensions for steady flow conditions. However, knowledge of the role of unsteady flow conditions in shaping bed forms is important, because dune characteristics, like the time lag between the maximum discharge and maximum dune height, depend on the flow conditions. This knowledge can help engineers, concerned with navigation, harbor operation and river management, to exploit and control the system and dimensions of the riverbed [Allen, 1976]. Several methods for unsteady flow conditions were developed.

1.3 Research objective

The objective of this research is to determine the influence of river dunes on the water depth in the Bovenrijn in the Netherlands, due to changing discharges as a result of climate change during the next 100 years, in order to quantify the possible effect on the hindrance of navigation.
In order to achieve the objective the following research questions are answered:
1. What is the effect of climate change on the river discharge and water depth in the Bovenrijn?
2. What is the effect of changing flow conditions on the development and dimensions of river dunes in the Rhine?
3. What is the influence of changing dune heights on the water depth and the hindrance of navigation?

### 1.4 Outline of the research

The approach of the research, schematised in the research model (Figure 1.3), can be divided into three subjects; climate change, river dunes and navigation. The effect of climate change on the discharge in the Rhine is described with climate change scenarios in Chapter 2.

![Figure 1.3: Outline of the research](image-url)
In Chapter 3, the development of river dunes and the relation to discharge and water depth is explained. Methods for the calculation of dune dimensions are described. The importance of navigation and the method to calculate the restriction of the loading capacity at certain water depth are discussed in Chapter 4. The calculation of the discharges for different climate change scenarios and the corresponding water depths is described in Chapter 5. In Chapter 6, the results of the effect of changing flow conditions on the dune height is analyzed and the effect of climate change on the hindrance of navigation by river dunes are described. The results of the research are discussed in Chapter 7 and conclusions and recommendations are drawn in Chapter 8.
2 Climate change

2.1 Introduction

A simple definition of climate would be: the average state of weather over a long period of time. Nevertheless, climate is much more than only weather. Atmosphere, ocean, continents, snow and ice storage, and biosphere are the components of a climatic system. The climate is a result of a continuous interaction between these components [Buisman et al., 1995].

A process that occurs in the atmosphere is the greenhouse effect. In this process, greenhouse gasses, like carbon dioxide and methane, absorb the warmth radiation of the earth. This is a natural process that can be intensified by the increased emission of greenhouse gasses. Since 1750, the concentration of carbon dioxide and methane increased with respectively 30% and 150%. Over the past five decades, global temperature has increased with 0.3% [Nationmaster, 2003]. This warming is unlikely to be entirely natural, because it turned out that climate models, forced by changes in greenhouse gasses, reproduce the observed global changes. Those forced by natural factors alone did not. The prediction of the emission of greenhouse gasses depends on the worldwide changes of energy use, land use, population increase, technological development and economical expansion.

On a meeting of the Intergovernmental Panel on Climate Change (IPCC), which is part of the United Nations, scientists concluded an average global temperature rise of 2 °C for the year 2100. A low estimate of 1 °C and a high estimate of 4 °C were introduced as uncertainty intervals [Buisman et al., 2000]. In order to estimate the possible effect of the global temperature rise on the river regime of the Rhine, the global estimation was rendered into changes on smaller scale, like the river catchment of the Rhine, which covers a large part of Europe. Therefore, a study to investigate the influence of climate change on the discharge of the Rhine and the results for the water policy has been carried out [Asselman et al., 2000]. The study resulted in multiplying factors that can be used to calculate discharge scenarios on the basis of actual data, which is done in Chapter 5.

2.2 Impact of climate change on discharges in the Rhine

The Dutch National Program on Global Air Pollution and Climate Change (NRP) is a strategic research program, set up to promote the communication about climate change and stimulate climatic research in the Netherlands. The climate scenario used in NRP was based on the IPCC predictions and resulted in higher precipitation amounts in winter and lower precipitation amounts in summer [Asselman et al., 2000].

The hydrological modelling system Rhineflow [Kwadijk, 1993] has been developed to achieve discharges in the Rhine near Lobith for different climate scenarios of changing temperature and precipitation. It is a regional scale GIS-based model that was developed as a conceptual water balance model with a monthly time step. For each scenario, the output exists of multiplying factors per month for the discharge
of the Rhine, which can be used on both average and individual discharges of arbitrary time periods to calculate discharges for different scenarios.

Climate change scenarios are based on the emission of greenhouse gasses and a scenario that which defines the changing variables as a result of the changing concentration of greenhouse gasses. To retain special patterns of average world temperature, General Circulation Models (GCMs) were used. GCMs are numerical models for the simulation of circulations in the atmosphere.

2.3 Climate change scenarios

The impact of climate change on river discharge in the Rhine was forecasted with Rhineflow with two scenarios. The UHKI scenario, which is based on the results of an equilibrium GCM experiment with the atmospheric UK High resolution model, was used in the NRP study. In a later study, the Perspective scenario was also used in Rhineflow [Middelkoop et al, 2000, Shabalova et al, 2003, ICIS, 2002]. The UKHI scenario and Perspective scenario are called respectively, Scenario A and Scenario B. The scenarios generate predictions for 2050 and 2100, for the low, central and high estimation of global average temperature change of the IPCC and are described in Table 2.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A1</td>
<td>Scenario for the high estimation of IPCC for the year 2050 (the same as the central estimation of IPCC for the year 2100, by interpolation)</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>Scenario for the high estimation of IPCC for the year 2100</td>
</tr>
<tr>
<td>Scenario B1</td>
<td>Scenario for the low estimation of IPCC for the year 2050</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>Dry scenario for the high estimation of IPCC for the year 2050</td>
</tr>
<tr>
<td>Scenario B3</td>
<td>Scenario for the low estimation of IPCC for the year 2100 (the same as the central estimation of IPCC for the year 2050, by interpolation)</td>
</tr>
<tr>
<td>Scenario B4</td>
<td>Scenario for the central estimation of IPCC for the year 2100 (the same as the high estimation of IPCC for the year 2050, by interpolation)</td>
</tr>
<tr>
<td>Scenario B5</td>
<td>Scenario for the high estimation of IPCC for the year 2100</td>
</tr>
</tbody>
</table>

Table 2.1: Description of Scenario A and Scenario B

2.3.1 Scenario A

The changes for temperature and precipitation are divided in year, winter and summer changes for the three main areas in the catchment of the Rhine (Appendix A) [Middelkoop et al, 1999]. The results for the discharges at Lobith are given as multiplying factors in Table 2.2. The accuracy of the factors is supposed to be 5%, because there are uncertainties in the worldwide changes of energy use, land use etcetera, so climate change cannot be predicted exactly.
Table 2.2: Multiplying factors for the discharges of the Rhine near Lobith per month

<table>
<thead>
<tr>
<th>Month</th>
<th>Scenario A1</th>
<th>Scenario A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.15</td>
<td>1.45</td>
</tr>
<tr>
<td>February</td>
<td>1.15</td>
<td>1.45</td>
</tr>
<tr>
<td>March</td>
<td>1.05</td>
<td>1.30</td>
</tr>
<tr>
<td>April</td>
<td>1.00</td>
<td>1.20</td>
</tr>
<tr>
<td>May</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>June</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>July</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>August</td>
<td>0.85</td>
<td>0.70</td>
</tr>
<tr>
<td>September</td>
<td>0.85</td>
<td>0.65</td>
</tr>
<tr>
<td>October</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>November</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>December</td>
<td>1.10</td>
<td>1.30</td>
</tr>
</tbody>
</table>

This scenario predicts higher discharges in winter and lower discharges in summer. The discharge increases with maximally 45% in winter for the year 2100 and the maximum decrease for the year 2100 in summer is about 35%. These are extreme predictions, based on the high estimation of temperature increase. The central scenario for 2100, which equals the high scenario for 2050, predicts a maximum increase of the discharge of 15% and a maximum decrease of 15% in summer.

2.3.2 Scenario B

In Scenario B the winter precipitation is raised, while the decrease of the summer precipitation is the same as Scenario A. Drought during the entire year could also be an effect of temperature increase. This has led to a drought scenario (Scenario B2), which is developed for the Drought Study (Droogtestudie) [ICIS, 2002] that focuses on a decrease of summer and winter precipitation, based on the maximum increase estimation of global temperature for the year 2050.

Table 2.3: Multiplying factors for changing discharges of the Rhine near Lobith

<table>
<thead>
<tr>
<th>Month</th>
<th>Scenario B1</th>
<th>Scenario B2</th>
<th>Scenario B3</th>
<th>Scenario B4</th>
<th>Scenario B5</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.05</td>
<td>0.95</td>
<td>1.10</td>
<td>1.20</td>
<td>1.55</td>
</tr>
<tr>
<td>February</td>
<td>1.05</td>
<td>0.90</td>
<td>1.10</td>
<td>1.15</td>
<td>1.45</td>
</tr>
<tr>
<td>March</td>
<td>1.00</td>
<td>0.85</td>
<td>1.00</td>
<td>1.05</td>
<td>1.25</td>
</tr>
<tr>
<td>April</td>
<td>1.00</td>
<td>0.80</td>
<td>1.00</td>
<td>0.95</td>
<td>1.15</td>
</tr>
<tr>
<td>May</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.95</td>
<td>1.05</td>
</tr>
<tr>
<td>June</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>July</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>August</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td>September</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td>October</td>
<td>1.00</td>
<td>0.80</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>November</td>
<td>1.00</td>
<td>0.80</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>December</td>
<td>1.05</td>
<td>0.85</td>
<td>1.05</td>
<td>1.10</td>
<td>1.35</td>
</tr>
</tbody>
</table>
The results for the discharge of Scenario B (Table 2.3) show increasing discharges during winter and decreasing discharges in summer, except for Scenario B2. Scenario B2 results in decreasing discharges over the entire year. The accuracy of 5% is supposed again.

The multiplying factors for Scenario B1 vary only 5%. Scenario B2 results in a maximum decrease of discharge of 20% in summer. The peak discharges in winter decrease less (about 5%). For the year 2100, Scenario B3 changes vary from +10% to -5% and Scenario B4 gives increasing discharges with maximally 20% in winter and a decrease of 10% in summer. Scenario B5 results in a maximum discharge increase of 55% and a decrease in summer of 15%.

### 2.4 Comparison of the scenarios

The scenarios are compared in Table 2.4. The discharges during spring and autumn do not change much in all scenarios. Scenario A gives 5% smaller increases in winter than Scenario B for the year 2100. The maximum decreases of summer discharges are more extreme in Scenario A. The change of the discharge for Scenario B1 is very small, with a maximum of 5% increase. The drought scenario (Scenario B2) gives different results, especially during winter. The decrease of summer discharge is the most extreme scenario for 2050, compared to Scenarios A1 and B1. Scenario B5 results in the highest increase of discharge in winter, compared to Scenario A2.

In a general comparison it can be concluded that the scenarios are similar, except for the decrease of discharge in summer, which is more extreme for Scenario A. Scenario B2 is different from all scenarios, because it forecasts only decreasing discharges during the entire year.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum increase of discharge [%]</th>
<th>Maximum decrease of discharge [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A1</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Scenario B1</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>-5</td>
<td>20</td>
</tr>
<tr>
<td>Scenario B3</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Scenario B4</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Scenario B5</td>
<td>55</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table 2.4: Comparison of the UKHI and Perspective scenarios for the maximum increases and decreases of discharge in the Rhine*
3 Development of river dunes

3.1 Introduction

The interaction between flow conditions and sediment transport results in a dynamic morphological riverbed system. The development of bed forms on the riverbed (Figure 3.1), for example river dunes, is a process that occurs. The interaction between flow conditions and the development of river dunes is described more extensively.

![Diagram of flow conditions, sediment transport, and development of bed forms]

Figure 3.1: The interaction between flow and sediment transport

The development of dunes lags behind the changing flow conditions. Therefore, dunes can cause problems for the water depth for navigation. There are many different methods for predicting the dune dimensions. Most of them predict equilibrium dune dimensions, which occur in steady uniform flow conditions. However, steady uniform flow conditions do not occur at flood events in the Rhine, which makes the prediction of dune dimensions difficult, as changing flow conditions and sediment transport rates are difficult to predict and calculate. Several methods for unsteady flow conditions were developed. The method of Wilbers (2004) was specially developed for the Rhine branches. In Chapter 6, this method is used to calculate the height of river dunes for different climate change scenarios.

3.2 Interaction between flow conditions and sediment transport

In equilibrium flow, the following continuity equation and impulse (Chézy) equation are applicable:

\[ Q = u \times h \times B = \text{constant} \quad (3.1) \quad \text{and} \quad u = C \sqrt{R \times i_b} \quad (3.2) \]

In which Q is the discharge; u represents the flow velocity; h is the water depth and B the width of the channel. The discharge is constant. If, for example, the width increases, the water depth and velocity decrease. C is the Chézy coefficient; R is the hydraulic radius and \( i_b \) the slope of the riverbed. The Chézy coefficient
gives the inverse roughness, so $C$ decreases at increasing roughness. The hydraulic radius is expressed by the cross-sectional area divided by the wetted perimeter of the main channel.

Roughness causes friction to the flow, through which the flow velocity decreases, according to the equation of Chézy. As a result, the water depth increases according to the continuity equation. The resistance of the riverbed to the friction of the flow is called the bed shear stress ($\tau_b$) and is expressed as:

$$\tau_b = \rho u_*^2 \quad (3.3) \quad \text{with} \quad u_* = u \frac{\sqrt{g}}{C} \quad (3.4)$$

In which $\rho$ is the density of water and $u_*$ is the shear velocity, which is a function of the flow velocity, the gravitational acceleration ($g$) and the Chézy coefficient.

In steady uniform flow, the bed shear stress creates equilibrium between the water flow and the friction of the flow, depending on the roughness of the riverbed. In these conditions the sediment transport and shape of the riverbed are also in equilibrium.

However, steady flow conditions hardly occur in the Rhine. A flood event causes unsteady flow conditions at which equilibrium conditions change. Sediment transport takes place at a certain critical velocity (and accompanying bed shear stress). At first, particles roll and slide on the bed, which is called bed load transport. At larger velocities, particles rise higher in the water column, depending on grain size, and stay for a while as suspended transport. If the flow velocity decreases again, the particles fall out of suspension, back on the riverbed. During these processes, the form of the riverbed changes. As a result, the roughness changes and so the flow conditions change.

### 3.3 Type of bed forms

The type of bed forms (Figure 3.2) and their dimensions depend on the flow conditions, the characteristics of the bed material and the Froude number. The Froude number tells if a flow is sub-critical (flowing) or supercritical (jumping). Sub-critical flow occurs when the Froude number is smaller than 1, and supercritical flow occurs when the Froude number is larger than 1. In that case, the flow velocity ($u$) is high, compared to the celerity of the flood wave ($\sqrt{gh}$). The Froude number yields:

$$Fr = \frac{u}{\sqrt{gh}} \quad (3.5)$$

The velocity in the Bovenrijn increases at floods, but the water depth increases as well. The result is sub-critical flow, because the Froude number is smaller than 1. Upstream in mountainous areas with steep slopes, the flow can be supercritical when the velocity is very high at low water depth and a flood wave moves much slower than the flow.

In general, at the beginning of a flood event, when the flow is sub-critical and the flow velocity is low, bed forms are ripples, which are small, sharp-crested features
of roughly triangular cross section. At increasing flow velocities, but Froude number still smaller than 1, the ripples are transformed into dunes, which are much larger, flat-crested bed forms with steep downstream and gentle upstream slopes, on which small features can be superimposed [Van Rijn, 1993]. At a certain maximum flow velocity, when the Froude number is larger than 1, the bed form dimensions decrease at still increasing flow velocity and flat bed, or even anti-dunes, occur. In the Bovenrijn, at large floods, only the transformation of ripples into dunes occurs. Flat bed and anti-dunes do not occur in the Bovenrijn [Julien et al, 2002; Wilbers & Ten Brinke, 2003].

3.4 River dune dimensions

The cross-section of a large river dune is asymmetrical [Wilbers & Ten Brinke, 2003]. The upstream side of the dune erodes as the velocity increases towards the top of the dune caused by the decreasing depth. The downstream side of the dune is relatively steep. A sudden increase of the water depth causes turbulence after the separation point where the flow does not follow the riverbed anymore (Figure 3.3). An energy loss occurs, which results in sedimentation, because there is less energy left for sediment transport. Erosion and sedimentation of sediment over the dune result in the migration of the dune, which is not part of this research.

From former research it was concluded that there is a noticeable hysteresis effect of the dune height versus discharge with maximum values of dune height observed a couple of days after the peak discharge [Julien et al, 2002]. The development of the
dune height lags behind the bed shear stress at high discharge, which is called the time lag. Equilibrium conditions change and time is needed for changing the bed form volume, due to a limited amount of sediment transport. Hence, the change in bed form dimensions is slow compared to the change in flow conditions [Lai, 1998]. A few findings about the time lag are listed:

- The time lag is relatively small during increasing discharge and relatively large during decreasing discharge. The change in bed form height is approximately twice as fast during the growth, compared to the change during the decay of the dune height [Wijbenga, 1990].

- Large dunes alter their size slower than smaller dunes. This is due to their greater volume that simultaneously depends on the sediment transport [Allen, 1976].

- The time lag for dune length is larger than the time lag for dune height [Wijbenga, 1990].

Another phenomenon is the development of secondary dunes on top of the primary dunes after a peak discharge in the Bovenrijn (Figure 3.4). Superimposed dunes are generally an order of magnitude smaller in height and length than the dunes that they are superimposed on [Allen, 1976a] and they occur only when there is enough space and time to develop on the larger forms. These secondary dunes have a similar hysteresis as the primary dune heights [Julien et al, 2002].

\[ (3.6) \]

\[ (3.7) \]

An important effect of river dunes is the influence on the roughness. For example, Van Rijn (1993) divided the hydraulic roughness into two parts: one depending on grain roughness \( k_s \) and the other on account of bed forms \( k_s^* \) [Van Rijn, 1993; Karim, 1995]:

\[ k_s = k_s' + k_s^* \]  

\[ k_s^* = 1.1H\left[1 - \exp(-25H/L)\right] \]

In which H is the dune height and L the dune length. This expression of the dune height corresponds fairly well to the bed resistance measurements during the flood of 1998 [Julien et al, 2002].
3.5 Steady flow conditions

In predicting dune dimensions, most methods were developed for steady and uniform flow conditions. In steady uniform flow, with assumed homogeneous sediment, there is a unique dune height and length for each specific combination of flow characteristics, independent of previous conditions. Steady and uniform flow, therefore, enables the prediction of dune dimensions with a single function, often based on a combination of flow strength (velocity or shear stress), water depth and grain size. Most predictors are empirically fitted functions through data from different flume and river measurements. Others are based on theoretical considerations. The methods of Allen (1976), Van Rijn (1982) and Julien and Klaassen (1995) are discussed. Other steady flow methods for dune dimensions were developed by for example Yalin (1985) and Karim (1995, 1999).

3.5.1 Method of Allen

Allen (1976) developed a method for steady flow conditions in which the dune height depends on the water depth only. The method of Allen predicted most common dune heights and lengths correctly for the Rhine [Wilbers, 2004]. Allen described the dune dimensions by the following equations, which are valid in a range for the water depth (h) between 0.6 and 40 m:

\[
H = 0.086h^{1.19} \\
L = 1.16h^{1.55}
\]

(3.8)

(3.9)

3.5.2 Method of Van Rijn

Van Rijn (1982) studied the dimensions and effective roughness of bed forms. He assumed that the dimensions of bed forms are mainly controlled by the bed load transport rate. He defined a dimensionless particle parameter (Dₜ) and transport stage parameter (T), which describe the bed load transport rate (Appendix B). The relative dune height can be expressed as:

\[
\frac{H}{h} = F\left(\frac{D_{50}}{h}, D_*, T\right) = 0.11 \left(\frac{D_{50}}{h}\right)^{0.3} \left[1 - \exp(-0.5T)\right] [25 - T]
\]

(3.10)

In the same way, the dune height and dune length ratio is expressed as:

\[
\frac{H}{L} = F\left(\frac{D_{50}}{h}, D_*, T\right) = 0.015 \left(\frac{D_{50}}{h}\right)^{0.3} \left[1 - \exp(-0.5T)\right] [25 - T]
\]

(3.11)

In which H is dune height and D₅₀ is the median grain size.

Van Rijn defined three flow regimes: the lower, transition and upper regime. In the lower regime (at small Froude numbers), Van Rijn found that the dune type bed forms are dominant features for T smaller than 15 (Table 3.1). Only for particles
smaller than about 450 µm ($D_50 \leq 450 \mu m$), ripples are generated after initiation of motion, but become dunes for $T$ larger than about 3. The upper regime with plane bed and anti-dunes can be defined to occur for $T$ larger than 25. In the transition zone the bed configuration is somewhat obscure. It may range from that typical of the lower flow regime (dunes) to that typical of the upper flow regime (plane bed), depending mainly on the flow conditions (rising or falling stage).

<table>
<thead>
<tr>
<th>Lower regime</th>
<th>flow</th>
<th>$1 \leq D_50 \leq 10$ [(50 \leq D_{50} \leq 450 \mu m)]</th>
<th>$D_50 \geq 10$ [(D_{50} \geq 450 \mu m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition</td>
<td></td>
<td>$0 \leq T \leq 3$</td>
<td>Ripples</td>
</tr>
<tr>
<td>Flow regime</td>
<td></td>
<td>$3 \leq T \leq 15$</td>
<td>Dunes</td>
</tr>
<tr>
<td>Upper</td>
<td></td>
<td>$15 \leq T \leq 25$</td>
<td>Washed-out dunes and plane bed</td>
</tr>
<tr>
<td>Regime</td>
<td></td>
<td>$T \geq 25$</td>
<td>Plane bed and anti-dunes</td>
</tr>
</tbody>
</table>

Table 3.1: Classification of bed forms (source: Van Rijn, 1982)

### 3.5.3 Method of Julien and Klaassen

Several researches resulted in good fittings of the Van Rijn method for both flume data and field data [Wijbenga, 1990]. Nevertheless, Van Rijn (1982) underestimates the dune height of most large rivers and underestimates the dune steepness in sand bed rivers [Julien & Klaassen, 1995]. Therefore, Julien and Klaassen (1995) extended the applicability of the Van Rijn method, particularly at high values of $T$.

The analysis was focused on changes in dune geometry in the Rhine branches and the River Meuse during the 1988 flood. It could be concluded, regarding the applicability of a dune height parameter to large sand-bed rivers, that the parameter does not vary significantly with $T$. The dune height parameter remains relatively constant at values of $T$ exceeding 25 and the flow in the Rhine does not reach upper regime plane bed.

The Froude number in a flume is much higher for laboratory data than for field data and in laboratory channels the flow becomes critical ($Fr=1$) as $T$ approaches 25, which corresponds to Van Rijn’s upper regime plane bed. The Froude number in the Rhine is much smaller than in a flume, so no flat bed occurs. As a first approximation, the average dune height and the average dune length in large sand-bed rivers can be calculated by:

$$ H = \xi h \left(\frac{D_{50}}{h}\right)^{0.3} \quad (3.12) \quad L = \eta h \left(\frac{h}{D_{50}}\right)^{0.3} \quad (3.13) $$

With dune height coefficient $\xi$ and dune length coefficient $\eta$.

$0.8 < \xi < 8$ and $0.8 < \eta < 8$, with both the average value of 2.5.
3.6 Unsteady flow conditions

Discharges constantly vary and bed forms tend to adjust their size to the flow conditions. In unsteady flows, a specific combination of flow characteristics does not result in the same unique dune dimensions. Instead, the dune dimensions at a specific moment are greatly influenced by previous flow characteristics and dune development [Fredsøe, 1979]. Nevertheless, equilibrium dune dimensions may be reached in the unsteady flow in the Rhine at two moments. First, if the flow conditions are almost constant for a long time, for example during summer. This means that, at the start of the flood wave in autumn or winter, the dunes have reached equilibrium dimensions. The second moment of equilibrium dune dimensions occurs during a flood. When the discharge is already decreasing, the equilibrium conditions change, while the dune height is still increasing, because the equilibrium height corresponding to the occurring discharge is still larger than the actual dune height. At a certain point, the actual dune height reaches the equilibrium height corresponding to the current flow conditions of the decreasing discharge. From that moment, the dune height starts to decrease.

For unsteady, non-uniform flow conditions several prediction methods were developed. The methods of Fredsøe (1979), Allen (1976) and Wilbers (2004) are described.

3.6.1 Method of Fredsøe

Fredsøe (1979) gives a physical understanding of the process that modifies the dimensions of the individual dunes as the hydraulic conditions change. Before the change of discharge, the dune pattern is supposed to be in equilibrium. The initial change in dune height was related to total sediment transport. This resulted in the initial change in bed form height, formulated as:

$$\frac{dH}{dt} = \sqrt{\Delta gD_{50}} \left[ \frac{1 - (\theta F)_{\text{new}}}{(\theta F)_{\text{old}}} \right] \Phi \text{ with } F = \frac{1}{\Phi} \frac{d\Phi}{d\theta}$$ (3.14)

In which $\Delta = (\rho_s - \rho)/\rho$; $\varepsilon$ is the porosity; $F$ a friction factor; $\Phi$ the sediment transport parameter and $\theta$ the Shields parameter.

Bed load transport formulas, like Meyer-Peter & Müller (Appendix C), can be used to define the sediment transport parameter $\Phi$. Fredsøe (1979) concluded that the form drag mainly depends on the height of the dune. Bed load is assumed to be the dominant transport mechanism [Fredsøe, 1979].

3.6.2 Method of Allen

In addition to the method for steady flow conditions, Allen (1976) developed a method for unsteady flow conditions. It is a general step-by-step computational model of dune time lag in periodically varying unidirectional flows, based on existing knowledge of dune population dynamics and hydraulic controls. The model assumes the growth and decay of dunes to be a stochastic process and is furthermore based on the inability of the individual dune to respond perfectly to...
changes of the flow. During the growth of the dune, the dune dimensions correspond to the instantaneous flow conditions as if steady flow exists, so flow conditions are considered to be quasi steady. At each time step the equilibrium bed form dimensions are calculated from the water depth, according to Yalin’s (1985) relations:

\[
H(t)_\infty = b \cdot h(t) \quad \text{with } b = 0.167
\]
\[
L(t)_\infty = a \cdot h(t) \quad \text{with } a = 5
\]

The inability of the dunes to respond to the changing flow is expressed by:

\[
\frac{dH(t)}{dt} = \frac{Ac_b}{H(t)}(H_\infty - H(t))
\]

With A = coefficient of change (0 ≤ A ≥ 1); \(c_b\) is the migration celerity of the dune; \(H(t)\) the dune height at time step \(t\) and \(H_\infty\) is the equilibrium height for the occurring flow conditions. The influence of the dune size and sediment transport on the rate of change in bed forms dimensions have been ignored.

Wijbenga and Klaassen (1983) carried out a number of flume tests to compare the methods of Allen and Fredsøe and to study the changes in bed form dimensions due to a sudden increase or decrease in discharge. The flume tests were also done to verify whether a first order system for the growth of bed forms could be applied. The conclusions were:
- The coefficient of adaptation (A) for the dune height is higher for decreasing discharge than for increasing discharge, in the case of equal changes in water depth;
- The adaptation coefficient is not constant, but increases for increasing discharge variation;
- Fredsøe’s method does not adequately describe the observed increase and decrease of bed form dimensions during the described test, while a number of adaptations should be made to the model of Allen before it can be applied for the simulation of the time-dependent behavior of dune dimensions. The coefficient of adaptation should be known, but depends on the dune dimensions. A deviation in theory and experimental results was found especially for large decreases in the discharge.

### 3.6.3 Method of Wilbers

Wilbers (2004) adapted the method of Allen. He generated calculation models for dune height and dune length in two Rhine branches, based on the ideas of Allen, in which the rate of dune development depends on the difference between the dune dimensions before a change in flow conditions and the new equilibrium dimension belonging to those flow conditions (Appendix D). He integrated the function of Allen to:

\[
H(t) = H_{t-1} + (1 - \exp(-A\Delta t))(H_\infty - H_{t-1})
\]
The adaptation constant was determined directly from measurement data, with time step $\Delta t$ being one day. The difference in the development of dune height and length in the Rhine resulted in two different average adaptation constants; for the rising and the falling discharges of the Rhine. They were calculated by fitting the function $(1-\exp(-A\Delta t))$ from the equation above. This resulted in an average value for the adaptation constant of 0.12 for the dune height and 0.06 for the dune length valid for the Rhine between Lobith and the Pannerdensche Kop and any flood event.

There is no single predictor that predicts the observed dune height or length correctly at the two moments of equilibrium dune dimensions during any flood event. Therefore, the equilibrium dune dimensions have to be calculated with a set of two predictors. The model for predicting the dune dimensions in the Rhine between Lobith and the Pannerdensche Kop uses the equilibrium predictors of Van Rijn, mentioned in the previous paragraph, and an adjusted predictor of Tsuchiya, which is described as follows.

$$H = h \times F_r^2 \times \left(1 - \frac{1}{\beta^2} + 2(1 - \beta)\right)$$

(3.19)

Wilbers adjusted this method by replacing the last term by $\alpha = 0.9$ (Appendix D). The calculation of dune height starts with the equilibrium height of the adapted Tsuchiya method at the beginning of a flood event. When the discharge increases, the dune height is calculated with the following equation, still using the adapted Tsuchiya equilibrium height.

$$H(t) = H_{t-1} + (1 - \exp(-0.12\Delta t))(H_{eq} - H_{t-1})$$

(3.20)

When the bed shear stress exceeds 10 N/m$^2$, the equilibrium dune height of Van Rijn is used. At falling flood, when the bed shear decreases below 13 N/m$^2$, the equilibrium height of the adapted Tsuchiya is used again. The bed shear stress for the unsteady flow conditions is determined by a formula, which is based on a fit through the graph of bed shear stress against discharge. This method could be limited and not valid for the high discharges of the climate change scenarios.

### 3.7 Conclusion

Different methods were developed for the calculation of dune dimensions. Methods for steady flow conditions predict the equilibrium dune dimensions that correspond to the instantaneous flow conditions. However, dune development lags behind the flow conditions, because the change of dune volume takes time to adapt. Therefore, dune dimensions never reach equilibrium immediately.

Methods for unsteady flow conditions were developed by for example Fredsoe (1979), Allen (1976) and Wilbers (2004). Wijbenga and Klaassen (1983) tested the methods of Fredsoe and Allen and concluded that the method of Fredsoe did not describe the dune dimensions correctly and is therefore not suitable for predicting
dune heights. The method of Allen needed to be adapted, before it could be used for predictions.
The method of Wilbers (2004) was based on the method of Allen and is suitable for predicting dune dimensions in the Rhine branches in the Netherlands. Wilbers concluded that his model accurately simulate the trends of dune development, the moments of maximum dune dimensions and the occurrence of superposition of secondary dunes. For the Bovenrijn, the method overestimates the dune height. The grain size was presumed constant, caused by a lack of measurement data on changes in grain size during flood events. The method of Wilbers (2004) can be used events to predict the dune dimensions in the Rhine branches in future flood [Wilbers, 2004]. Therefore, in this study this method is used to calculate the development of dune height during a flood in the Bovenrijn.
4 Navigation

4.1 Introduction
The Rhine is a very important inland waterway for freight traffic towards Europe. The maximum loading of a ship depends on the minimum water depth on the route the ship is traveling. This water depth, at a certain location on the route, is normative for the loading capacity of the ship. When the depth is too low, navigation can be hindered, which results in a restriction of the loading capacity. River dunes are possibly significant in the restriction of the water depth. In order to determine the hindrance of navigation, a normative ship on the Rhine is supposed. The hindrance of navigation can be described in terms of loading capacity compared to the restricted water depth.

4.2 Navigation on the Rhine
The Rhine, as a waterway, is of large economic importance for the Netherlands, linking the world port of Rotterdam to the Ruhr area and central Europe as far as Basel. The inland waterways handle about 40% of the nation’s international freight traffic and 20% of domestic freight traffic. An annual total of about 290 million tonnes of freight travels along the inland waterways and in the next 25 years, the annual volume of freight traffic by inland navigation in the Netherlands is expected to rise to over 350 million tonnes [Middelkoop & Van Deursen, 1999]. Some 165000 vessels pass Lobith every year; they come in all shapes and sizes. The Conference of European Ministers of Transport (CEMT) has divided the vessels on the Rhine into types and classes, which was last changed in 1992. Table 4.1 gives a summary of the so-called CEMT-classes of vessel types on the Rhine.

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Vessel length [m]</th>
<th>Vessel width [m]</th>
<th>Vessel depth [m]</th>
<th>Load [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Spits</td>
<td>38</td>
<td>5.0</td>
<td>1.8 - 2.2</td>
<td>30</td>
</tr>
<tr>
<td>II</td>
<td>Kempenaar</td>
<td>50</td>
<td>6.6</td>
<td>2.5</td>
<td>600</td>
</tr>
<tr>
<td>III</td>
<td>Dortmund-Eemscanal</td>
<td>67</td>
<td>8.2</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>IVa</td>
<td>Rijn-Herder ship</td>
<td>80</td>
<td>9.5</td>
<td>2.5</td>
<td>1350</td>
</tr>
<tr>
<td>IVb</td>
<td>Push, 1 barge</td>
<td>85</td>
<td>9.5</td>
<td>2.5 - 2.8</td>
<td>1250 – 1450</td>
</tr>
<tr>
<td>Va</td>
<td>Large Rhine vessel</td>
<td>95</td>
<td>11.4</td>
<td>2.5 - 2.8</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>Push, 1 barge</td>
<td>95 – 110</td>
<td>11.4</td>
<td>2.5 - 4.5</td>
<td>1600–3000</td>
</tr>
<tr>
<td>Vb</td>
<td>Push, 2 barges (long)</td>
<td>170 – 185</td>
<td>11.4</td>
<td>2.5 - 4.5</td>
<td>3200–6000</td>
</tr>
<tr>
<td>VIa</td>
<td>Push, 2 barges (wide)</td>
<td>95 – 110</td>
<td>22.8</td>
<td>2.5 - 4.5</td>
<td>3200–6000</td>
</tr>
<tr>
<td></td>
<td>Motor vessel</td>
<td>140</td>
<td>15.0</td>
<td>3.2 - 3.5</td>
<td>3300–6000</td>
</tr>
<tr>
<td>VIb</td>
<td>Push, 4 barges</td>
<td>185 – 195</td>
<td>22.8</td>
<td>2.5 - 4.5</td>
<td>6400–12000</td>
</tr>
<tr>
<td>VIc</td>
<td>Push, 6 barges (long)</td>
<td>270 – 280</td>
<td>22.8</td>
<td>2.5 - 4.5</td>
<td>9600–18000</td>
</tr>
<tr>
<td></td>
<td>Push, 6 barges (wide)</td>
<td>193 – 200</td>
<td>34.2</td>
<td>2.5 - 4.5</td>
<td>9600–18000</td>
</tr>
</tbody>
</table>

Table 4.1: Vessel types on the River Rhine
The active Dutch fleet consists mostly of large vessels from class III (22.5%), IV (22.7%) and V (21.1%) [Van Bennekom et al, 2001].

The critical water depth in the Rhine at Lobith is 2.8 m, which is the depth at minimum loading capacity [Middelkoop & Van Deursen, 1999]. The water level corresponding to that depth is called the Agreed Low Water level (Overeengekomen Lage Rivierstand (OLR) in Dutch). On average, the water level is higher than the OLR for about 95% of the time [CCR, 1997]. Due to riverbed decrease, the OLR is changed every ten years. Since 2002, OLR with a water level of 7.52 m +NAP is agreed at Lobith.

For this research, vessels from class V are supposed as the normative ships on the Rhine. The depth of these vessels is given 4.5 m at maximum loading capacity, according to Table 4.1. However, the actual depth of most class V ships is 4 m, so this is assumed to be the normative depth. The vessels are hindered when the water depth is smaller than 4 m, because then the loading capacity decreases.

Both extremely high and low water levels can hinder inland navigation. During flood periods, navigation can be brought to a stop for safety reasons, and during periods of extremely low discharge, ships can only use very little of their capacity or cannot navigate at all.

As a part of the NRP program, described in paragraph 2.2, the effect of climate change on navigation was also investigated [Middelkoop & Van Deursen, 1999]. In scenario A, discharges increase in winter and decrease in summer. Climate change causes more frequent periods of reduced water depth for navigation and these periods may last longer. These changes are unfavorable for navigation in general.

The consequences of these hydrological changes are [Middelkoop & Van Deursen, 1999]:

- The cargo capacity decreases due to increased drought with decreased discharge, because low discharges occur more often and then especially the large vessels cannot be fully loaded;
- The hydrological changes caused by climate change substantially increase transport costs by inland shipping in the case of an inflexible inland shipping sector. When the shipping sector does not change, for example the distribution of vessel types, the costs increase, because large vessels have more problems, because of their larger depth. If the sector changes the distribution and for example more small vessels are used, the damage may be less.

Thus, it is expected that hindrance of navigation occurs more often, due to climate change. River dunes can possibly increase that hindrance.

4.3 **Restriction of loading capacity**

In order to determine a rough estimate of the effect of river dunes on the navigation depth, the restriction of the loading capacity will be calculated in Chapter 6. The calculation method is based on the depth at maximum loading and the restriction of the depth, compared to the minimum navigation depth for maximum loaded ships of class V [Van Toorenburg, 2000]. The minimum depth of an empty class Vb push barge is 1.8 m and the required maximum depth of a class V vessel is 4 m. The wake depth (K), between the bottom of the ship and the
riverbed, is 0.2 m for class V ships on the Rhine, but that also depends on the journey the ship is going to make and the possible restrictions of the depth on the way [Van Toorenburg, 2004]. The percentage of the restriction of the loading capacity ($L_m$) is calculated with Equation 4.1.

\[
L_m = \frac{T_v - T_n}{T_m - T_i}
\]  

(4.1)

In which:

\[
T_v = r \times D_{\text{max}} + K  
\]  

(4.2)

\[
T_n = h  
\]  

(4.3) or \[
T_n = h - \frac{1}{2}H  
\]  

(4.4)

\[
T_m = D_{\text{max}} + K  
\]  

(4.5)

\[
T_i = D_{\text{min}}  
\]  

(4.6)

The different depths are visualized in Figure 4.1. $T_v$ is the required water depth for fully loaded vessels of class V, with a value of 3.8 m, determined by the loading rate ($r = 0.9$) and the maximum depth of the normative class V ship ($D_{\text{max}} = 4$). The loading rate ($r$) indicates that the depth of ships is never precisely 4 m at a loading of 100%. $T_n$ is the actual depth, which can be taken with and without the dune height, to determine the actual effect of river dunes. $T_m$ is the maximum required water depth for navigation, which is 4.2 m. $T_i$ is the ship depth of an empty class V vessel, which is 1.8 m (including wake depth).

For example; if the water depth is 3.7 m, the restriction of the loading capacity is calculated as follows.

\[
\frac{3.8 - 3.7}{4.2 - 1.8} = 0.042
\]

So the loading capacity is restricted with 4% at a water depth of 3.7 m.

Figure 4.1: Visualization of maximum, minimum and actual vessel depths and water depth
5 Effect of climate change on discharge and water depth

5.1 Introduction
As discussed in Chapter 2, the effect of climate change on discharges in the Rhine is forecasted with multiplying factors of two scenarios. These factors can be used on both average and individual discharges of arbitrary time periods. Three time periods of individual discharges, called base years, are used for the prediction of discharges. The determination of the base years requires attention for the return period of the occurred peak discharges. This is discussed more extensively. The water depths, corresponding to the discharges of the scenarios, are calculated with Sobek. The results of these calculations are used in Chapter 6 for the prediction of dune heights.

5.2 Selection of base years
There are four important criteria in the selection of base years used for the calculation of discharges for the scenarios:
- Data should not be outdated because the climate is already changing. Hence, recent data is used from a dataset of discharges (Figure 5.1) and water levels (Appendix E) from 1990 to October 2003.
- The peak discharge should be high enough for dunes to develop, i.e. over 7000 m³/s, according to the echo-sounding results [Wilbers & Ten Brinke, 2003].
- The rate of decrease of the discharge after the peak is taken into account, considering the time lag of the dune development.
- Finally, the return period [Berger et al, 2001] of the peak discharge is important for the possible occurrence of such a peak in the future.

Figure 5.1: Dataset of discharges from 1990 to 2003 (J = January)
Each discharge has a certain return period. The effect of climate change on the return periods result in higher discharges at unchanged return period (Figure 5.2), as higher discharges occur more often as a result of more precipitation. The return period of a high discharge, for example 12000 m$^3$/s, is 50 years, so it does not occur very often. When a discharge with such a return period is upgraded in a climate change scenario, it should be taken into account that the predicted discharge has the same return period of 50 years and it still represents an extreme situation. Therefore, the occurrence of the discharge should be considered in order to determine a plausible effect of climate change. The return periods for Scenario B are given in Appendix F.

Discharges of about 7000 m$^3$/s and higher occur very often; on average about once every 2 years (Figure 5.2). In the 14 years between 1990 and 2003 it occurred 10 times (Figure 5.1). Very high discharges, with a return period of about 50 years, occurred in 1993 and 1995. Peak discharges of about 9000 m$^3$/s, which occurred in 1998 and 2003, have a return period of 10 years. Some discharges decrease fast and some are followed by another, smaller, peak. The selection resulted in the following base years (Figure 5.3):

- 1991: the peak discharge is about 7000 m$^3$/s and has a return period of 2 years. The discharge decreases within a month to 1000 m$^3$/s. The discharge pattern of this year is also representative for 1990 and 1997;
- 1995: the peak discharge is extremely high and has a return period of 50 years. The peak is steep, after which the discharge drops within two weeks to 4000 m$^3$/s, and after that to 2500 m$^3$/s. This is an interesting base year, to look at extreme situations that occur not very often. This is also representative for 1993;
2003: the peak discharge is 9000 m³/s, which is in between the peaks of 1991 and 1995. The return period is 10 years. This year has an extremely dry period that starts already in April. The discharge decreases within three weeks to 3000 m³/s in January. This base year has the same order of peak discharge as 1998, 2001 and 2002, but the rate of decrease is higher.

![Discharges at Lobith](image)

**Figure 5.3: Discharges of the Rhine from the base years 1991, 1995 and 2003 at Lobith**

### 5.3 Calculation of discharges for the scenarios

#### 5.3.1 Scenario A

This scenario predicts higher discharges in winter and lower discharges in summer, as discussed in Chapter 2. The expected discharges for 2050 and 2100, based on this scenario and base year 1991, show large changes in January and December (Figure 5.4). The peak discharge in January for the years 2050 and 2100 can cause high river dunes.

The discharges of Scenario A2 for base year 1995 (Appendix G) show a very extreme peak of about 18000 m³/s. The discharge drops fast afterwards, which could give interesting results for the influence of river dunes on the water depth. On the other hand, it is taken into account that other events could happen at such an extreme discharge, for example flooding in Germany, and the results for the development of river dunes can be very different.

Scenario A2, for base year 2003 (Appendix G) results in a discharge in January of about 14000 m³/s. Such a peak discharge is an extreme discharge and did not occur in the dataset of 1990 to 2003. The Bovenrijn should be able to handle that peak discharge as the height of the embankments is based on a design discharge of
about 15000 m$^3$/s. For Scenario A1, the discharge results in a peak of 11000 m$^3$/s that reduces to 3000 m$^3$/s.

![UKHI scenario for base year 1991](image)

**Figure 5.4: Discharges at Lobith for Scenarios A1 and A2 with base year 1991**

### 5.3.2 Scenario B

The results for base year 1991 are shown in Figure 5.5. Scenario B2 results in largest differences for the summer months. The results for Scenario B1 are not significant, as the peak discharge increases with only 5%. For Scenario B3 (Appendix H), the changes are not significant either. The peak discharge for Scenarios B3 and B4 rises to about respectively 7500 m$^3$/s and 8000 m$^3$/s, but during the rest of the year there are no important changes for both scenarios. Scenario B5 results in a peak discharge of 10500 m$^3$/s.

The Scenario B results for the base year 1995 (Appendix I) give a change of 500 m$^3$/s for the peak discharge of Scenario B1, an increase of 3000 m$^3$/s for Scenario B4 and an increase of 6000 m$^3$/s for Scenario B5. The summer discharge for Scenario B2 decreases with about 500 m$^3$/s. In comparison with Scenarios B4 and B5, Scenario B1 does not seem to be significant.

The results for base year 2003 (Appendix J) show that the peak discharges do not change significantly for Scenario B1 again. The peak discharges for Scenarios B4 and B5 are respectively 14500 m$^3$/s and 18500 m$^3$/s. These changes are in the order of 2000 m$^3$/s and more significant than a change of 500 m$^3$/s.
5.4 Calculation of the water depths

The actual discharges of the base years and the scenario discharges for each base year are input in the calculation of water depths, which is done with the modeling system Sobek. Sobek is a one-dimensional open-channel dynamic numerical modeling system, which is capable of solving the equations that describe unsteady water flow, salt intrusion, sediment transport, morphology and water quality. It was developed by WL | Delft Hydraulics in full partnership with the Institute for Inland Water Management and Waste Water Treatment (RIZA) of the Dutch government. A model of the Rhine branches in the Netherlands was available. A calculation of water levels is compared to measured levels [Waterbase, 2003] in order to determine the preciseness of the prediction with Sobek. Next to that, the way of comparing the water depth and the height of river dunes is explained, because Sobek generates an average water depth. Then the water depths are calculated. Next to the water depth, output was obtained for the flow velocity, Chézy coefficient, Froude number and the discharge, which are parameters needed for the prediction of dune heights.

5.4.1 Comparison of calculated and actual water levels

Water levels are calculated with Sobek, with the input of actual discharges. The calculated levels are compared to the actual levels. Differences could influence the prediction of dune heights. Next to that, the model of the Rhine branches contains lateral discharges. These may change as a result of climate change. While there is no information about the impact of climate change on the lateral discharges of the
Rhine branches in the Netherlands, the significance of these discharges to the water levels in the Bovenrijn is determined.

The water depth by Sobek is underestimated with about 0.2 m for lower depths. This should be taken into account in analysing results for dune heights. The maximum water levels are predicted very precise (Figure 5.6), which may be explained by the fact that Sobek is often used for the prediction of high water levels at floods. It is probably calibrated to maximum water levels, which could explain the underprediction of low water levels. The influence of the lateral discharges of the Rhine branches in the Netherlands turns out to be insignificant. The calculated water levels with and without the lateral discharge, in Figure 5.6, do practically coincide. Climate change effects on the lateral discharges are therefore neglected.

![Water levels at Lobith 1991](image)

**Figure 5.6: Water levels at Lobith in the Rhine in 1991, actual levels compared to calculated levels by Sobek**

Similar conclusions can be drawn from the comparison of water levels for the base years 1995 and 2003 (Appendix K). Another comparison was made for possible differences between Lobith and the Pannerdensche Kop (Appendix L), only for base year 1991. Sobek also underestimates water levels at the Pannerdensche Kop; there is no significant difference with Lobith.

### 5.4.2 Water depth versus dune height

The water depth generated by Sobek is an average water depth; local changes in the riverbed, like dunes, are not taken into account. Sobek assumes the riverbed to be flat on the middle of the dune, so the dune amplitude is neglected (Figure 5.7).
Therefore, in order to compare the dune height with the water depth, the dune amplitude (half the dune height) has to be taken. The actual water depth is determined by subtracting the dune amplitude from the water depth generated by Sobek [WL Delft Hydraulics].

### 5.4.3 Effect of changing discharges on the water depth

The effect of climate change on the water depth is related to the effect on discharges, according to the relation $Q = u^*B^*h$. Hence, the water depths for the different scenarios show identical changes of climate change as discharge. In the Scenario A the water depth increases in winter and decreases in summer. It decreases the entire year as a result of Scenario B2 (Figure 5.8). The results for base years 1995 and 2003 are given in Appendix M. Low water depths occur earlier, especially for Scenario B2, but also for Scenario A. Low water levels are achieved earlier, because the discharges decrease in summer.
5.5 Comparison of scenarios

In comparison, Scenario A and Scenario B give roughly the same results: the discharges with a return period of 2 years increase to such an extent that they can be important discharges in the development of river dunes in the future. Scenario B gives more sub-scenarios, because next to the high estimations of climate change for the years 2050 and 2100, the low and central estimates for 2050 and 2100 are taken into account.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual discharge</td>
<td>7*10³</td>
<td>12*10³</td>
<td>9*10³</td>
</tr>
<tr>
<td>Scenario A1</td>
<td>8*10³</td>
<td>14*10³</td>
<td>11*10³</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>10*10³</td>
<td>18*10³</td>
<td>14*10³</td>
</tr>
<tr>
<td>Scenario B1</td>
<td>7*10³</td>
<td>13*10³</td>
<td>10*10³</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>6*10³</td>
<td>11*10³</td>
<td>9*10³</td>
</tr>
<tr>
<td>Scenario B3</td>
<td>7.5*10³</td>
<td>12*10³</td>
<td>10*10³</td>
</tr>
<tr>
<td>Scenario B4</td>
<td>8*10³</td>
<td>15*10³</td>
<td>12*10³</td>
</tr>
<tr>
<td>Scenario B5</td>
<td>10*10³</td>
<td>18*10³</td>
<td>15*10³</td>
</tr>
</tbody>
</table>

Table 5.1: Results for peak discharges of UKHI and Perspective scenarios

Only Scenario A1, A2, B4 and B5 give significant changes of the peak discharges and the scenarios are similar. Consequently, Scenario A is used, as a representative climate change scenario, in the calculation of dune heights. Scenario B2 is also applied to take into account another prospect of climate change, although the discharge changes in summer are only in the order of 100 m³/s.
6 Effect of climate change on river dunes and navigation

6.1 Introduction
The development of river dunes and their dimensions depend on flow conditions, for example the water depth, discharge and Froude number. The method of Wilbers (2004) is used to calculate dune heights for Scenario A and B2 for each base year. In order to give insight in the influence of climate change on the effect of river dunes on navigation, the resulting dune heights are analyzed thoroughly. The effect of climate change on dune height and time lag is discussed. The dune height is calculated for 9 locations in the Rhine between Lobith and the Pannerdensche Kop and the significance of the dune amplitude compared to the water depth is determined. Superposition of secondary dunes may influence the water depth in addition to the primary dunes. It is a process that complicates the calculations. Superposition is described and its significance is discussed. Finally, the effect of dune height on the depth for navigation is determined and discussed.

6.2 Calculation of the dune heights

6.2.1 Influence of Froude number on dune height calculation
The calculation of dune height showed some odd results at a certain location in the Rhine. The dune height decreased where it should be at its maximum. The output of the Froude numbers from Sobek resulted in much higher values than the results for the Froude number calculated by Equation 5.1. This caused the irregular results.

\[
Fr = \frac{u}{\sqrt{gh}} \quad (5.1)
\]

Sobek calculates the water depth \( h \) in the Froude number not with the water depth in the main channel, but with the flow area and storage width, as is shown in Equation 5.2.

\[
Fr = \frac{u}{\sqrt{\frac{gA_f}{W_t}}} \quad (5.2) \quad A_f = \text{flow area} \quad W_t = \text{storage width}
\]

The storage width can be very different from the width of the flow area at different locations in the Rhine (Appendix N), so the calculated Froude number is not the Froude number of the main channel. The main channel is the main issue. Therefore, the Froude number is calculated with Equation 5.1, with the velocity and water depth generated by Sobek.
6.2.2 Calculation of the bed shear stress

In the model of Wilbers (Appendix D), the use of the equilibrium predictor is determined by the value of the bed shear stress. As described in Chapter 3, the boundaries are 10 N/m² for rising flood and 13 N/m² for falling flood. In order to determine the bed shear stress in unsteady flow, Wilbers uses a formula, based on a fit of the bed shear stress against discharge. The discharges that occur in the climate change scenarios of this research do not connect to the method that Wilbers used. The dune heights are not predicted correctly with this method. Therefore, the bed shear stress is calculated with Equation 3.3, depending on the density of water and the shear velocity, assuming quasi-steady flow [Ribberink, 2002].

6.2.3 Analysis of dune heights

The results for the dune height at Lobith for base year 2003 are shown in Figure 6.1. The Scenario B2 results show a lower dune height, which is to be expected, because the discharge at the flood event decreases with 5%. The effect of the higher discharges, as predicted by Scenario A, on the dune height is clearly perceptible; the dune height is larger, in response to the higher discharges. The effect of Scenario A2 is the most extreme, which corresponds with the extreme changes of the discharge for this scenario, which is for the year 2100. Although the peak of the discharge occurs at the same day in the scenarios (indicated by the dashed line in Figure 6.1) the top of the dune is reached later for Scenario A1 and A2. This means that the time lag increases at increasing dune height. This occurs for every base year and in particular for base year 1991 at the Pannerdensche Kop (Appendix O). The time lag even increases with a week.

![Figure 6.1: Dune height for different scenarios of base year 2003, at Lobith. The dashed line indicates the date of the peak discharge.](image)
The increase of the time lag can be explained by the fact that the new flow conditions of the scenarios relate to higher equilibrium dune height, even at falling flood. The bed shear stress at falling flood is above 13 N/m² for a longer period and so the dune height is still calculated with the Van Rijn method (Figure 6.2). As the method of Van Rijn predicts a higher equilibrium height than the equilibrium height of the adapted Tsuchiya method, the growth of the dune continues for a longer period of time. When the bed shear stress is smaller than 13 N/m², the decay of the dune starts. The adapted Tsuchiya determines the equilibrium dune height, which is lower than the actual height, so the dune height decreases towards this equilibrium very quickly.

The dune height for the scenarios of base year 1991 (Appendix O) show similar results as for base year 2003, except for Scenario B2. For Scenario B2 the time lag of the dune development is larger than for the base year, but the maximum dune height is similar. This is possibly caused by the fact that the graph does not have an exponential course.

The dune height for base year 2003 at the Pannerdensche Kop (Appendix O) shows expected results of smaller dune height and time lag for Scenario B2 and larger dune heights and time lags for Scenario A1 and A2.

The scenarios of base year 1995 (Appendix O) show similar results, but the changes for dune height are smaller. This is clearly perceptible in Table 6.1, in which the dune height per scenario at two locations at the Rhine is shown. The dune height can be different for every location at the Rhine, due to small changes in the cross-section.

The dunes for base year 1991 have the smallest dune heights and base year 1995 results in the largest dunes (Table 6.1). This is to be expected, because the peak discharge in 1991 was the smallest and the peak discharge of 1995 was the largest discharge, of the three base years.
Table 6.1: Maximum dune heights in the Rhine, base years and climate change scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum dune heights (m)</th>
<th>Base year</th>
<th>Scenario B2</th>
<th>Scenario A1</th>
<th>Scenario A2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1991</td>
<td>2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobith</td>
<td>0.8</td>
<td>0.8</td>
<td>1</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Pannerdensche Kop</td>
<td>0.8</td>
<td>0.8</td>
<td>1.1</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Lobith</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Pannerdensche Kop</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Lobith</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Pannerdensche Kop</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

The difference between the maximum dune heights of base years 1995 and 2003 for Scenario A2 is very small, but the increase of the dune height of base year 2003 for Scenario A2 is much larger than the increase for the dune height of base year 1995 (Table 6.1). The magnitude of this increase depends on the proportion of the dune height in relation to the equilibrium height that corresponds to the peak discharge. Next to that, the growth rate of the dune height is exponential, so it is fast for initial growth and slow when the maximum dune height is closer to the equilibrium height. For example, in 1991 the dune height at 7000 m$^3$/s reaches 40% of the equilibrium height (that corresponds to 7000 m$^3$/s) (Figure 6.3). When the discharge increases to 10000 m$^3$/s the dune height increases with about 0.6 m. For 1995, the dune height at 12000 m$^3$/s reached about 80% of the equilibrium height and the increase of dune height for a discharge of 18000 m$^3$/s was only 0.2 m (Appendix P).

It can be concluded that the growth rate at a discharge of 7000 m$^3$/s is larger than the growth rate at a discharge of 12000 m$^3$/s, because the increase of the dune height is more for base year 1991.

![Figure 6.3: Calculated dune height versus dune height at constant Q for base year 1991 and Scenario A2. The dashed line indicates the date of the peak discharge](image-url)
The increase of the discharge causes, next to the increase of the calculated dune height, a higher equilibrium dune height. The increase of the calculated dune height is larger than the increase of the equilibrium dune height (Figure 6.3). The growth of the equilibrium dune height in 2100 is much faster than the growth of the equilibrium dune height of the base year 1991. This explains that the maximum calculated dune height is much higher for Scenario A2 (Figure 6.3).

The discharge for base year 1995 increases with about 6000 m³/s in Scenario A2, but the equilibrium height does not seem to increase (Appendix P). This indicates that the dune height is limited, according to the calculation model.

### 6.2.4 Dune amplitude versus water depth

Compared to the water depth, the dune amplitude does not seem to be very significant at first sight (Figure 6.4). The time lag in the growth of the dune is clearly perceptible for Scenario A2 for base year 2003, as described above. After one week the dune amplitude is decreased by half and after a month the dune amplitude is 0.1 m. The water depth is still about 10 m at that moment. The other scenarios for 2003 show similar results for the growth, as well as the decay of the dunes (Appendix Q). For Scenario A2 for base year 1995 (Appendix R), the dune amplitude shows some small peaks before the peak discharge occurs, but decreases to 10 cm in about a month. After a few months, the dune amplitude is about 0.04 m. This occurs from the end of March. The results for base year 1991 (Appendix S) are less extreme. The dunes are smaller and the effect on the water depth seems insignificant.

![Dune height at Lobith](image)

*Figure 6.4: Half dune height, compared to the water depth in 2100 at Lobith, for base year 2003*
6.3 Superposition of secondary dunes

Secondary dunes develop at falling flood, when the bed shear stress decreases to less than 10 \text{N/m}^2 [Wilbers, 2004]. These dunes could influence the water depth for navigation in addition to the amplitude of the primary dunes.

This is a very difficult process and it is unclear why superposition occurs in the Rhine [Julien et al, 2003]. It is possible that the superimposed dunes are the bed forms that should be present under the governing flow conditions. The conditions change fast, so the development of the primary dunes cannot keep up and they become relicts as new, smaller dunes, develop [Allen & Collinson, 1974]. Another possibility is that the largest bed forms alter the local flow in such a way that bed forms with smaller dimensions, or even other types of bed forms, can develop on top of the larger ones. Superposition complicates the calculation of dune characteristics and dune migration rate. In the Rhine, secondary dunes cover the upstream side of the dune, but they only influence the water depth when they also cover the crest of the dune. Therefore, the abundance of the secondary dunes is calculated. It is assumed that, if the abundance is larger than 80\%, dunes cover the crest of the primary dunes [Wilbers, 2004]. This occurs when \( \frac{H}{L} \) is smaller than 0.01. The abundance is expressed with the following equation.

\[
Abundance = \frac{N_s \cdot L_s}{L_{\text{prof}}} = 0.0014 \left( \frac{H}{L} \right)^{-1.41}
\]

(6.1)

Where \( N_s \) is the number of secondary dunes in the profile, \( L_s \) is the average length of the secondary dunes and \( L_{\text{prof}} \) the total length of the profile. Another process is the disappearance of primary dunes at \( \frac{H}{L} < 0.01 \). This happens at the same time, when the abundance of the secondary dunes is 100\% and the transition occurs from primary to secondary dunes. After the transition, the height of secondary dunes (\( H_s \)) is approximately the same as the calculated height of the primary dunes (Figure 6.5). The primary dunes disappear at the moment the secondary dunes could possibly have effect on the water depth. Then secondary dunes have a similar height as the calculated primary dune height. The effect for the navigation depth is not noticeable and secondary dunes are not further considered.

![Figure 6.5: Height of primary (H) and secondary dunes (H_s)](image-url)
6.4 The effect on navigation

According to paragraph 6.2, the dune height is not very significant compared to the water depth. In general when dunes are large, the water depth is large too and navigation is not hindered. When the water depth decreased to about 4 m, the dunes have decayed significantly. The decrease of the water depth below 4 m occurs in August for base years 1991 and 1995 and in June for base year 2003. As described in Chapter 5, these low discharges become even lower and the period of water depths below 4 m is reached sooner, due to climate change.

The water depth will be lower for longer periods in the future. The method for calculating the restriction of the loading capacity \( L_m \) is described in Chapter 4. The effect of climate change and the effect of river dunes on the restriction of loading capacity for navigation are calculated with Equation 6.2.

\[
L_m = \frac{T_v - T_n}{T_v - T_l}
\]

In which:
- \( T_v = r*D_{\text{max}} + K = 3.8 \text{ m} \)
- \( T_n = h \text{ or } h - \frac{1}{2}H \)
- \( T_m = D_{\text{max}} + K = 4.2 \text{ m} \)
- \( T_l = D_{\text{min}} = 1.8 \)

The effect on navigation was calculated for Scenario A1 and Scenario A2 for the three base years (Appendix T). The effect of climate change is noticeable for base year 1991 (Figure 6.6); the loading capacity decreases with maximum 20% during summer. In June, there is little restriction for Scenario A2 and not for the base year, because the decrease of discharge by climate change causes a water depth below 4 m. In December, the loading capacity is restricted for base year 1991 and not for Scenario A2, because due to climate change the discharge increases during winter and the water depth is therefore larger for the scenario. There is no restriction of the depth for navigation in December for the scenario.

The effect on navigation of climate change for base year 1995 shows that during August and October, the loading capacity is restricted for Scenario A2. In the base year, a small restriction occurs only in October. The difference is about 10% to 15%. For base year 2003, the maximum restriction of loading capacity is about 30%. Scenario A2 predicts even lower discharges in summer and consequently the maximum loading capacity decreases to about 50%.
Unlike the noticeable effect of climate change on the hindrance of navigation, the influence of river dunes on the hindrance of navigation is found not significant. The effect of river dunes is in the order of 1% for all three base years. The restriction by river dunes is indicated by $x_1$ for the base year and $x_2$ for Scenario A2 in Figure 6.6. It seems that $x_1$ is even larger than $x_2$, which could mean that the effect of river dunes on the hindrance of navigation is decreasing due to climate change. Nevertheless, the effect is not significant compared to the effect of climate change.

The effect of climate change on the hindrance for navigation is clearly perceptible. The impact of river dunes, on the other hand, is insignificant; the order of 1 or 2% is negligible at an accuracy of 5%, as supposed at the climate change scenarios in Chapter 2.
7 Discussion of the results

7.1 Introduction

We determined the effect of climate change on the hindrance for navigation by river dunes. The three parts of the research are (1) the effect of climate change on the river discharge in the Rhine at Lobith, (2) the effect of changing flow conditions on the development and dimensions of river dunes and (3) the effect of river dunes on the restriction of the water depth for navigation. In this chapter, the results are discussed and the possible effects of certain choices and factors are described.

7.2 Climate change and discharge scenarios

7.2.1 Scenarios

The base of this research is climate change, which directly indicates a large uncertainty, because climate change is difficult to predict. There are both proponents and opponents of prediction of expected global temperature rise. Opponents do not believe that the global temperature rise is strengthened by human activities. However, in this research climate change is assumed to be true. The climate change scenarios are chosen on the basis of the results of Rhineflow \[Asselman et al, 2000\], which restricted the range of available scenarios for this research.

The elimination of Scenario B from the calculation of dune heights should not affect the results, because the resulting dune heights for Scenario A turned out to have no significant influence on the hindrance of navigation. Scenario A distinguishes three parts in the Rhine catchment, which gives reliable results.

The scenarios result in multiplying factors, which were multiplied with the discharges of three base years. Therefore, the discharge patterns are the similar to the patterns of the base years. This means that the possible of effect of climate change on changes in discharge patterns are not taken into account. Different discharge patterns may influence the results. For example when a peak discharge occurs for a longer period of time, the time lag of the dune development might increase. In combination with, for example, a fast decrease of the discharge after the peak, river dunes may have effect on the water depth for navigation.

Higher discharges that occur in the scenarios could hinder navigation anyway, because at high water depths, it could be dangerous to navigate. This should also be taken into account when looking at the hindrance of navigation.

7.2.2 Modelling with Sobek

Sobek is a widely accepted and applied modelling system. Note that, the boundary conditions in the model of the Rhine branches were not adapted to climate changes; only the discharge at the upstream boundary was adapted to climate change. Boundary conditions are, for example, the water level at Kattendiep,
Keteldiep and the port of Rotterdam, and also the regulation of the weirs in the Nederrijn at Driel, Amerongen and Hagestein. As a result of climate change, these boundaries could change, which may influence the water depth in the Bovenrijn. On the other hand; the Bovenrijn is not close to the downstream boundary conditions, so it can be expected that the influence on the water depth of changing boundary conditions is not very significant. Moreover, Q-h relations determine several boundary conditions through which the effects of climate change are taken into account anyway.

Soebek underestimates the water levels in the Bovenrijn at low discharges. High water levels at peak discharges are simulated correctly, which indicates that the model is calibrated on high discharges. The prediction of dune heights is supposed to be accurate and not influenced by this. At low discharges, when the water depth is underestimated, dunes do not influence the water depth, as the actual water depth is higher than predicted.

7.3 Calculation of dune heights

The method of Wilbers gives reasonable results for river dune heights in the Rhine, but it overestimates the dune height [Wilbers, 2004]. This means that the dunes are actually even lower, so the influence of dunes is less significant.

The adaptation of the Tsuchiya method by Wilbers seemed to have accurate results. However, the method was calibrated with few data, which indicates an uncertainty. For extreme large discharges the method results can be doubted; it is unsure whether the development of river dunes shows the same behaviour as for lower discharges.

The adaptation of the calculation of the bed shear stress extended the utility of the method for this research.

The transport parameter of Van Rijn does not exceed the value of 25, so the method should be valid for the range of discharges in this research. However, it seems odd that the equilibrium dune height is similar for both discharges of 9000 m$^3$/s and 18000 m$^3$/s.

Grain size and the composition of the riverbed were not taken into account in the method of Wilbers (2004). It is very complex to determine the composition of the different grain sizes on the riverbed in the Rhine. It could be of influence, but the eventual effect on the results of this study is difficult to estimate.

7.4 Hindrance of navigation

The method for calculating the decrease of loading capacity for navigation is based on some experience values for the maximum and minimum shipping depth. The reliability of these values is unknown, but it gives a first indication of the influence of river dunes and the significance of the presence of river dunes.

For the hindrance of navigation by river dunes, the largest dune heights are important, instead of the average height. Average dune heights were determined with the calculation method. The knowledge about the spreading in the calculated dune height is limited. It turned out that the restriction of the loading capacity is not significantly sensitive for the dune height (Appendix U). When the dune height
is doubled, the restriction of the loading capacity increases with about 1%. The insignificant effect of the dune height is twice as large at a dune height that is twice as large. The influence of river dunes on the restriction of the loading capacity is still insignificant.
8  Conclusions and recommendations

8.1  Conclusions

The effect of climate change on discharges in the Rhine has results for several perceptions of the consequences of temperature rise. Scenarios A1 (2050) and A2 (2100) forecast higher discharges in winter and lower discharges in summer. Scenario B2, which is a drought scenario for 2050, forecasts decreasing discharge for the entire year.

The influence of the changing flow conditions for each scenario on the development of river dunes was determined with the method of Wilbers (2004), which was based on the ideas of Allen (1976). The influence of the discharges of Scenario A1 and A2 on the maximum dune height is clearly perceptible (Table 8.1). The maximum dune height increases at increasing discharge. Scenario B2 effects are less noticeable.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1991 H [m]</th>
<th>1991 Q [m³/s]</th>
<th>1995 H [m]</th>
<th>1995 Q [m³/s]</th>
<th>2003 H [m]</th>
<th>2003 Q [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>0.8</td>
<td>7*10³</td>
<td>1.6</td>
<td>12*10³</td>
<td>1.2</td>
<td>9*10³</td>
</tr>
<tr>
<td>Return period</td>
<td>2</td>
<td>50</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario A1</td>
<td>1</td>
<td>8*10³</td>
<td>1.6</td>
<td>14*10³</td>
<td>1.4</td>
<td>11*10³</td>
</tr>
<tr>
<td>Scenario A2</td>
<td>1.4</td>
<td>10*10³</td>
<td>1.8</td>
<td>18*10³</td>
<td>1.7</td>
<td>14*10³</td>
</tr>
<tr>
<td>Scenario B2</td>
<td>0.8</td>
<td>6*10³</td>
<td>1.5</td>
<td>11*10³</td>
<td>1</td>
<td>9*10³</td>
</tr>
</tbody>
</table>

Figure 8.1: Discharges and dune heights for base years 1991, 1995 and 2003 and the scenarios

It can be concluded that higher river dunes occur more often in the future, as frequent occurring discharges (once in two years) will increase. This effect is larger than for the river dunes at the extreme, less frequent occurring, discharges of base year 1995. This can be explained by the fact that the growth of the dune height is exponential, which means that the growth rate is fast at initiation of the growth and slow when the maximum dune height is close to the equilibrium height. Therefore, the maximum dune height for base year 1991 increases more than the maximum dune height for base year 1995, when the maximum dune height at the extreme discharge was already close to its equilibrium height.

This also causes larger increases of the time lag of dune development for base year 1991.

It is found that there is no normative local depth in the Boventijn, because no certain pattern was found in the local differences of maximum 0.2 m at nine locations at the Rhine. In addition, at the locations where the dune height was lower, the water depth was also lower and vice versa. No clear local changes were observed in the influence of dune amplitude on the water depth. When the water depth is 4 m, the dune amplitude is about merely 0.04 m. This means that dune height compared to water depth is not significant.
It can be concluded that river dunes do not significantly hinder navigation. When the dunes are at maximum height, the water depth is too large for the dunes to cause serious restriction. In the period of falling discharges after the flood event, the decay of river dunes in the Bovenrijn is fast and water depths are still too large, so dunes do not hinder navigation then. The only period in which they have little, not significant, effect is during summer, when the water depth is restricted (below 4 m) anyway. The loading capacity decreases with 20% to 50%, depending on the base year.
The effect of river dunes is only in the order of 1%, for both the base year and the scenario for 2100. This is not significant compared to 20% - 50%. It seems that the hindrance by river dunes even decreases for the climate change scenario, in the order of 0.5%. Therefore, it is supposed to be insignificant.
It can be concluded that climate change has no influence on the hindrance of navigation by river dunes.

As the most extreme scenario results (for 2100) show no significant effects on the influence of river dunes on hindrance of navigation, the other scenarios are supposed to have no effect either. Scenario A1 has lower peak discharges and higher summer discharges, so the effect will be less than Scenario A2. Scenario B, which is not used in the calculation of dune heights, is not expected to have different results for the same reason.

8.2 Recommendations
The effect of climate change on the pattern of the discharge in the Rhine should be investigated. Only the discharge amount is calculated with multiplying factors, but the duration of a peak discharge may also be different as a result of climate change.
The calculation method of Wilbers contains an adapted equilibrium height of Tsuchiya. This adaptation performed coincidental well in the prediction of equilibrium dune height at low discharges. In Tsuchiya (1967) it was not clear how method was supposed to be used, so there is no argumentation for the use of this method.
The influence of the grain size was not taken into account in the method of Wilbers. This could influence the development and decay of the dunes and should therefore be studied extensively.
The determination of the effect on navigation could be extended, whereas only class V vessels were taken into account in this research. The restriction of the water depth can be calculated for every type of ship on the Rhine. Furthermore, the method for calculating the restriction of the loading capacity should be analysed more extensively.
High peak discharges also hinder navigation and could possibly be of greater importance than the hindrance by low discharges or by river dunes.
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Appendix A: Basis of the UKHI scenario

The results for temperature and precipitation change are divided in year, winter and summer changes for the three main areas in the catchment of the Rhine [Middelkoop et al, 1999].

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Alpine area</th>
<th>Central Germany</th>
<th>Lowland area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>W</td>
<td>S</td>
</tr>
<tr>
<td>C2050</td>
<td>dT (°C)</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>(L2100)</td>
<td>dP (%)</td>
<td>0.8</td>
<td>3.9</td>
</tr>
<tr>
<td>H2050</td>
<td>dT (°C)</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>(C2100)</td>
<td>dP (%)</td>
<td>1.8</td>
<td>8.6</td>
</tr>
<tr>
<td>H2100</td>
<td>dT (°C)</td>
<td>4.2</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>dP (%)</td>
<td>3.4</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Table A.1: Estimations for changing temperature and precipitation

C = central estimation
L = low estimation
H = high estimation
Appendix B: Method of Van Rijn

The dimensionless particle diameter of Van Rijn (1982) depends on the median grain size \(D_{s0}\), the specific density, gravitational acceleration and the kinematic viscosity coefficient.

\[
D_s = D_{s0} \left[ \frac{\Delta g}{v^2} \right]^{1/3}
\]  

(B.1)

\[
\Delta = \frac{\rho_s - \rho}{\rho} = \text{specific density [-]}
\]

\[
v = \frac{\mu}{\rho} = \text{kinematic viscosity coefficient [m/s]}
\]

The transport parameter can be expressed as follows.

\[
T = \frac{(u_{*b})^2 - (u_{*cr})^2}{(u_{*cr})^2}
\]  

(B.2)

\[
u_{*b} = \frac{u \sqrt{g}}{C} = \text{effective bed shear velocity related to grains [m/s]}
\]

\[
u_{*cr} = \text{critical shear velocity according to Shields [m/s]}
\]

The critical shear stress can be calculated from the equation for the Shields parameter, which represents the mobility of the sediment [Ribberink, 2002].

\[
\theta_{cr} = \frac{(u_{*cr})^2}{\Delta g D_{s0}}
\]

The critical value of the Shields parameter gives a boundary condition, from which the bed particles start moving. The critical values can be represented by:

\[
\theta_{cr} = 0.24(D_s)^{-1} \quad \text{for } D_s \leq 4
\]

\[
\theta_{cr} = 0.14(D_s)^{-0.64} \quad \text{for } 4 < D_s \leq 10
\]

\[
\theta_{cr} = 0.04(D_s)^{-0.1} \quad \text{for } 10 < D_s \leq 20
\]

\[
\theta_{cr} = 0.013(D_s)^{0.29} \quad \text{for } 20 < D_s \leq 150
\]

\[
\theta_{cr} = 0.055 \quad \text{for } D_s > 150
\]

It is assumed that the dimensions as well as the migration of the bed forms are mainly determined by the bed load transport rate. To find an equation for the calculation of the dune height, Van Rijn described the bed load transport rate as a
function of the thickness of the bed load layer, the velocity of the particles and the concentration in the bed load layer:

\[ s_b = \delta_b u_b c_b \]  

(B.3)

It can also be described, using simple kinematic considerations and the continuity equation:

\[ s_b = (1 - \varepsilon)\alpha * H u_d \]  

(B.4)

In which \( H \) is the dune height and \( \alpha \) the shape factor of the bed forms. The migration velocity of the bed forms is described by \( u_d \). From these two equations for bed load transport rate is can be derived that:

\[ \frac{H}{h} = \frac{\delta_b u_b c_b}{(1 - \varepsilon)\alpha * D_{50} u_d} \]  

(B.5)

The relative dune height can be expressed as:

\[ \frac{H}{h} = \exp(11.0) \left( \frac{D_{50}}{h} \right)^{0.3} \left[ 1 - \exp(-0.5T) \right][25 - T] \]  

(B.6)

In the same way, the dune height and dune length ratio could be expressed as:

\[ \frac{H}{L} = \exp(10.0) \left( \frac{D_{50}}{h} \right)^{0.3} \left[ 1 - \exp(-0.5T) \right][25 - T] \]  

(B.7)
Appendix C: Meyer-Peter-Müller

Many transport formulas exist of the dimensionless transport parameter ($\Phi$) and flow parameter ($\Psi$).

$$\Phi = \frac{s}{\sqrt{\Delta g D^3}} \quad \text{and} \quad \Psi = \mu \frac{h_i}{\Delta D}$$

$s =$ sediment transport
\(\mu =$ ripple factor

The ripple factor takes into account the influence of the bed forms.

$$\mu = f\left(\frac{C}{C_{90}}\right)$$

$C_{90}$ is the Chézy coefficient, related to the $D_{90}$ grain size.

$$C_{90} = 18 \log \frac{12 h}{D_{90}}$$

The method of Meyer-Peter-Müller concerns bed load transport. The formula is valid when the fall velocity exceeds the shear stress velocity.

$$\frac{w}{u_*} > 1$$

In terms of the transport and flow parameters, the formula can be written as follows.

$$\Phi = 8 (\Psi - 0.047)^{3/2}$$

The ripple factor according to Meyer-Peter-Müller is:

$$\mu = \left(\frac{C}{C_{90}}\right)^{3/2}$$
Appendix D: Method of Wilbers

Adapted Tsuchiya & Ishizaki (1967)

Tsuchiya & Ishizaki created predictors for both dune height and length from theoretical stability analysis. They found out that $\beta = 0.9$, but Wilbers (2004) replaced the entire term with $\beta$ in it by 0.9. So Equation D1 formulates the adapted Tsuchiya.

\[ H = h \cdot Fr^2 \cdot \alpha \]
\[ \alpha = \left( 1 - \frac{1}{\beta^2} \right) + 2(1 - \beta) = 0.9 \]
\[ Fr = \frac{u}{\sqrt{gh}} \]
\[ k = \frac{2\pi}{L} \]
\[ Fr = \sqrt{\frac{2}{kh} \tanh(2kh) - \frac{1}{kh} \tanh(kh)} \]

Symbols:
- $Fr$ = Froude number
- $\beta$ = roughness parameter
- $u_{top}$ = average flow velocity at dune crest [m/s]
- $k$ = wave number [m⁻¹]

Dune height model Pannerdensche Kop

Initiation:
Measured height or equ. D.1

Rising flood:
If $\tau_b < 10$ Then
\[ H(t) = H_{t-1} + (1 - \exp(-0.12\Delta t))(H_{w,t} - H_{t-1}) \]
with $H_{w,t} =$ equ. D.1
If $\tau_b > 10$ Then
\[ H(t) = H_{t-1} + (1 - \exp(-0.12\Delta t))(H_{w,t} - H_{t-1}) \]
with $H_{w,t} =$ equ. B.6
Falling flood:
If $\tau_b < 13$ Then

$$H(t) = H_{t-1} + (1 - \exp(-0.12\Delta t))(H_{\infty,t} - H_{t-1})$$

with $H_{\infty,t} = \text{equ. D.1}$

If $\tau_b < 10$ Then
Superposition
with $H(t) = H_{\infty,t} = \text{equ. D.1}$

If $H/L < 0.01$ Then
Primary dunes disappear and secondary, superimposed dunes become primary

Dune length model Pannerdensche Kop

Initiation:
Measured height or equ. D.5

Rising flood:
If $\tau_b < 10$ Then

$$L(t) = L_{t-1} + (1 - \exp(-0.05\Delta t))(L_{\infty,t} - L_{t-1})$$

with $L_{\infty,t} = \text{equ. D.5}$

If $\tau_b > 10$ and Then

$$L(t) = L_{t-1} + (1 - \exp(-0.05\Delta t))(L_{\infty,t} - L_{t-1})$$

with $L_{\infty,t} = \text{equ. B.7}$

Falling flood:
If $H/L > 0.01$ Then

$$L(t) = L_{t-1} + (1 - \exp(-0.05\Delta t))(L_{\infty,t} - L_{t-1})$$

with $L_{\infty,t} = \text{equ. B.7}$

If $\tau_b < 10$ Then
Superposition
with $L(t) = L_{\infty,t} = \text{equ. D.5}$

If $H/L < 0.01$ Then
Primary dunes disappear and secondary, superimposed dunes become primary
Appendix E: Water levels at Lobith

A peak discharge, according to Rijkswaterstaat, occurs when the water level will get 14.00 m +NAP and it is expected to rise up to at least 15.00 m +NAP [Van Bennekom et al, 2001]. The water levels of base years 1991, 1995 and 2003 are shown below.

![Water levels at Lobith 1990-1992](image)

*Figure E.1: Actual water levels at Lobith in the period 1990 - 1992*

It is clear that the water level in 1991 is above 14 m +NAP, but it is not rising up to 15 m +NAP. However, a peak with the return period of 2 years can rise up to 15 m +NAP in the future, due to climate change.
The peak of 1995 has a very extreme water level of about 16.50 m +NAP.

In 2003, the water level did rise over 15 m +NAP. The water level decreases to very low levels.
Appendix F: Return period for Scenario B

The return period for Scenario B shows results in the same order as Scenario A. The discharges will be higher at more extreme climate changes. For Scenario B2, the discharges will be lower at certain return periods. This is clear in the graph at the return period of 2 years: at present a discharge of 7000 m$^3$/s will occur every 2 years, in 2100, according to Scenario B5 a discharge of 11000 m$^3$/s has a return period of 2 years. According to Scenario B2 a discharge of about 6500 m$^3$/s corresponds to a return period of 2 years.

Figure F.1: Return period for Scenario B
Appendix G : Discharges for Scenario A

Figure G.1: Discharges for Scenario A for base year 1995

Figure G.2: Discharges for Scenario A for base year 2003
Appendix H : Discharges Scenario B base year 1991

Figure H.1: Discharges for Scenario B3, B4 and B5, for base year 1991
Appendix I: Discharges Scenario B base year 1995

Figure I.1: Discharges for scenarios B2 and B3, for base year 1995

Figure I.2: Discharges for scenarios B4 and B5, for base year 1995
Appendix J :  Discharges Scenario B base year 2003

Figure J.1: Discharges for scenarios B2 and B3 for base year 2003

Figure J.2: Discharges for scenarios B4 and B5, for base year 2003
Appendix K: Water level comparison 1995 and 2003

Figure K.1: Actual water levels versus calculated water levels for base year 1995

Figure K.2: Actual water levels versus calculated water levels for base year 2003
Appendix L: Water level comparison Pannerdensche Kop

Figure L.1: Actual water levels versus calculated water levels at Pannerdensche Kop for base year 1991
Appendix M: Water depths for scenarios

Figure M1: Water depths for scenarios at Lobith, for base year 1995

Figure M2: Water depths for scenarios at Lobith, for base year 2003
Appendix N: Cross-section comparison

The cross-section at Lobith shows only a large difference in flow area and storage area in the floodplains. The cross-section at 3 km downstream of Lobith shows a huge difference in flow area and storage area in the main channel, due to a lake in the floodplain at that location. Both cross-sections have a width of approximately 340 m in the main channel.
Appendix O:  Dune height scenarios

Figure O.1: Dune height per scenario for base year 2003 at the Pannerdensche Kop

Figure O.2: Dune height per scenario for base year 1991 at Lobith
Figure O.3: Dune height per scenario for base year 1991 at the Pannerdensche Kop
Figure O.4: Dune height per scenario for base year 1995 at Lobith

Figure O.5: Dune height per scenario for base year 1995 at the Pannerdensche Kop
Appendix P: Dune height at constant discharge for 1995

The equilibrium height is reached on the 2nd of April and is 2 m. The maximum actual dune height reaches 76% of the equilibrium dune height.

About the 15th of March, the equilibrium height is reached. The peak of the dune height has a little larger time lag than the dune height at constant discharge.
Appendix Q: Dune height compared to water depth (2003)

Figure Q.1: Dune height versus water depth at Lobith for Scenario B2 of base year 2003

Figure Q.2: Dune height versus water depth at Lobith Scenario A1 of base year 2003
Appendix R: Dune height compared to water depth (1995)

Figure R.1: Dune height versus water depth at Lobith in base year 1995

Figure R.2: Dune height versus water depth at Lobith for Scenario B2 of base year 1995
Figure R.3: Dune height versus water depth at Lobith for Scenario A1 of base year 1995

Figure R.4: Dune height versus water depth at Lobith for Scenario A2 of base year 1995
Appendix S: Dune height compared to water depth (1991)

Figure S.1: Dune height versus water depth at Lobith for base year 1991

Figure S.2: Dune height versus water depth at Lobith for Scenario B2 of base year 1991
Figure S.3: Dune height versus water depth at Lobith for Scenario A1 of base year 1991

Figure S.4: Dune height versus water depth at Lobith for Scenario A2 of base year 1991
Appendix T: Loading capacity for base years 1995 and 2003

Figure T.1: Loading capacity for class V ships on the Rhine, due to river dunes and climate change, base year 1995

Figure T.2: Loading capacity for class V ships on the Rhine, due to river dunes and climate change, base year 2003
Appendix U: Sensitivity of restriction

Figure U.1: Restriction of loading capacity against water depth with river dunes, without river dunes and with twice the calculated dune height