Knowledge for Climate

Flood risk in unembanked areas

Part B Flooding characteristics: flow velocities in the downstream reaches of the river Rhine and Meuse

KfC report number **KfC 022B/2010**

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Contents

Samenvatting

In het kader van het HSRR02 project zijn waterdieptekaarten ontwikkeld voor de buitendijks gelegen gebieden in het benedenrivierengebied. Deze kaarten zijn vervolgens gebruikt om schade aan woningen en chemische industrie te berekenen. Echter, een deel van de schade kan ook het gevolg zijn van hoge stroomsnelheden. Omdat geen informatie over stroomsnelheden in de buitendijkse gebieden nabij Rotterdam beschikbaar was, is besloten een schatting te maken op basis van kennis en informatie over stroomsnelheden in vergelijkbare gebieden. De verzamelde informatie bestond zowel uit gemeten stroomsnelheden in het zomerbed van de rivier (gegevens van Rijkswaterstaat en het havenbedrijf Rotterdam), als berekende stroomsnelheden in de hoofdgeul (dit project), in uiterwaarden langs de Waal en onbedijkte terreinen nabij Dordrecht (het Stadswerven gebied). De beschikbare informatie heeft dus betrekking op verschillende gebieden en verschillende omstandigheden en is daarom alleen gebruikt om een indicatie te krijgen van de stroomsnelheden die zich in de buitendijkse gebieden in Rijnmond – Drechtsteden voor kunnen doen.

Op basis van de verzamelde gegevens en de uitgevoerde berekeningen is geconcludeerd dat de stroomsnelheden in de opgehoogde buitendijks gelegen gebieden nabij Rotterdam laag zullen zijn (orde 0,1 tot 0,25 m/s). Snelheden in de orde van 0,5 m/s of meer kunnen wel voorkomen in een smalle zone nabij de hoofdgeul of lokaal rond gebouwen of andere obstakels. Bij stroomsnelheden van minder dan 0,5 m/s is de schade aan gebouwen gering en zijn overstroomde gebieden doorwaadbaar (mits de waterdiepte beperkt blijft tot orde 1 m).

Summary

In the HSRR02 project, much effort was put on the development of water depth maps. The maps were used to estimate both the damage to private properties and chemical industries. However, when flow velocities are high, part of the damage may also be caused by these high flow velocities, and not solely due to large water depths.

Estimates of flow velocities generally are obtained through measurements and hydraulic models. However, in the downstream river reaches near Dordrecht and Rotterdam, flow velocities only are measured in the channel. The measurements do not provide information on flow velocities at the adjacent quays. As the water depth maps that were developed as part of the HSRR02 project are based on GIS instead of a hydraulic model, they do not provide information on flow velocities either. It was therefore decided to collect information and knowledge on flow velocities in floodplains located upstream of the study area and an unembanked area in the city of Dordrecht, which is part of the study area. The collected information on flow velocities thus applies to different areas with different flooding conditions. It can therefore only be used to deduce *estimates* of flow velocities that are expected to occur at the unembanked areas near Rotterdam.

Combination of knowledge and information on flow characteristics collected for various locations along the rivers Rhine and Meuse suggests that flow velocities at the unembanked areas along the downstream river reaches near Dordrecht and Rotterdam will generally be low (0.1 to 0.25 m/s). Locally, i.e. close to the main channel, higher flow velocities of about 0.5 m/s or more can be expected. Higher flow velocities are also expected at locations where water is forced between or around obstacles (similar to wind that is forced between tall buildings). Damage to buildings will be limited when flow velocities are less than 0.5 m/s. Also, the flooded areas are wadable as long as maximum water depths are in the order of 1 m or less.

1. Introduction

1.1 HSRR02

The Knowledge for Climate (KvK) project HSRR02 focuses on the downstream reaches of the rivers Rhine and Meuse (the so-called 'Rijn- Maasmonding' Figure 1.1), that are not protected against flooding by dikes. These areas comprise parts of the city of Dordrecht and the harbours of Rotterdam. Although the elevation of these unembanked areas is relatively high, climate change and sea level rise may result in more frequent flooding. This may, in turn, result in an increase in damage of houses, infrastructure and industries that are present in these areas.

Figure 1.1 The Rijn- Maasmonding (source: Rijkswaterstaat & Port of Rotterdam)

The HSRR02-project Flood risk in unembanked areas consists of four studies:

A. Flooding characteristics - flood depth and extent: development of water depth maps for the tidal river area of Rotterdam, for different climate change scenario's and during floods of different magnitudes, i.e. various frequencies of occurrence;
B. Flooding characteristics – flow velocities: estimation of flow velocities at the unembanked areas;
C. Vulnerability assessment based on direct flooding damages: estimation of direct economical damage to buildings that is expected to occur when the unembanked areas are flooded;
D. Vulnerability of port infrastructure: assessment of damage to port infrastructure and chemical industries due to flooding.

The water depth maps developed in the first study (Part A, Huizinga, 2010) are used to estimate both the economical damage (part C, Veerbeek, 2010) and the vulnerability of port infrastructure (part D, Lansen and Jonkman, 2010). However, when flow velocities are high, part of the damage may be due to these high flow velocities, and not solely due to large water depths.

Estimates of flow velocities can be obtained from measurements and hydraulic models. However, flow velocities only are measured in the channel. Hence, they provide no information on flow velocities at the adjacent floodplains and quays. As the water depth maps are developed using GIS instead of an hydraulic model, they do not provide information on flow velocities either.

This document provides an overview of knowledge on flow velocities in the main channels of the tidal river reaches of the rivers Rhine and Meuse, in unembanked floodplains along the river Waal (upstream of the study area) and an unembanked area in the city of Dordrecht, i.e. the Stadswerven area. The information is used to deduce estimates of flow velocities that are expected to occur at the unembanked areas in the tidal river area near Rotterdam.

1.2 Aim

The aim of this part of the HSRR02 project was to deduce estimates of flow velocities that are expected to occur at the unembanked areas along the downstream parts of the rivers Rhine and Meuse, using flow velocities that were computed for other river reaches.

1.3 This report

Chapter 1 briefly introduces the HSRR02 project and gives the aim of this part of the study. Chapters 2 through 4 describe flow velocities that were measured and / or computed in other river sections. Results from the Urban Flood Management project in Dordrecht are reported in Chapter 2. Chapter 3 provides graphs of flow velocities that were measured in the main channel near Rotterdam and Dordrecht, by the ministry of transport, public works and water management and the port of Rotterdam. Measured flow velocities are compared with flow velocities that were computed in this study. A description of flow velocities computed in unembanked areas along upstream river reaches (middle section of the river Waal) is given in Chapter 4. The information is combined in Chapter 5 to assess the range of flow velocities that are most likely to occur at the unembanked areas near Rotterdam.

2. Dordrecht: Urban Flood Management

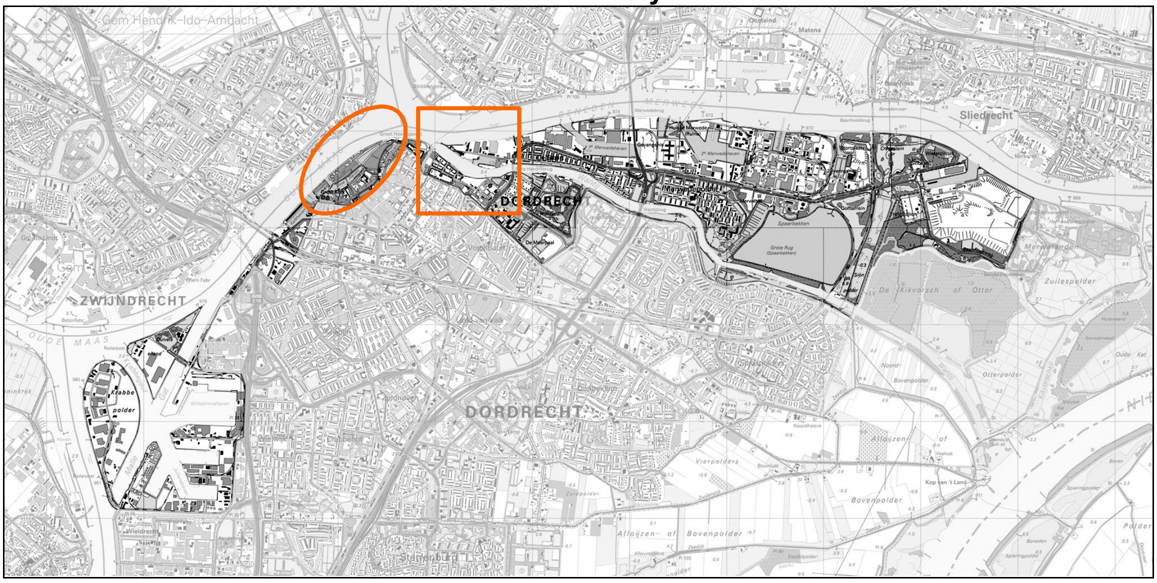
2.1 Introduction

The present study covers the unembanked areas that border the downstream reaches of the rivers Rhine and Meuse (Figure 1.1). This includes unembanked areas near Rotterdam and Dordrecht. Large parts of the port of Rotterdam are not protected by dikes. No information on flow velocities is available for these areas. Large areas on the Island of Dordrecht are not protected by dikes either. However, for these areas flow velocities were computed during the Urban Flood Management project (UFM) (Stone et al., 2008). As the city of Dordrecht is part of the present project area, the results of the UFM-computations could be used to obtain insight in flow conditions that occur in unembanked areas at other locations in the Rhine- Maasmonding.

2.2 Description of the study area

Large areas on the Island of Dordrecht are not protected by dikes. Parts of these areas are urbanized. An example of such an area is the old city of Dordrecht. The Urban Flood Management (UFM) study focused on the area called Stadswerven, which is also located in this zone. The Stadswerven area used to be an industrial site dominated by shipyards. The river Wantij runs through the Stadswerven area dividing it into a northern and southern part (Figure 2.1). The terrain levels within these unembanked areas are relatively high. In the Stadswerven the average elevation is approximately NAP +3m or higher.

Figure 2.1 City of Dordrecht. In black the urban areas that are not protected by dikes. The area of Stadswerven lies within the box. The old city of Dordrecht is encircled.



Dordrecht is enclosed by rivers. Clockwise starting at the north side, the island is bounded by the ‘Beneden Merwede’, ‘Nieuwe Merwede’, ‘Amer’, ‘Dordtse Kil’ and ‘Oude Maas’ (Figure 2.2).

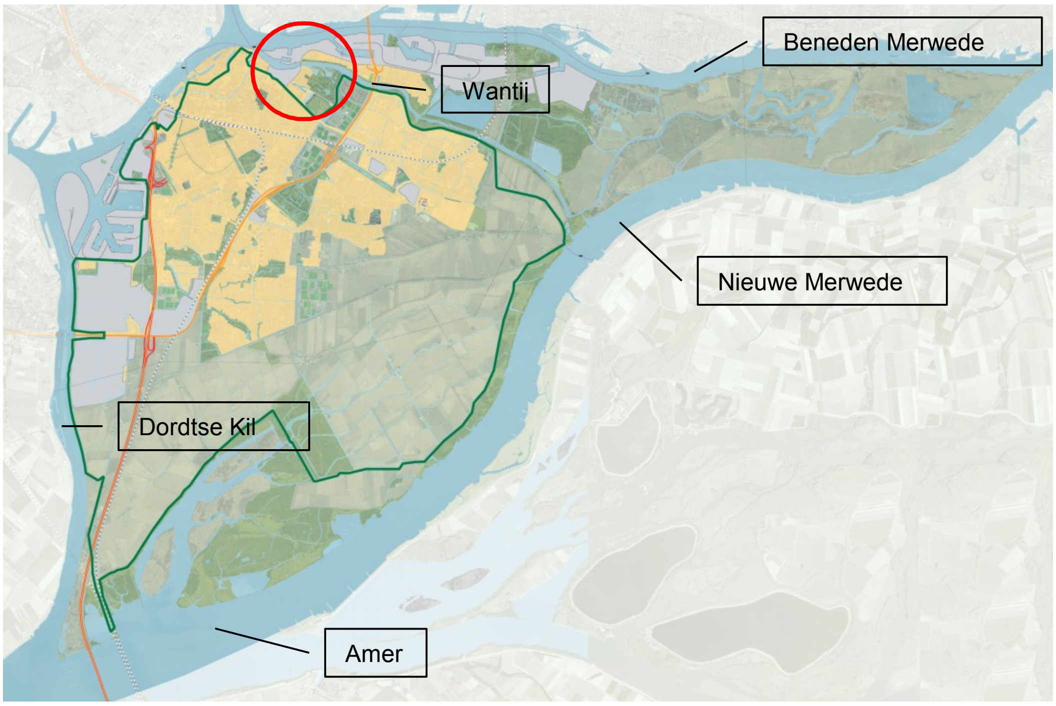


Figure 2.2 Island of Dordrecht. The city of Dordrecht is indicated in yellow. The green line shows the location of the primary dike. The study area Stadswerven is situated within the encircled area.

Dordrecht lies in the transition zone where the water levels are determined by both the discharge of the rivers Rhine and Meuse and the sea water levels. The coastal influence is also noticed by the fact that the water levels follow the tidal cycle.
When the discharge at the river Rhine is less than 4000 m^3/s, the flow direction is intermittent, depending on the tide. When the river discharge exceeds 10,000 m^3/s at Lobith, flow directions are always towards the west, i.e. in a downstream direction.

2.3 Hydraulic conditions

2.3.1 Water Levels

Because of the high terrain elevation of the Stadswerven area (at about NAP +3m), the present probability for flooding is estimated to be about 1:2000 (Table 2.1).
It is expected that due to climate change, extreme water levels at Dordrecht will occur more often. This is a result of sea level rise and an expected increase of extreme river discharges. Both these factors influence the water levels at Dordrecht. As a consequence, the water levels for a given return period will increase. Table 2.1 outlines this effect. The results are based on the WB21 average climate scenario. This scenario assumes a moderate climate effect and was, at the time that the UFM study was carried out, recommended for use in area development studies (Ministerie Verkeer en Waterstaat, 2000) The WB21 average climate change scenario assumes a sea level rise of 0.3 m in 2050 and 0.6 m in the year 2100. Extreme river discharges are expected to increase as well. Under present conditions, the design discharge (probability of occurrence of 1:1250 per year) is 16.000 m^3/s for the Rhine at Lobith and 3800 m^3/s for the river Meuse. The design discharge of the river Rhine is expected to increase to 16.800 m/s in 2050 and 17.600 m^3/s in 2100. The design discharge of the river Meuse is expected to increase to 4.200 m^3/s in 2050 and 4.600 m^3/s in 2100.

Table 2.1 Present and future water levels (m +NAP) near Dordrecht, based on the WB21 average climate scenario.

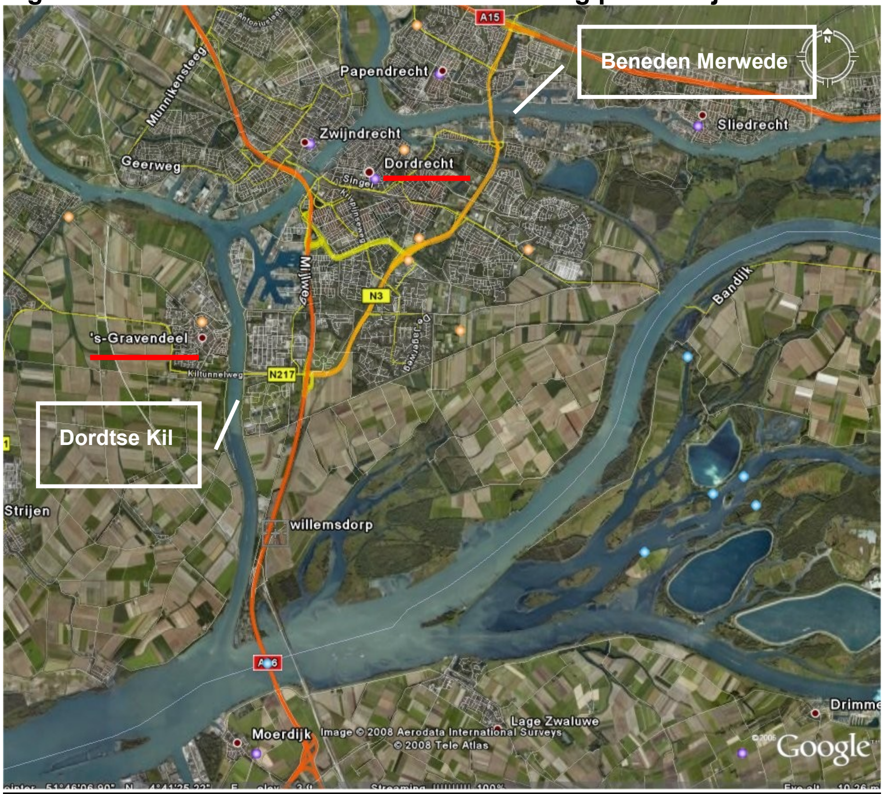
return period (years)	2001 (present)	2050	2100
10	2.30	2.51	2.71
25	2.44	2.64	2.85
50	2.53	2.74	2.94
100	2.63	2.83	3.02
250	2.75	2.94	3.13
500	2.84	3.02	3.21
1000	2.93	3.11	3.31
1250	2.96	3.14	3.34
2000	3.01	3.20	3.41
4000	3.10	3.30	3.51
10,000	3.22	3.43	3.65
20,000	3.32	3.53	3.75

Table 2.1 shows that the design water level (probability of 1:2000 per year) is expected to rise from NAP +3.01m up to NAP +3.41m in 2100. This water level corresponds to a return period larger than 20,000 years in the present situation. The return period for the current design water level (NAP +3.01m) will increase to 100 years in 2100.

2.3.2 Flow velocities in the main channel

Information on flow velocities in the main rivers around Dordrecht is gathered through the measuring program of Rijkswaterstaat. The measuring points of interest for Dordrecht are 'Dordrecht' (Beneden-Merwede) and ''s Gravendeel' (Dordtse Kil). The measuring points are illustrated in Figure 2.3.

Figure 2.3 Location of relevant measuring points Rijkswaterstaat



Under influence of the tide, the water flows in two directions. The actual flow velocity depends on the tide, the discharge of the rivers Rhine and Meuse and the regime of the Haringvliet locks. As mentioned earlier, the duration of the outgoing flow increases with an increasing river discharge and for certain parts of the river at a certain level of river discharge, only an outgoing flow occurs.

Table 2.2 gives an impression of the maximum low and high tide velocities that occur under average tide conditions and for three different Rhine discharges. Negative velocities indicate a flow in inland (upstream) direction. Positive velocities indicate a flow towards the North Sea (downstream direction).

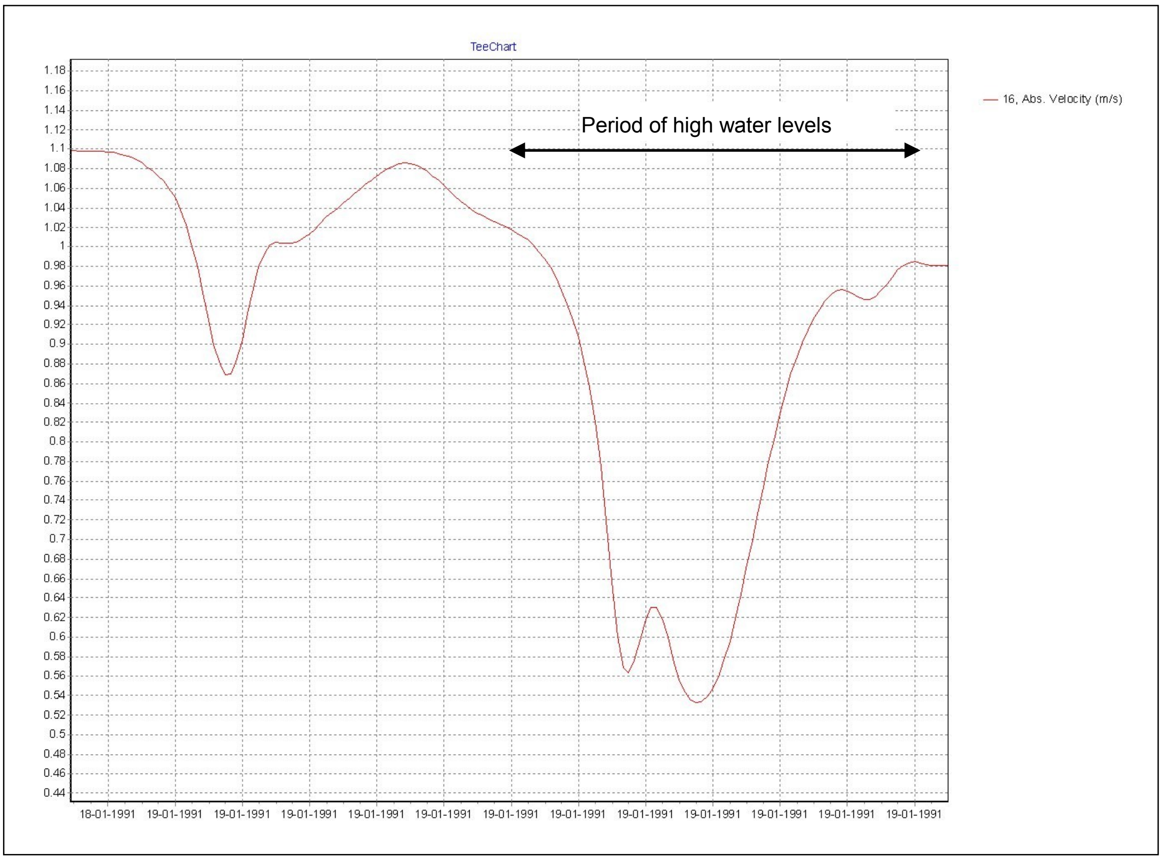
Table 2.2 Maximum flow velocity (m/s) measured at the main rivers near Dordrecht for several Rhine discharges

	Discharge Rhine at Lobith in m^3/s					
	800		2200		6000	
Location:	low tide	high tide	low tide	high tide	low tide	high tide
Dordrecht (Beneden Merwede)	0.31	- 0.19	0.56	- 0.12	0.90	0.46
’s Gravendeel (Dordtse Kil)	0.70	- 0.78	0.71	- 0.80	0.16	- 1.03

The velocities do not exceed 1 m/s up to a river discharge of 6000 m^3 at Lobith. From simulations that were carried out using a 1D SOBEK model, it was concluded that the results of the SOBEK model are similar to the measured flow velocities, and that flow velocities on the Beneden Merwede can increase up to 1.2 m/s when river discharges increase to about 10.000 m^3/s at Lobith.

Flow velocities near Dordrecht decrease when high water levels at Dordrecht are caused by a storm surge. Figure 2.4 shows the results of the 1D SOBEK model for a flood with water levels of about NAP +3.4 m, caused by a storm surge. In this case flow velocities decrease from about 1.1 m/s to about 0.5 to 0.6 m/s.

Figure 2.4 Computed flow velocities on the Beneden Merwede during a flood. The maximum water level in the river reaches NAP +3.4m, the predicted design water level for 2100.



For the Wantij no measured data are available. To gain insight in the flow velocities in this water body, simulations were performed using the 1D SOBEK model. Both an average and a flood situation were simulated. For the simulation of an average event, average boundary conditions for both the river discharges and tide were applied. For the high water level simulation, a situation dominated by high river discharges was regarded. In such a situation, the water levels upstream of Dordrecht reach such a height, that the locks at the entrance of the Wantij are flooded resulting in an upstream inflow of water (under average conditions, no water enters the Wantij through its upstream end). The inflow of water over the upstream locks results in an increase of the water velocity on the Wantij. The high water simulation was related to a 1:4000 year water level at Dordrecht (NAP +3.10m). The results are shown in Table 2.3.

Table 2.3 Computed maximum flow velocity at the Wantij river (in m/s) for an average situation and a high water level situation

	Average conditions	flood with a probability of occurrence of about 1:4000 per year
Flow velocity (m/s)	0.10 – 0.40	+/- 0.9

2.3.3. Water depths and flow velocities in flooded areas

A 2D inundation model was developed to calculate the flooding depths and flow velocities. The model simulates flooding of the Stadswerven area in the present state. No lowering or increase in elevation of the ground level was applied. Buildings were schematized as solid blocks (visible in orange colours in Figure 2.5). The simulated floods were induced by extreme river discharges resulting in a water level at Stadswerven of NAP +3.1m. and NAP +3.4m. A flooding caused by an extreme storm surge was not considered because this would not provide additional information. Both type of floods can result in the same maximum water levels, but the duration of a flood caused by extreme river discharges is longer than the duration of a flood caused by an extreme storm surge. The effect of waves was not included in the calculations. The flooding results are illustrated in Figure 2.5 through Figure 2.8.

Figure 2.5 Maximum water depths (m) when the maximum water level in the river reaches NAP +3.1m.

Figure 2.6 Maximum flow velocities (m/s) when the maximum water level in the river reaches NAP +3.1m

Figure 2.5 and Figure 2.6 show that for a flooding corresponding with a river level of NAP +3.1 m, only the area along the river becomes flooded and water depths are mostly in the range up to 0.75 m. Flow velocities are low. Only in specific areas does the water velocity exceed the 0.1 m/s range.

Figure 2.7 Maximum water depths (m) when the maximum water level in the river reaches NAP +3.4m, the predicted design water level for 2100

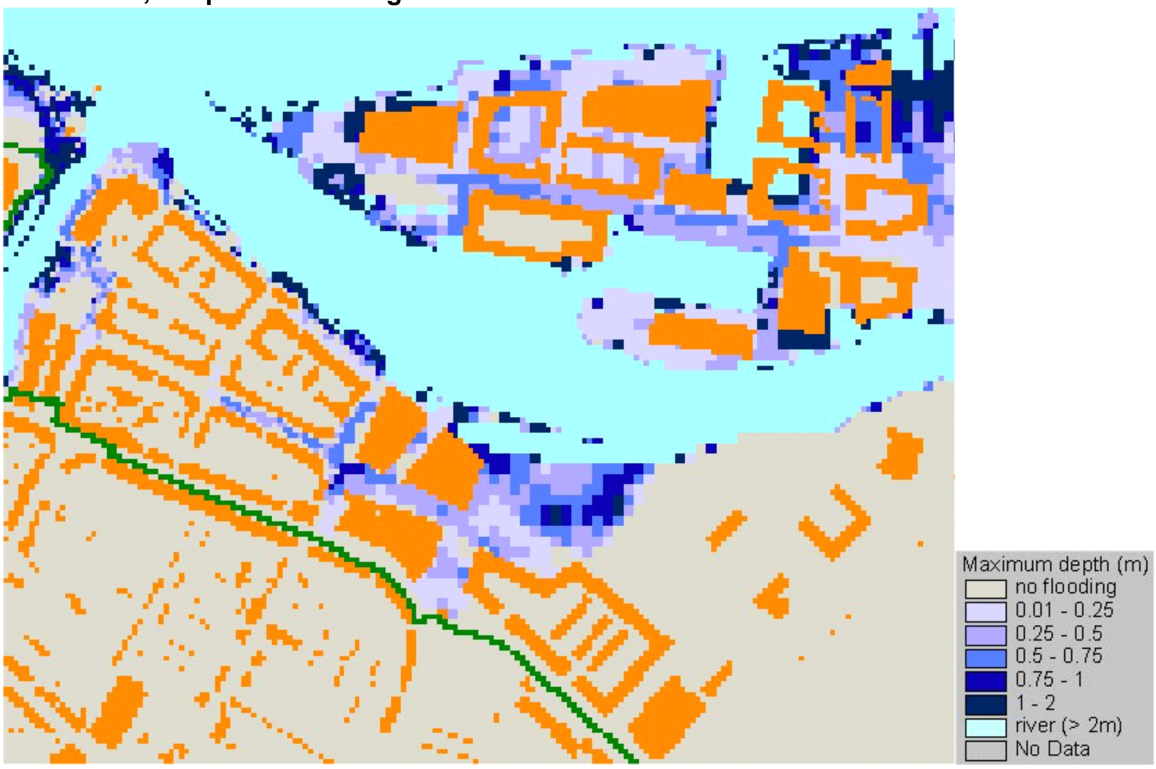


Figure 2.8 Maximum flow velocities (m/s) when the maximum water level in the river reaches NAP +3.4m, the predicted design water level for 2100

When the water level in the river reaches NAP +3.4 m, the entire area is flooded. Maximum water depths reach up to 0.75 m. The maximum velocities mainly are less than 0.25 m/s. Only at a limited number of locations, flow velocities of more than 0.5 m/s are observed. At those locations, it is not safe to wade through the water. Also, damage to brick buildings may occur.

Although a water level of NAP +3.4 m represents an extreme condition (probability of about 1:4000 per year), flow velocities remain relatively low. Flow velocities caused by flooding through a dike breach often result in much higher flow velocities. This is caused by the fact that the water depth rises gradually. In case of flooding through a breach, the difference in river water level and the terrain level in the polder is large. For instance, at the island of Dordrecht this difference would be more than 3 m. This difference results in a large water level slope at the initial phases of breaching. Which in turn results in very high flow velocities (2 m/s or even more near the breach). Farther from the breach, flow velocities generally decrease to about 0.2 to 0.3 m/s, with higher velocities over regional dikes or elevated roads. In the unembanked areas, the water level rises gradually, with the same rate as the water level in the main channel. Hence, there is no 'wall' of water entering these areas. The minor water level slope results in much lower flow velocities.

2.4 Conclusion

Flow velocities computed for the Stadswerven area in Dordrecht vary from less than 0.1 m/s to about 0.25 m/s. Higher flow velocities of more than 0.5 m/s are found only locally.

3. The tidal River area

3.1 Introduction

Dordrecht and Rotterdam are both located along river reaches that are influenced by tides. Also, both cities have large areas that are not protected by dikes. Flow velocities computed for unembanked areas in Dordrecht were discussed in the previous chapter. It is, however, unknown if flow characteristics in unembanked areas near Rotterdam are similar to those in Dordrecht. This chapter compares flow velocities computed and measured in the main channels in both areas. If flow velocities in the main channels are comparable, it seems correct to assume that flow velocities at the rarely inundated unembanked areas are similar as well.

3.2 Hydraulic simulations

Water levels and flow velocities in the tidal river area were simulated using the 1D SOBEK model. Simulations were carried out for three conditions:

1. Severe storm surge (maximum water level at Hoek van Holland NAP +4.72 m) and relatively low river discharge (2145 m^3/s at Lobith);
2. Average tidal conditions and moderate river discharge of about 5000 m^3/s at Lobith
3. Minor storm surge (maximum water level at Hoek van Holland NAP +3m) and relatively high river discharge (10000 m^3/s at Lobith).

The boundary conditions do not directly correspond with the conditions shown in the water depth maps. The water depth maps show the depths that occur during events with varying probabilities of occurrence. However, a 1:4.000 year event near Rotterdam will probably be related to an extreme storm surge, whereas a 1:4.000 year event near Dordrecht can be the result of a combination of high river discharge and a moderate storm surge. In other words: the conditions (storm surge or extreme river discharge) that result in an extreme flood differ for different parts of the study area. Storm surges are dominant in the downstream parts. High river discharges are most important at the upstream boundaries and a combination of both factors is likely to occur in the middle reaches. It was therefore decided to carry out simulations for varying combinations of river discharge and storm surges, that can also be compared with the events for which flow velocities were measured in the main channel (for validation purposes).

The first simulation provides information on flow velocities that occur under severe storm conditions (maximum water level at Hoek van Holland NAP + 4.72 m) and relatively low discharge conditions (2150 m^3/s at Lobith). It is assumed that the storm surge barrier remains open. The computed water levels in the Nieuwe Waterweg are about 0.4 m below the design water levels (probability of occurrence 1:10000 per year) west of the storm surge barrier, but 0.6 to 1 m above the design water level in the area upstream of the storm surge barrier. Under these conditions, parts of the unembanked area are flooded.

Under low discharge and average tidal conditions, flow velocities in the Nieuwe Waterweg, downstream of Maassluis range between -0.5 m/s and 1.5 m/s (Figure 3.1, locations are shown in Figure 3.2). Depending on the exact location, flow velocities may be somewhat higher. Velocities up to 1.75 m/s are observed in the model. In the Stadshavens area flow velocities are less and range from -0.5 to almost 1 m/s. In the main channel near Stadswerven (Dordrecht), flow velocities range from -0.2 m/s to about 0.6 m/s.

Figure 3.1 Flow velocities in the main channel computed for different locations in the tidal river area under low flow and average tidal conditions.

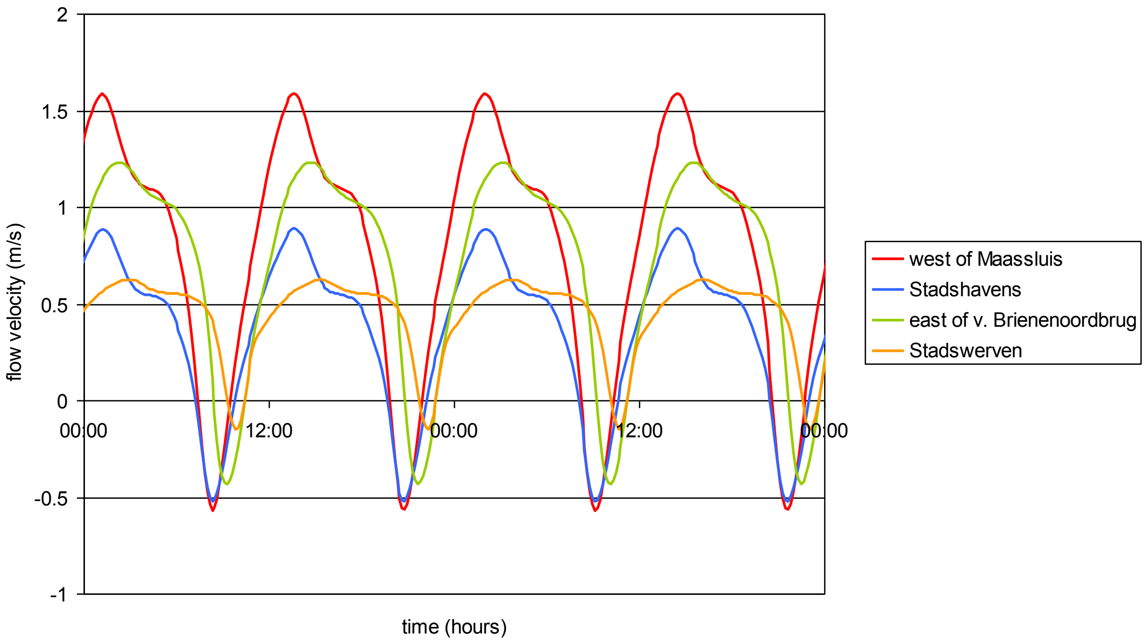
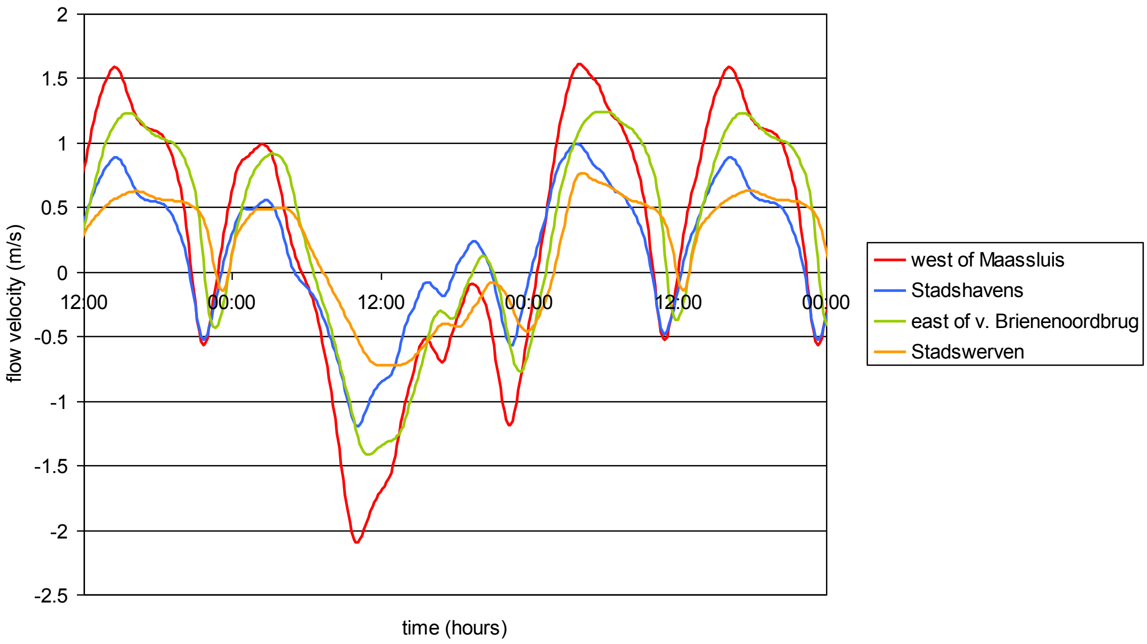


Figure 3.2 Locations mentioned in Figures 3.1 through 3.6

1 = Maassluis, 2 = Stadshavens (Nieuwe Maas), 3 = van Brienenoordbrug, 4 = Stadswerven (Dordrecht), 5 = Maasmond, 6 = Botlek bridge, 7 = Alblasserdam, 8 = Wieldrecht/'s Gravendeel.

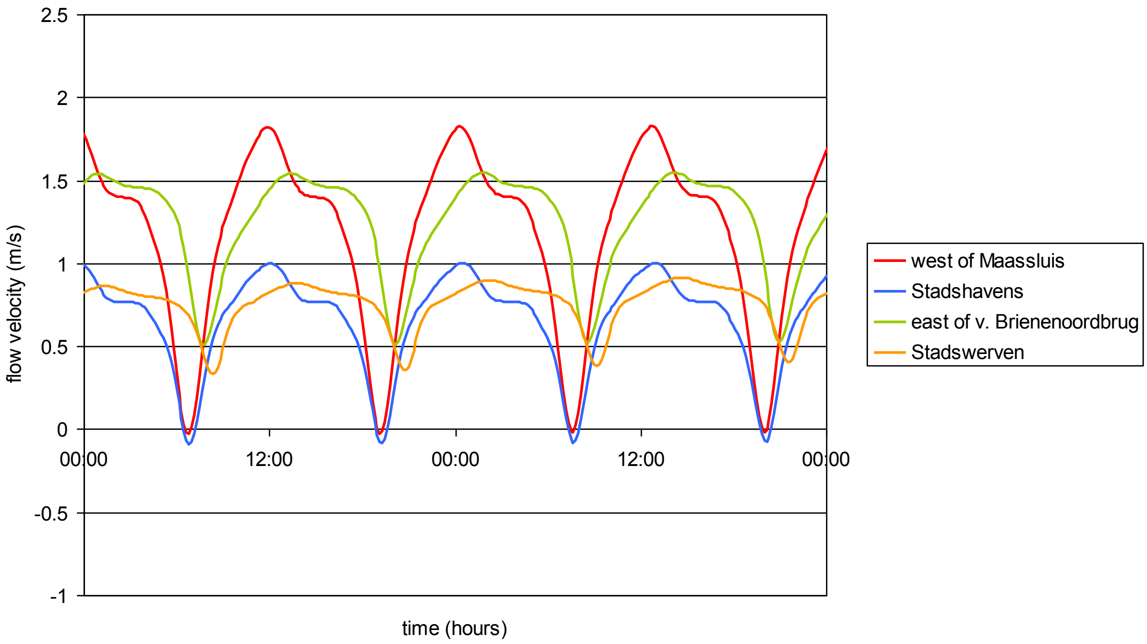
During the storm surge, flow velocities are high and directed inland. West of Maassluis maximum flow velocities are about 2 m/s (Figure 3.3). Near Stadshavens Rotterdam, maximum flow velocities are about -1.2 m/s and near Dordrecht they have decreased to -0.7 to -1 m/s (depending on the exact location).

Figure 3.3 Flow velocities in the main channel computed for different locations in the tidal river area under low flow conditions combined with a severe storm surge



The second simulation assumes moderately high discharge conditions (about 6500 m^3/s at Lobith). Computed flow velocities range between 0 m/s and 1.8 m/s in the Nieuwe Waterweg west of Maassluis. Near Stadshavens they vary between 0 and 1 m/s, whereas near Stadswerven (Dordrecht) they vary between 0.4 and 0.9 m/s (Figure 3.4). In other words, the results for Stadswerven and Stadshavens are quite similar, whereas higher flow velocities are computed for the area near the van Brienenoordbrug and west of Maassluis.

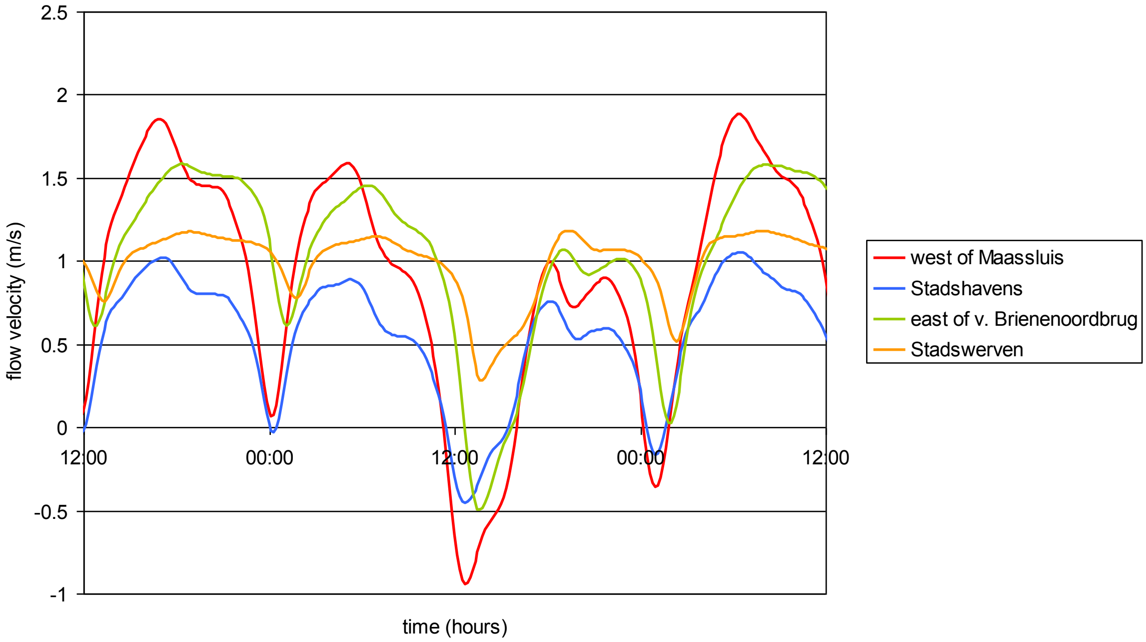
Figure 3.4 Flow velocities in the main channel computed for different locations in the tidal river area under moderate flow (discharge at Lobith 5000 m^3/s) and average tidal conditions.



When the river discharge at Lobith equals 10000 m^3/s and the minor storm surge occurs (third simulation), maximum flow velocities west of Maassluis are about -1 to 1.5 m/s. Flow velocities near Stadshavens are less. Near Stadswerven (Dordrecht) they vary between 0.3 and 1.2 m/s (Figure 3.5).

The impact of the storm surge on the computed flow velocities decreases upstream of Dordrecht (Stadswerven).

Figure 3.5 Flow velocities in the main channel computed for different locations in the tidal river area under high flow (discharge at Lobith 10000 m^3/s) conditions and a minor storm surge.



3.3 Measured flow velocities

Flow velocities are measured in the main channels at a number of locations. Information was obtained for two locations near Dordrecht for the UFM project. These locations were Dordrecht at the Beneden Merwede and 's Gravendeel at the Dordtse Kil. Table 3.1 gives an impression of the maximum low and high tide velocities that occur under average tide conditions and for three different Rhine discharges. Negative velocities indicate a flow in inland direction. Positive velocities indicate a flow in the direction of the sea.

Table 3.1 Maximum water velocity (m/s) main rivers at Dordrecht for several Rhine discharges

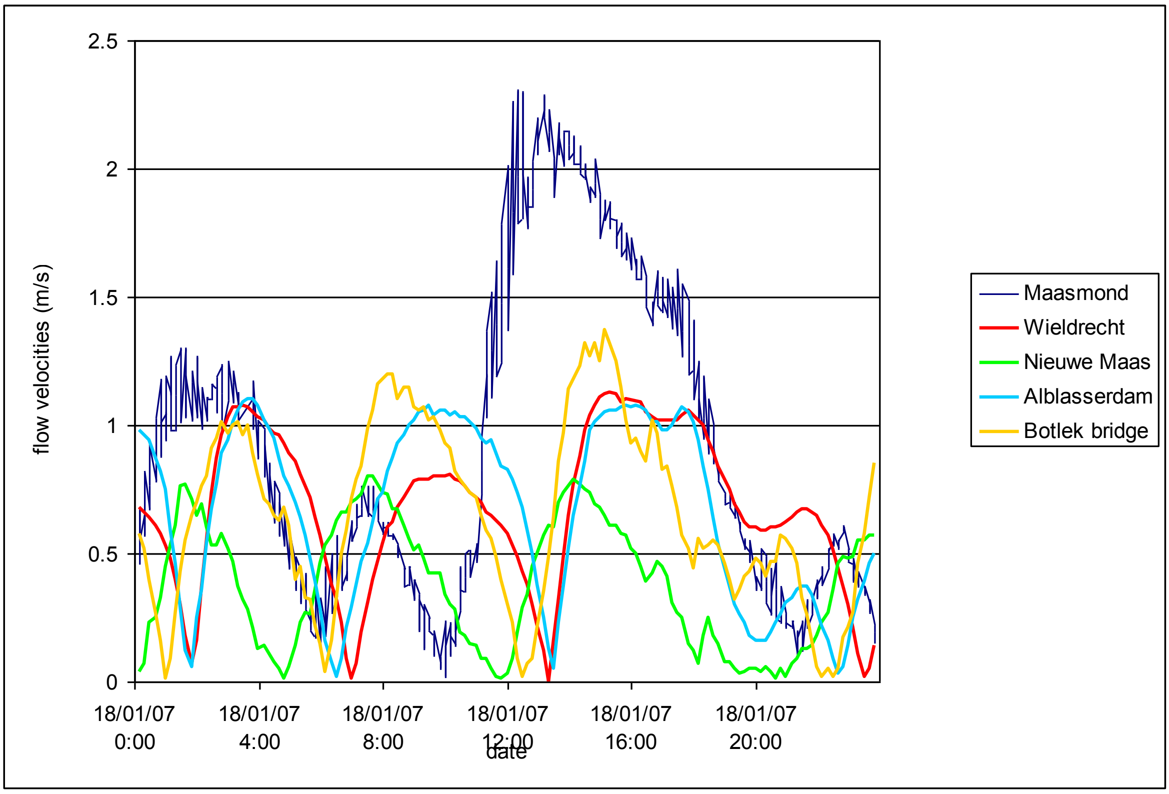
<table>
<tr><td rowspan="3">Location:</td><td colspan="6">Discharge Rhine at Lobith in m³/s</td></tr>
<tr><td colspan="2">800</td><td colspan="2">2200</td><td colspan="2">6000</td></tr>
<tr><td>low tide</td><td>high tide</td><td>low tide</td><td>high tide</td><td>low tide</td><td>high tide</td></tr>
<tr><td>Dordrecht (Beneden Merwede)</td><td>0.31</td><td>- 0.19</td><td>0.56</td><td>- 0.12</td><td>0.90</td><td>0.46</td></tr>
<tr><td>'s Gravendeel (Dortse Kil)</td><td>0.70</td><td>- 0.78</td><td>0.71</td><td>- 0.80</td><td>0.16</td><td>- 1.03</td></tr>
</table>

For the HSRR02-project, data on flow velocities were supplied by the Port of Rotterdam. Information was available for the storm of January 2007 for a number of locations, among which Wieldrecht. This location is on the opposite site of the Dordtse Kil as 's Gravendeel. The flow velocities for five locations are plotted in Figure 3.5.

Flow velocities are highest at the mouth of the river Maas ('Maasmond'). Here, flow velocities over 2 m/s are reached. This location is, however, very close to the open sea. The other locations have lower flow velocities that vary from about 0.75 m /s to 1.3 m /s.

This spatial distribution corresponds to the model findings that indicated maximum flow velocities west of Maassluis, i.e. closer to the mouth of the Maas, relatively low velocities in the Nieuwe Maas near the Stadshavens area and intermediate flow velocities further east (east of van Brienenoordbrug and Alblasserdam).

Figure 3.6 Flow velocities measured during the storm surge of January 2007



3.4 Conclusion

Flow velocities that were measured and computed in the channel near Dordrecht fall within the range of flow velocities measured and computed for the main channel near Rotterdam. Only at the most western end of the river mouth (i.e. closer to the sea) higher flow velocities are found. As flow velocities in the main channel are comparable, it seems likely to assume that flow velocities at the rarely inundated unembanked areas, with low water depths, are similar as well.

4. Floodplains along upstream River reaches

4.1 Introduction

The upstream river reaches along the rivers Nederrijn, Lek, Waal and IJssel also have areas that are not protected by dikes, the so-called 'uiterwaarden' or active floodplains. The elevation of these floodplains is lower than the unembanked areas near Rotterdam. Also, the hydraulic roughness is less as floodplains mainly are covered with grass, whereas the unembanked areas near Rotterdam are urbanized. Consequently, a large part of the total discharge is discharged over the floodplains along the upstream river reaches, whereas the discharge over the downstream unembanked areas near Rotterdam and Dordrecht is of minor importance. Therefore, flow velocities in the upstream floodplain areas are therefore expected to exceed flow velocities at the flood prone areas near Dordrecht and Rotterdam. In other words: if flow velocities in the main channel in these areas are similar to the velocities in the main channel near Rotterdam, one could argue that the flow velocities at the floodplains provide some sort of upper limit for the flow velocities that can be expected at the unembanked areas near Rotterdam and Dordrecht.

4.2 Hydraulic conditions

Figure 4.1 trough 4.4 show flow velocities that were computed with the RIVCUR model for the middle reach of the river Waal (WL | Delft Hydraulics, 1994). The results are based on simulations with a river discharge of 15000 m^3/s near Lobith.

Figure 4.1 shows an overview of the flow velocities computed over the entire reach. The legend is given in Figure 4.2. It can be observed from Figure 4.1 that flow velocities in the main channel vary between about 1.5 m/s at wide river sections and more than 2 m/s at narrow reaches. Flow velocities in the floodplains are generally less than 1 m/s.

Figure 4.1 Flow velocities computed with RIVCUR for the middle reach of the River Waal when the discharge at Lobith equals 15000 m^3/s (source: WL | Delft hydraulics, 1994)

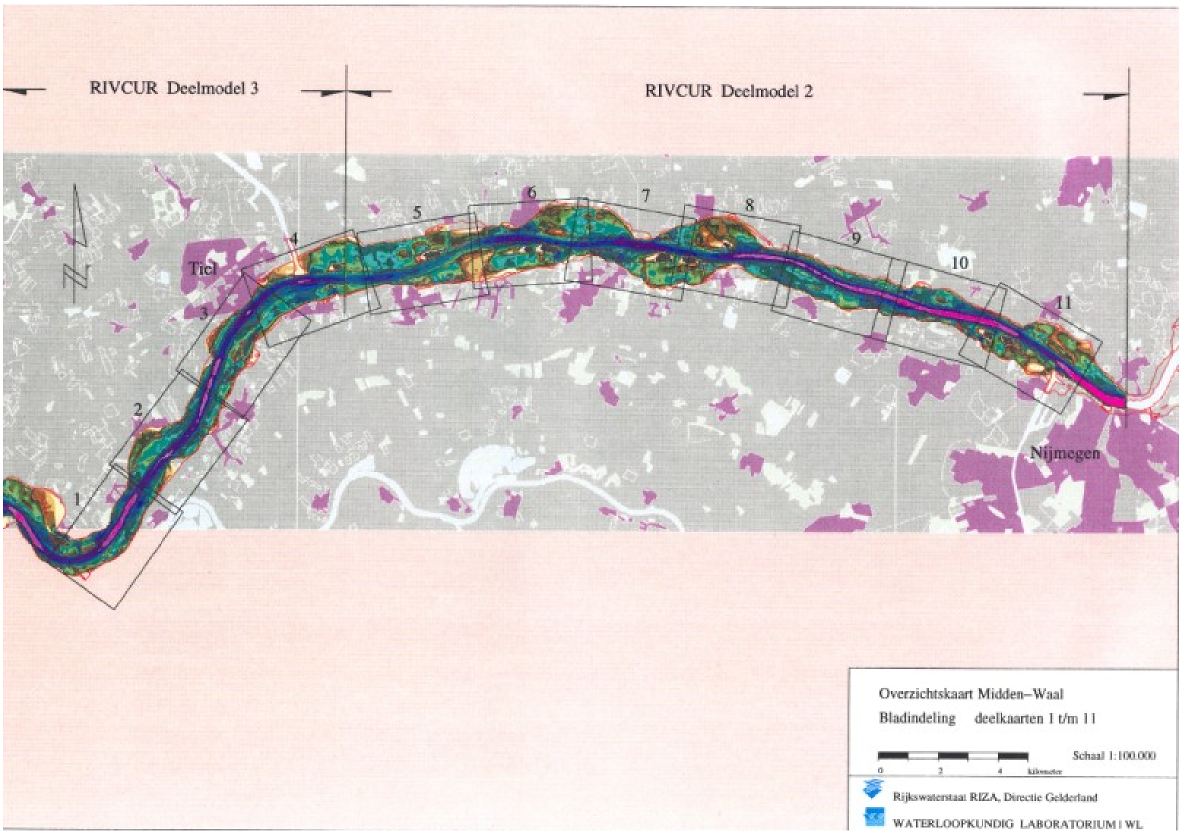


Figure 4.2 Legend of figures 4.1 through 4.6

Figure 4.3 shows a more detailed map of the flow velocities that were computed in a relatively narrow and straight reach near Winssen. Velocities in the centre of the main channel range from 1.8 m/s tot more than 2 m/s. Flow velocities at the floodplains also are relatively high and range from about 0.5 tot 1.2 m/s. Adjacent to the river dike flow velocities are less than 0.5 m/s.

Flow velocities near Ophemert (Figure 4.4), generally are less than 1 m/s.

Figure 4.3 Flow velocities computed with RIVCUR for the River Waal near Winssen (km 895) when the discharge at Lobith equals 15000 m^3/s (source: WL |Delft hydraulics, 1994)

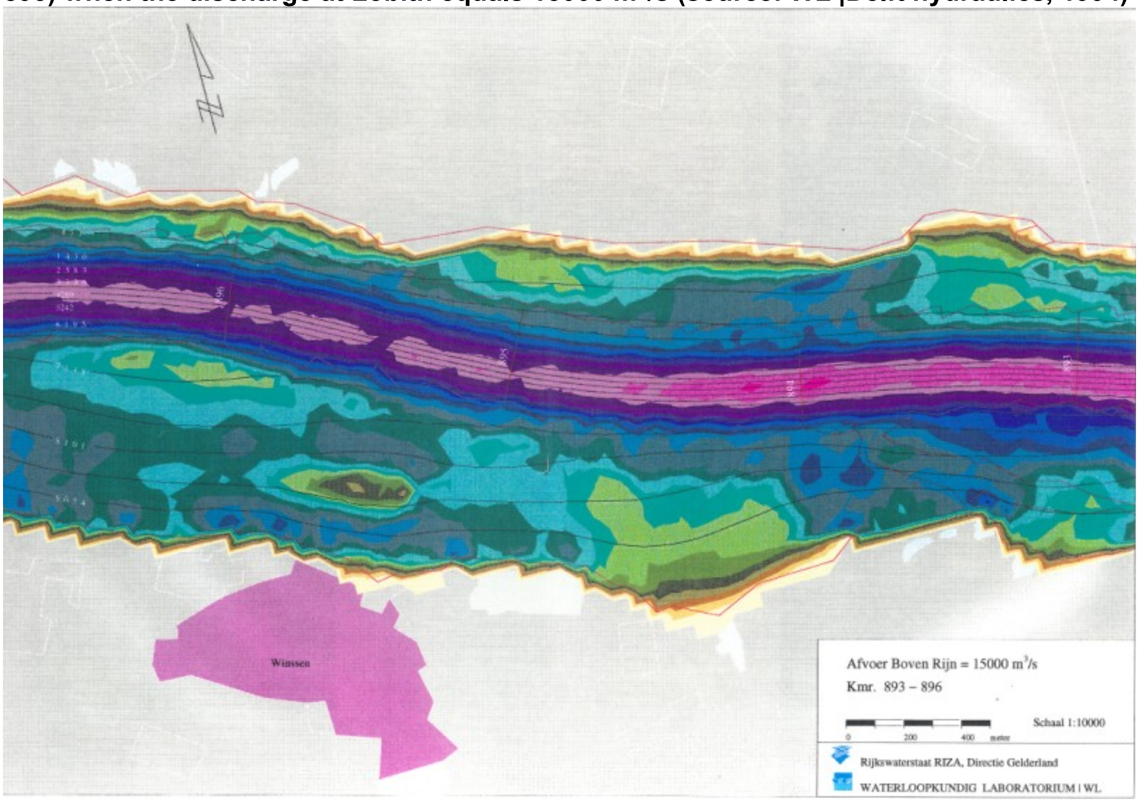
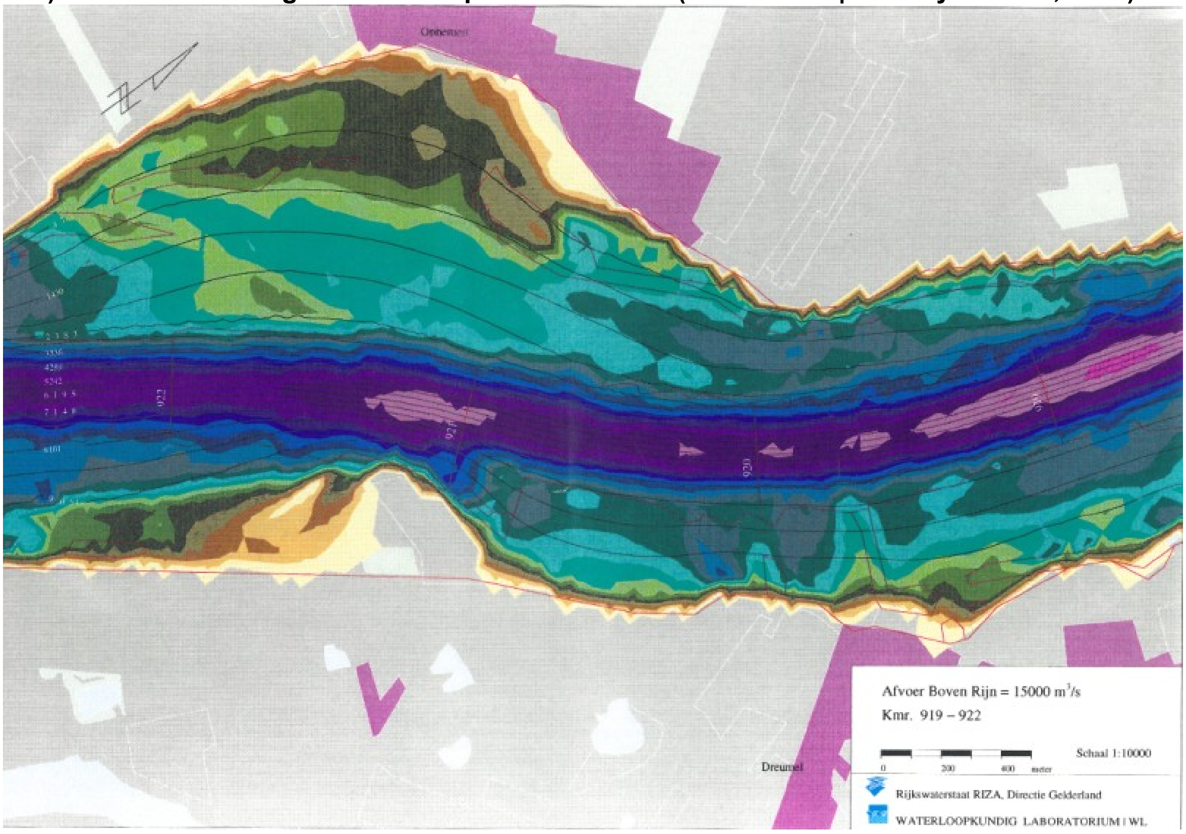


Figure 4.4 Flow velocities computed with RIVCUR for the River Waal near Ophemert (km 920) when the discharge at Lobith equals 15000 m^3/s (source: WL | Delft hydraulics, 1994)



The velocities shown in Figure 4.1 through 4.4 only occur when water depths are large and a substantial part of the discharge occurs over the floodplains. Near Winssen for example about 40% of the total discharge takes place over the floodplain. These circumstances are very different from those in Rotterdam, where water depths are small and discharge over the unembanked and built up areas is expected to be small as well.

When the discharge at Lobith is 8200 m^3/s flow velocities near Winssen are less than 1 m/s. In fact, large areas are characterized by flow velocities of less than 0.5 m/s. Near Ophemert flow velocities are less than 0.7 m/s and in large areas even less than 0.4 m/s.

The lowest river discharge for which velocities were computed was 6800 m^3/s at Lobith. Under these conditions both floodplains are inundated, but the total discharge over the floodplain is small. Computed flow velocities near Winssen mainly are less than 0.4 m/s (Figure 4.5). At a few locations velocities up to 0.8 m/s were computed. Near Ophemert the maximum flow velocities also generally are less than 0.4 m/s. Locally values of 0.6 m/s occur (Figure 4.6). Maximum flow velocities in the main channel are about 1.6 m/s.

Figure 4.5 Flow velocities computed with RIVCUR for the River Waal near Winssen (km 895) when the discharge at Lobith equals 6800 m³/s (source: WL |Delft hydraulics, 1994)

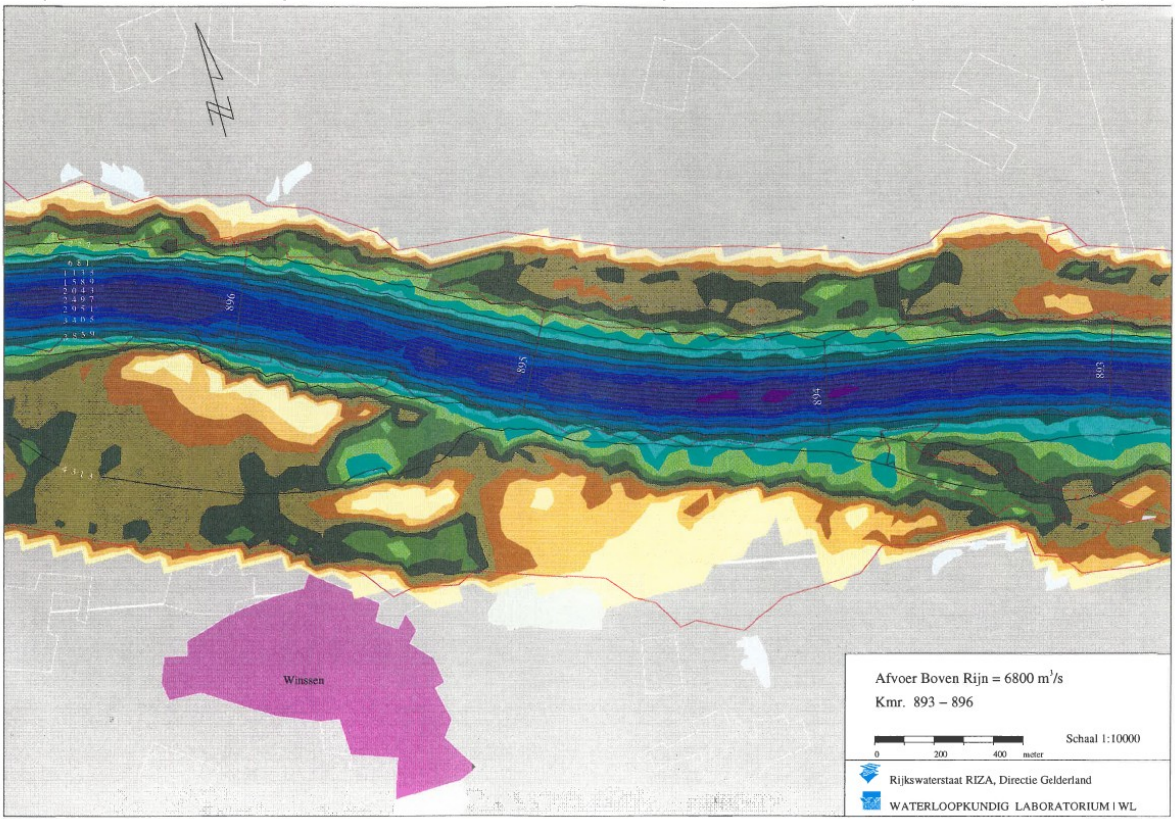
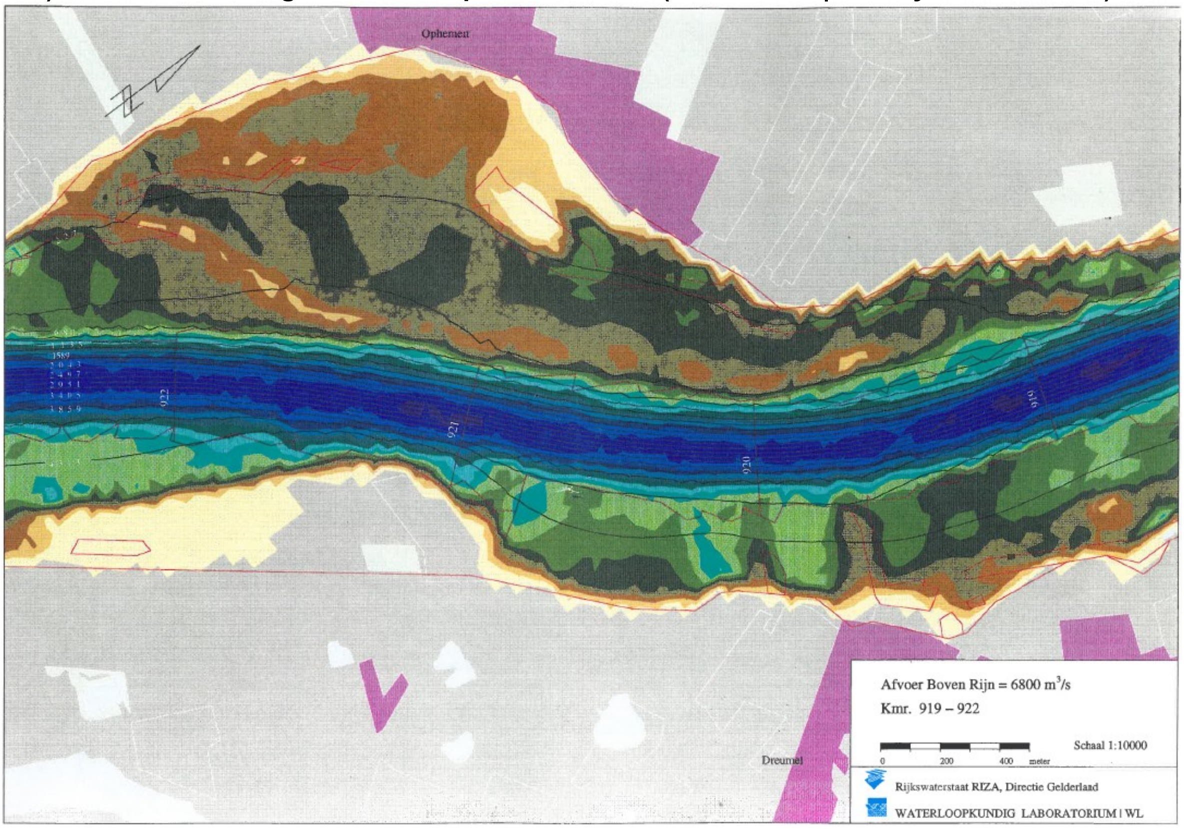


Figure 4.6 Flow velocities computed with RIVCUR for the River Waal near Ophemert (km 920) when the discharge at Lobith equals 6800 m³/s (source: WL |Delft hydraulics, 1994)



4.3 Conclusion

The conditions described in the last section, i.e. discharge of 6800 m^3/s at Lobith, are most similar to those in Rotterdam, because water depths in the adjacent floodplains are relatively shallow. Under these conditions, flow velocities in large parts of the floodplain are less than 0.5 m/s. Only locally velocities of 0.8 m/s occur. Flow velocities in the main channel seem somewhat lower than maximum flow velocities in some parts of the Nieuwe Waterweg, but they last for a longer period of time. In the Nieuwe Waterweg flow velocities vary with the tidal cycle, which means that they only remain high for a short period of time (hours instead of days or weeks).

Given the lower hydraulic roughness values in the active floodplains along the river Waal and the high percentage of the total river discharge that flows over these floodplains, the values computed here could be regarded as an upper limit for the flow velocities that occur at the unembanked areas near Rotterdam and Dordrecht. The unembanked areas near Rotterdam and Dordrecht are urbanised and therefore characterised by a high hydraulic roughness, which results in lower discharges and lower flow velocities.

5. Synthesis

The previous chapters provide an overview of knowledge on flow velocities in flood prone areas along the tidal river reaches of the rivers Rhine and Meuse as well as in unembanked flood plains in along upstream reaches of the river Rhine. The main findings are summarized here. Next, they are used to estimate flow velocities that are likely to occur at the quays in the tidal river area near Rotterdam.

Flow velocities computed for the Stadswerven area in Dordrecht vary from less than 0.1 m/s to about 0.25 m/s. Higher flow velocities of more than 0.5 m/s are found only locally. It could be assumed that flow velocities in the unembanked quays of Rotterdam are within the same range, because:

- both areas are flooded only under very extreme conditions that occur about once every 2000 years or less;
- water depths are small (decimetres instead of meters);
- both areas have a high hydraulic roughness due to buildings and other objects.

To verify this hypothesis as much as possible, flow velocities measured and computed in the main channel in both areas were compared. The idea behind this comparison was that when flow velocities in the main channel are comparable, it seems likely to assume that flow velocities at the rarely inundated unembanked areas and quays, with low water depths, are similar as well.

It appeared that flow velocities that were measured and computed in the channel near Dordrecht fall within the range of flow velocities measured and computed for the main channel near Rotterdam. Only at the most western end of the river mouth (i.e. closer to the Maasvlakte and the sea) higher flow velocities are found.
This would imply that hydraulic conditions in the main part of the unembanked area of Rotterdam are similar to those in Dordrecht, but that higher flow velocities could be expected at the Maasvlakte. The Maasvlakte is, however, protected by a sort of wall or dike that in some places directly protects the adjacent land and at other locations limits the effects of currents and waves as it is located off shore (Figure 5.1). This dike will limit the interaction with the adjacent waterbodies and are hence expected to limit flow velocities at the Maasvlakte as well.

Figure 5.1 The wall / dike that protects the Maasvlakte. Distance between the wall and the shoreline is about 300 meters (source: google earth)

Finally, flow velocities computed at floodplains along the river Waal were reported. As the hydraulic roughness of floodplains is less than the hydraulic roughness in unembanked areas near Rotterdam and Dordrecht, the computed flow velocities at floodplains are expected to exceed those computed for Rotterdam. It was found that river discharges that just flood the adjacent floodplains, result in flow velocities of less than 0.5 m/s in the main parts of the floodplains. At floodplain sections that discharge more water, higher flow velocities can be found (up to 0.8 m/s). Given the relatively low hydraulic roughness of floodplains, these values can be regarded as an upper estimate of the average flow velocities that can be expected near Rotterdam.

Combination of knowledge and information on flow characteristics collected for different locations along the rivers Rhine and Meuse suggests that flow velocities at the unembanked areas along the downstream river reaches near Dordrecht and Rotterdam will generally be low (0.1 to 0.25 m/s). Locally, i.e. close to the main channel and at locations where the water is forced through a narrow opening between buildings or other obstacles, higher flow velocities of about 0.5 m/s can be expected. Higher flow velocities are also expected at locations where water is forced between or around obstacles (similar to wind that is forced between tall buildings).

Roos (2003) studied damage to buildings caused by high flow velocities. Her results indicate that serious damage to brick walls can be expected when flow velocities exceed about 0.5 m/s. Concrete walls, however, are expected to remain intact as long as flow velocities are less than 2 m/s. Damage to buildings is thus expected to be limited in the unembanked areas near Rotterdam when flow velocities are less than 0.5 m/s. Also, the flooded areas are wadable as long as the product of the maximum water depth and flow velocity is less than 0.5. Military manuals even report threshold values of 1.

Climate change is expected to result in larger water depths under design flood conditions (see also the maps made in part 1 of this study). This increase, however, is not expected to result in dangerously high flow velocities. At most locations, flow velocities are expected to remain in the order of 0.5 m/s or less.

It is expected that a 2D hydraulic model will become available in 2010. This model can be used to compute flow velocities, under present and future conditions (i.e. with sea level rise), in more detail. A simpler option to determine the effect of sea level rise on flow velocities at the unembanked sections in the Rijn-Maasmonding would be to develop relationships between water depth and flow velocities. This, however, is not possible as flow velocities not only depend on water depth, but also on water level slope. Computer simulations show that maximum flow velocities occur before maximum water depth is reached. Maximum flow velocities at the flooded areas therefore depend on water depth and the time of flooding with respect to the time of maximum water level.
Sensitivity analysis of maximum flow velocities (during storm surges) in the main channel near Stadshavens and Krimpen a/d IJssel indicate that a 1,3 m rise in sea level may increase flow velocities by 10 to 20% (from about 1,4 m/s to 1,6 m/s for scenario 1 in chapter 3).

6. Conclusion

Flow velocities in the main parts of the unembanked areas near Rotterdam are expected to be low (0.1 to 0.25 m/s). Locally, i.e. close to the main channel, higher flow velocities of about 0.5 m/s can be expected. Higher flow velocities are also expected at locations where water is forced between or around obstacles (similar to wind that is forced between tall buildings). Damage to buildings will be limited when flow velocities are less than 0.5 m/s. Also, the flooded areas are wadable as long as maximum water depths are in the order of 1 m or less.

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