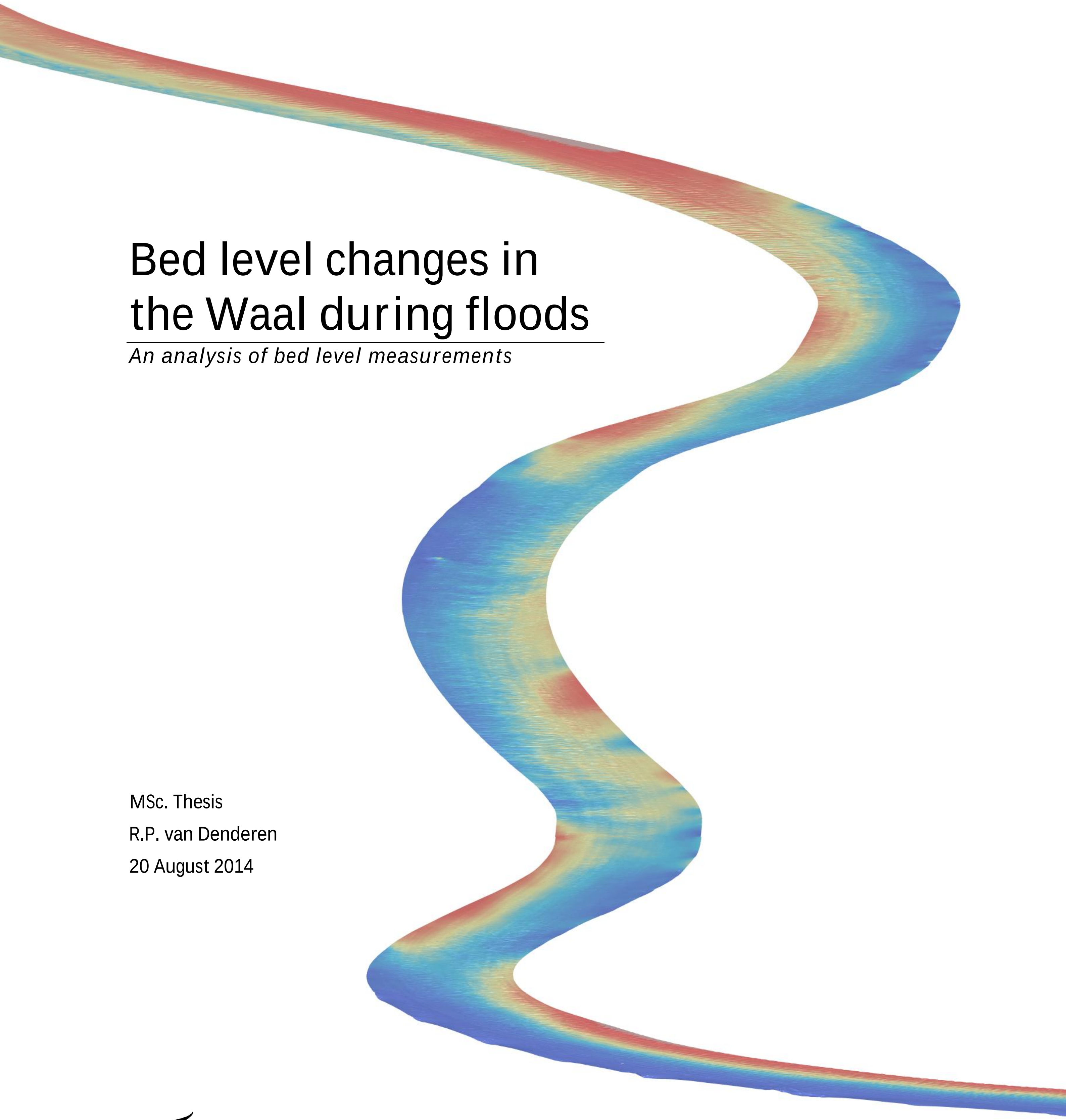
Bed level changes in the Waal during floods

An analysis of bed level measurements



MSc. Thesis

R.P. van Denderen

20 August 2014

TU Delft
Delft University of Technology

Deltares
Enabling Delta Life

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Abstract

Bed level changes during a flood can have large influence on the safety against flooding and the navigational function of a river. In 1997 measurements were carried out in the Waal during a flood. These measurements present an average decrease of the bed level in the order of 10 cm over a 10 km reach which is much larger than expected from the current morphological models. Two reasons for this bed level decrease are suggested: the unsteady sediment load and the influence of a measuring error. The goal of this thesis is to find the main processes which affect the average bed level during floods in rivers like the Waal.

The maximum influence of the unsteady sediment load is estimated using multiple empirical relations for the bed load transport, the bed particle velocity and the suspended load transport. With these models the maximum influence of the unsteady sediment load is estimated. The analysis shows that the maximum change of the sediment load can cause a bed level change in the order of 0.7 mm during the 1997 flood in the Waal. Therefore it is concluded that the influence of unsteady sediment load is too small to significantly affect the bed level and to explain a 10 cm decrease of the bed level.

The bed level measurements in the Waal during the 1997 flood were carried out with a single-beam echosounder. This means that the water depth is measured and that the water level is used to estimate the bed level. However, during the measurements the water level was not measured but estimated based on linear interpolation between station Dodewaard, which is in the upstream part of the measuring reach, and measuring station TielWaal, which is downstream of the reach. In addition, the water level at station Dodewaard was not measured but estimated based on a regression relation. Both the linear interpolation between the two stations and the regression relation at station Dodewaard are a source of inaccuracies. Therefore these water levels are compared to WAQUA-results for the 1997 flood and water level measurements during the 2011 flood. From this comparison is concluded that a combination of both sources of inaccuracies can be responsible for an average bed level decrease of 10 cm. Other possible errors like squat, the propagation velocity of sound in water or a bias in the bed level measurements due to dune height, have a too small influence or do not show a relation with the flood. The incorrect estimation of the water level is therefore assumed to be the main contributor to the large-scale bed level decrease during the 1997 flood in the Waal.

It is assumed that the WAQUA-result presents a better estimation for the water level during the flood and therefore the WAQUA-result is used to correct the bed level. The corrected bed level shows that the WAQUA-result contains errors and inaccuracies, but also shows that the bed level changes which do occur in the Waal are mainly caused by spatial variations of the river width. The corrected measurements are compared with results from a Delft3D model. The model shows similar trends to the measured bed level but the quantitative differences are large. These large differences

could be caused by the inaccuracies in the measurements or by the assumptions made in the Delft3D model. The model confirms that the spatial variation of the river geometry has the largest influence on the bed level changes during floods. The model is able to simulate the main areas of aggradation and degradation but it is impossible to validate the model results based on the measurements.

As a reference case the bed level changes at the Pannerdensche Kop during the 1997 and the 1998 flood are studied. An error in the estimation in the water level is not likely to have a large influence since the measuring station at the Pannerdensche Kop is located in the middle of the measured reach. During neither of the floods the measured bed level shows a large-scale bed level change. However, local bed level variations are large and are caused by spatial variations of the river width. Therefore the bed level measurements at the Pannerdensche Kop confirm that a large-scale bed level change during a flood in the Waal does not occur but that the spatial variation of the river geometry has a large influence on the bed level changes during a flood.

The main process which affects the average bed level in the Waal is the river geometry. The bed level measurements show that a spatial variation of the river width has a large effect on the bed level during a flood. With a Delft3D model it is possible to show these effects but the measurements still have large uncertainties and the model is based on incorrect assumptions. Therefore it is not possible to validate the model during a flood in more detail. A new bed level measuring campaign has to be carried out to be able to validate the morphological models during floods. The current measuring techniques and measuring guidelines make it possible to capture the bed level changes during a flood in the Waal more accurately. However, it is recommend to regularly check the bed levels during the measurements in order to prevent the large measuring errors which occurred during the 1997 and the 1998 floods.

Acknowledgements

This thesis presents the results of my graduation work which I carried out to conclude the master Civil Engineering at the Delft University of Technology. In cooperation with Deltares and the university I studied the bed level changes in the Waal during floods by analysing measurements and model computations.

I would like to thank the members of my graduation committee consisting of prof. dr. ir. W.S.J. Uijttewaal, dr. ir. A. Blom, dr. ir. S. Giri, dr. ir. A. Sieben and dr. S. Stecca for their feedback and support. The regular meetings with the research group of Astrid Blom were very helpful and gave an interesting insight into the work of other on-going research. I would also like to thank the employees and the students at the RIV department of Deltares who were able to help me during my thesis and made my stay enjoyable.

Pepijn van Denderen
Delft, July 2014

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1 Introduction

In the Netherlands a framework has been set up which is known as the Room for the River Programme. This programme was initiated after two near-floodings in 1993 and 1995 due to large discharges in the Rhine branches. The Rhine branches are shown in Figure 1.1. The river has two main bifurcations: the Pannerdensche Kop which results in the Pannerdensch Kanaal and the Waal, and the IJsselkop which results in the IJssel and the Nederrijn. The main objectives of the Room for the River Programme are to increase the discharge capacity of the Rhine branches to 16,000 m^3/s by 2015 and to improve the overall environmental quality of the river region (Ruimte voor de rivier, 2012). The programme started in 2006 and includes measures like: river widening, floodplain lowering and obstacle removal. These measures change the flow patterns which affect the morphodynamics of the river and these morphodynamic changes can have a negative impact on the safety against flooding and the navigational function of the river. The current morphological models are validated on the basis of regular flow conditions and can have inaccuracies in the prediction of the bed level during floods. The present study aims to improve the prediction of the bed level during floods by defining the importance of the sediment transport layers and by studying measured bed level changes during floods.

Figure 1.1 An overview of the Rhine branches with in green the floodplains. In the top left a map of the Rhine and Meuse basin which are divided by the red line (Modified version of Natuurdichtbij, 2009).

1.1 Bed level measurements during the 1997 flood

Floods can have a large influence on the large and small scale morphodynamics of a river. In 1997 measurements were carried out in the Waal during a flood. These measurements present the variation of the bed level during the flood period and from these measurements the average bed level and the bed form characteristics were determined. A significant decrease in the average bed level during the peak of the flood was found by Wilbers (1998) and Sieben (2006). Both found an average decrease of the bed level in the order of 10 cm which is much larger than expected from the current morphological models. This section reanalyses the measured bed levels during the 1997 flood and presents the time and spatial variation of the bed level changes.

1.1.1 Measurements

During the 1997 flood bed level measurements were made using a single-beam echosounder over a 10 km reach, Figure 1.2. The measurements were carried out from 27 February till 15 April with a peak discharge of 4660 m^3/s in the Waal on 3 March. Figure 1.3 shows the discharge and the water level at measuring station TielWaal during the 1997 flood.

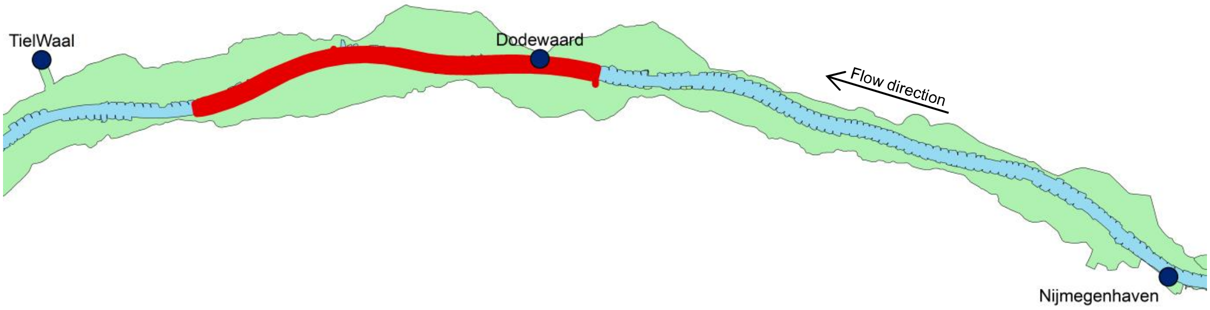

Figure 1.2 The measuring reach (red) with the surrounding water level measuring locations.

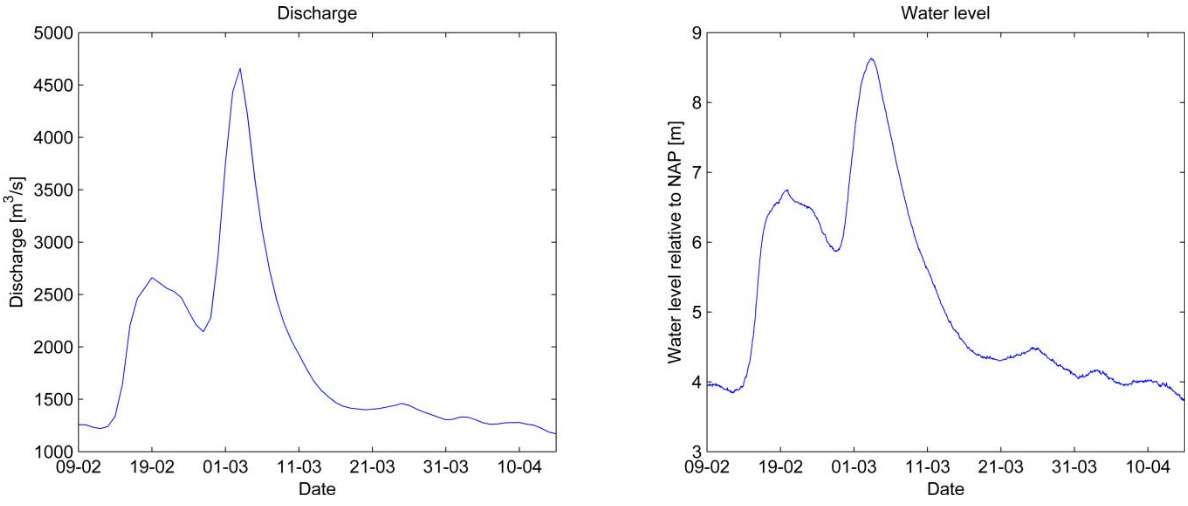

Figure 1.3 Discharge and water level at measuring station TielWaal during the 1997 flood.

The bed level was measured using a single-beam echosounder on three different vessels. The echosounder measures the depth by sending a sound pulse to the bed. This pulse can reflect on, for example, a fish or sediment particle before it reaches the bottom. Based on the time it takes for the pulse to reflect and return to the vessel, a distance is calculated on the basis of the propagation velocity of sound in the water. From Figure 1.4 can be seen that if the bundle of the echosounder is too wide or the bed forms are too steep that the pulse reflects at different heights for the same location of the vessel. In the processing of the data the choice was made to calculate the average value of the return pulses and use this as an estimation of the bed level.

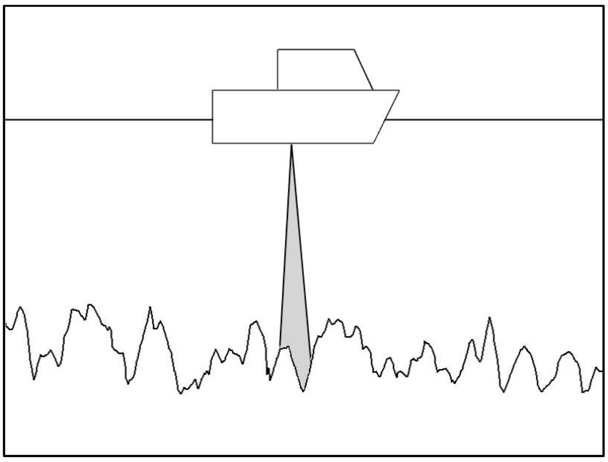

Figure 1.4 Sketch of the beam of a single-beam echosounder. The beam has a certain width when it reaches the bottom which results in multiple return signals corresponding with multiple water depths.

1.1.2 Data processing

The bed levels were measured in longitudinal trajectories as shown in Figure 1.5a. Every point on a trajectory is about 0.5 m apart and the distance between the trajectories is in the order of 20 m. This picture shows that the trajectories are not regular. The distances between the trajectories vary and at some locations the trajectory suddenly stops. On some days the water depths at the boundaries of the main channel were too small to be measured. To prevent large interpolation errors and a biased averaging, only the middle 100 m of the river is evaluated. A Triangular Irregular Network (TIN) is created by triangulating the data points which results in a height model build up from differently sized triangles, Figure 1.5b. This height model is interpolated to a grid (Figure 1.5c) which follows the river axis to make it possible to calculate a moving average of the river in longitudinal direction. The cell size of the grid is 2x2 m which means that small dunes are not filtered.

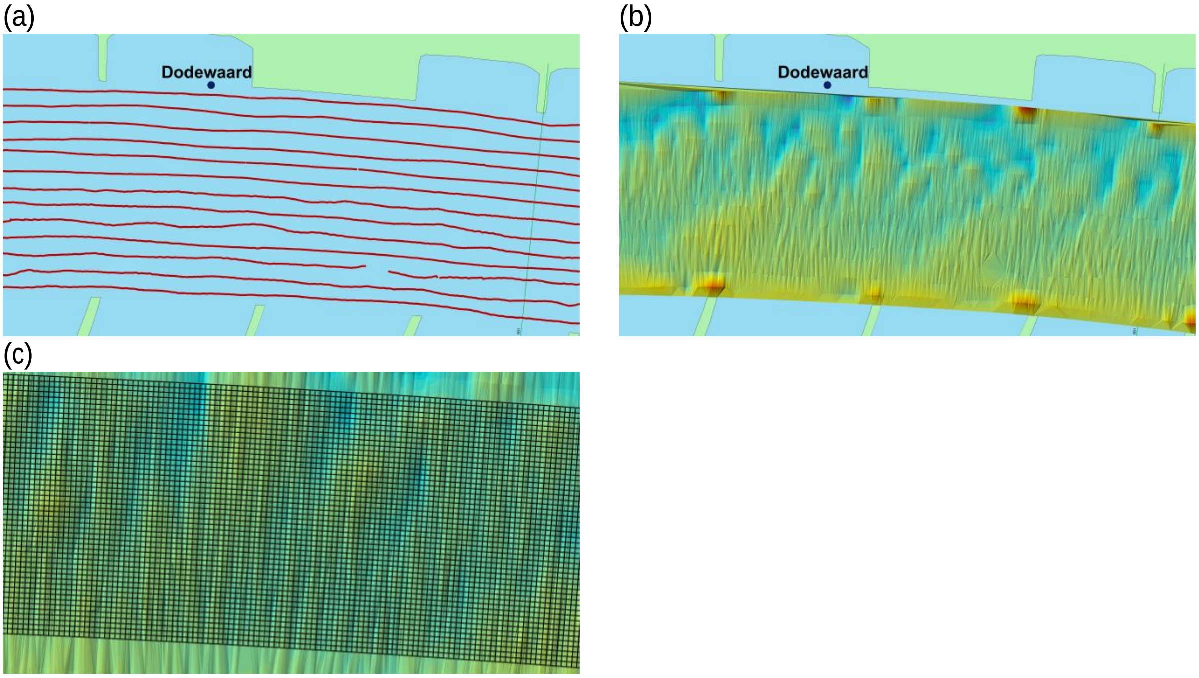

Figure 1.5 Overview of the data at a small area around Dodewaard. (a): Trajectories of the measuring vessel. (b): Height model created from a Triangular Irregular Network (TIN). (c) Grid to which the measurements are interpolated.

1.1.3 Average bed level

The effect of the flood is shown by calculating the average bed level. In the bed level data there are dunes which propagate downstream which need to be filtered. The filtering is done by using a moving average in longitudinal direction. An averaging distance has to contain multiple dune lengths to mitigate the effects of the irregular dunes. A distance of 390 m is chosen which means that the average will more or less include 6 dunes of 60 to 70 m (Sieben, 2006). The fluctuations which remain are in the order of 500 to 800 meters. An example of the results of the moving averaging is shown in Figure 1.6. The line shows that the largest fluctuations are filtered. On some days the average bed level deviates more than a metre from all the other bed level measurements which is caused by a malfunctioning of the echosounder. On other days there is too little data to cover the whole grid. These days are not taken into account in the following analysis.

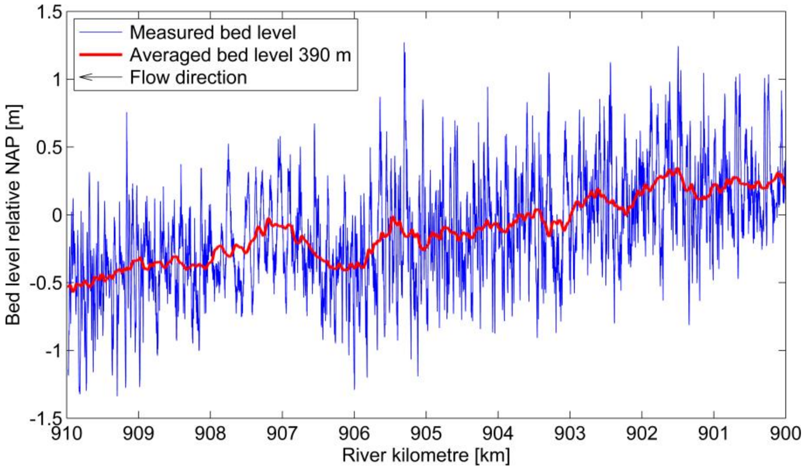

Figure 1.6 The measured bed level on 3 March along the river axis and the result of the moving average over a distance of 390 m.

In Figure 1.7 the bed elevation at each river kilometre is plotted as a function of the time. The values in this graph are averaged over 390 m in longitudinal direction and 100 m in width. At most of the locations the bed level decreases during the rising flood and increases during the falling period of the flood. On average this bed level change is in the order of 10 cm, but there are large differences over the measuring reach. In the upstream part of the reach the decrease seems to be largest (15cm), in the middle part smallest (0 cm) and in the downstream part the decrease is in the order of 10 cm. The 2D variation of the bed level is presented in Figures 1.10 and 1.11. Figure 1.10 presents the bed level relative to NAP and since the variations of the bed are much larger than the bed level changes between the days, the bed level changes are barely visible. Figure 1.11 therefore presents the bed level relative to the one of 7 March. Figure 1.7 shows that the bed level on 7 March is at many locations similar to the bed level before the peak of the flood.

Figure 1.11 shows a lot of local variation. Please note the development close to river kilometre 907. Both Figures 1.7 and 1.11 show that the bed level does not decrease much during the rising flood but during the falling period it does increase. This results in a bed level which is significantly higher after the flood compared to before the flood. This would only be possible when large deposition occurs during the flood.

In Figure 1.8 the bed profiles are shown for two days: 3 March which is at the peak of the flood and 7 March which is in the falling period of the flood after the largest changes of the bed level. In this graph it can be seen that there are fluctuations in the bed which slowly propagate downstream. In the difference plot of these two lines, Figure 1.9, large fluctuations are present which are partly caused by the propagation of the sand depositions and erosion pits over the bed. The difference plot (Figure 1.9) represents more or less the maximum change of the bed level during the flood. It can be seen that this change decreases from upstream to downstream with the lowest point at 906.5 km after which the difference increases again.

The measurements present an average bed level decrease of 10 cm over the reach. There are two possible reasons for a large-scale decrease of the bed level: a large change of the sediment load during the flood and measuring errors which vary during the flood. If the sediment load shows a large variation during the flood, an additional term has to be added to the sediment-mass balance which influences the average bed level. From Figures 1.7 and 1.9 follows that if the bed level change is caused by a measuring error, the measurement error has to have two characteristics to explain the measured bed level decrease: the error has to change in time with a maximum or minimum at the peak of the flood and the error has to show a spatial variation over the reach which corresponds to the values shown in Figure 1.9.

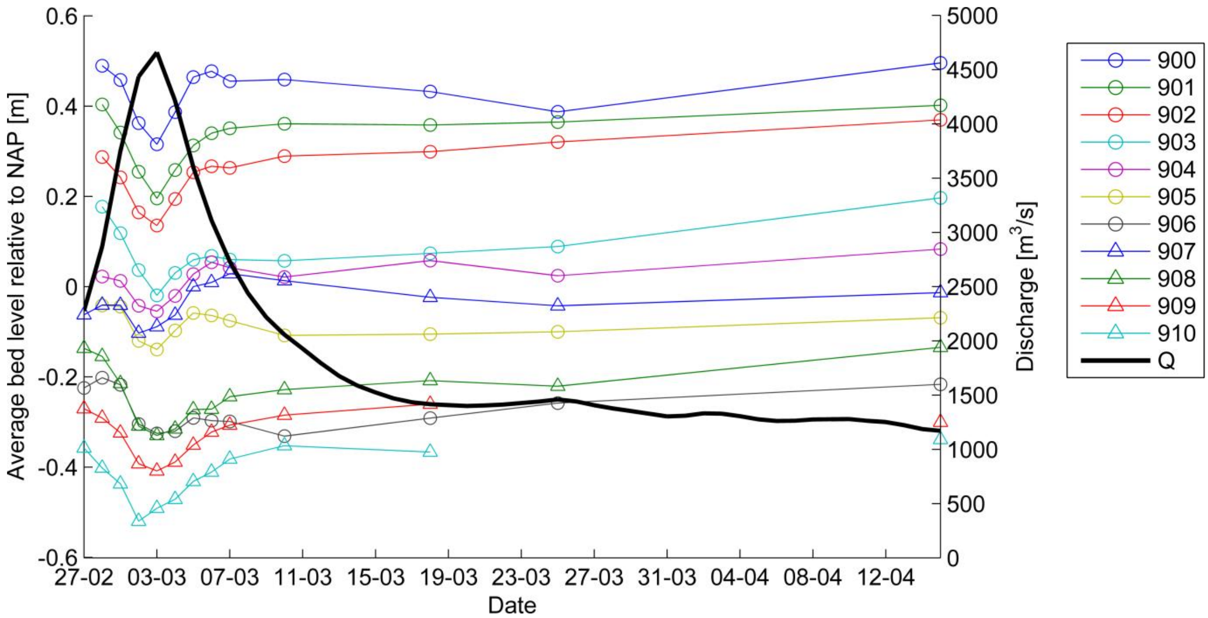

Figure 1.7 Average bed level during the 1997 flood at each river kilometre in the measuring reach. Q is the discharge in the Waal at measuring station TielWaal.

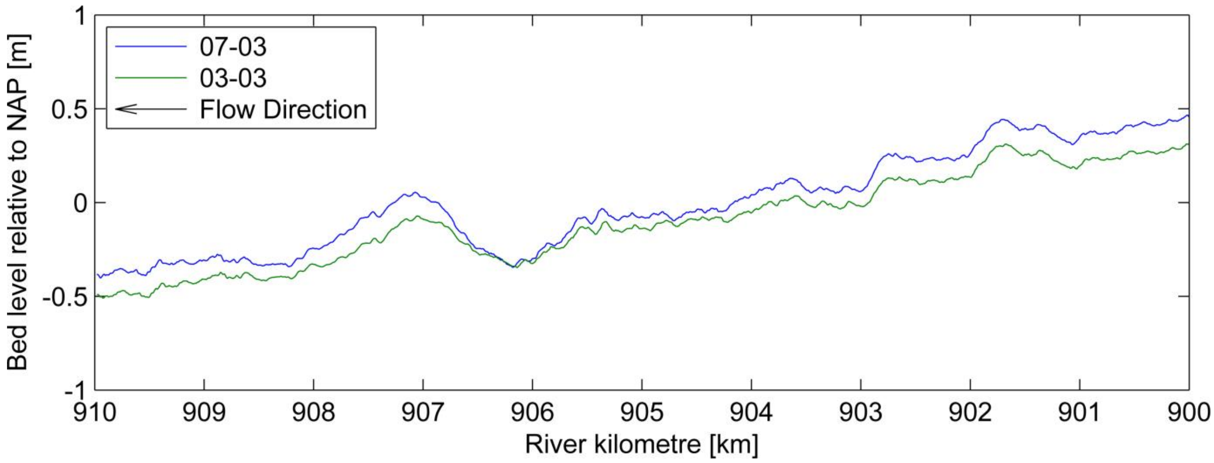

Figure 1.8 Bed profiles of 7 and 3 March created from a moving average with an averaging length of 390 m.

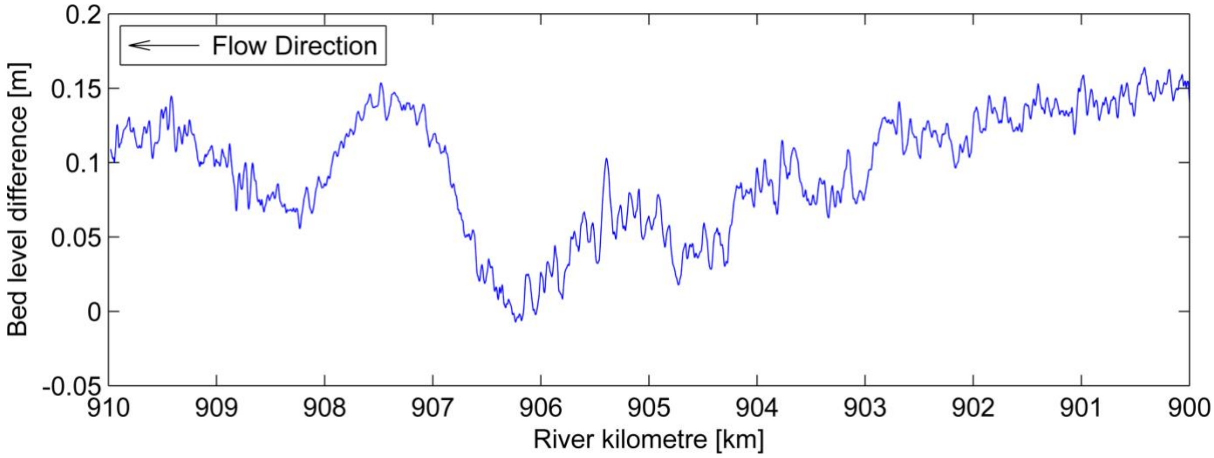

Figure 1.9 Spatial variation of the bed level difference between 7 and 3 March.

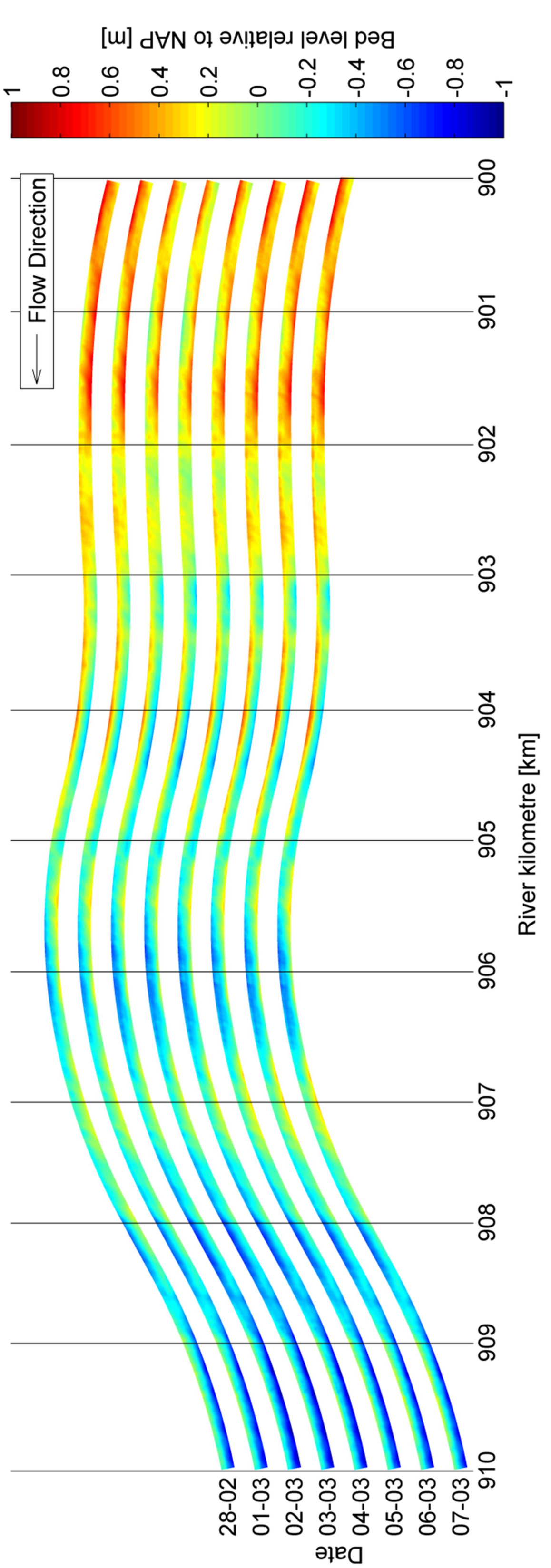

Figure 1.10 Bed levels during the 1997 flood averaged in longitudinal direction over a distance of 390 m.

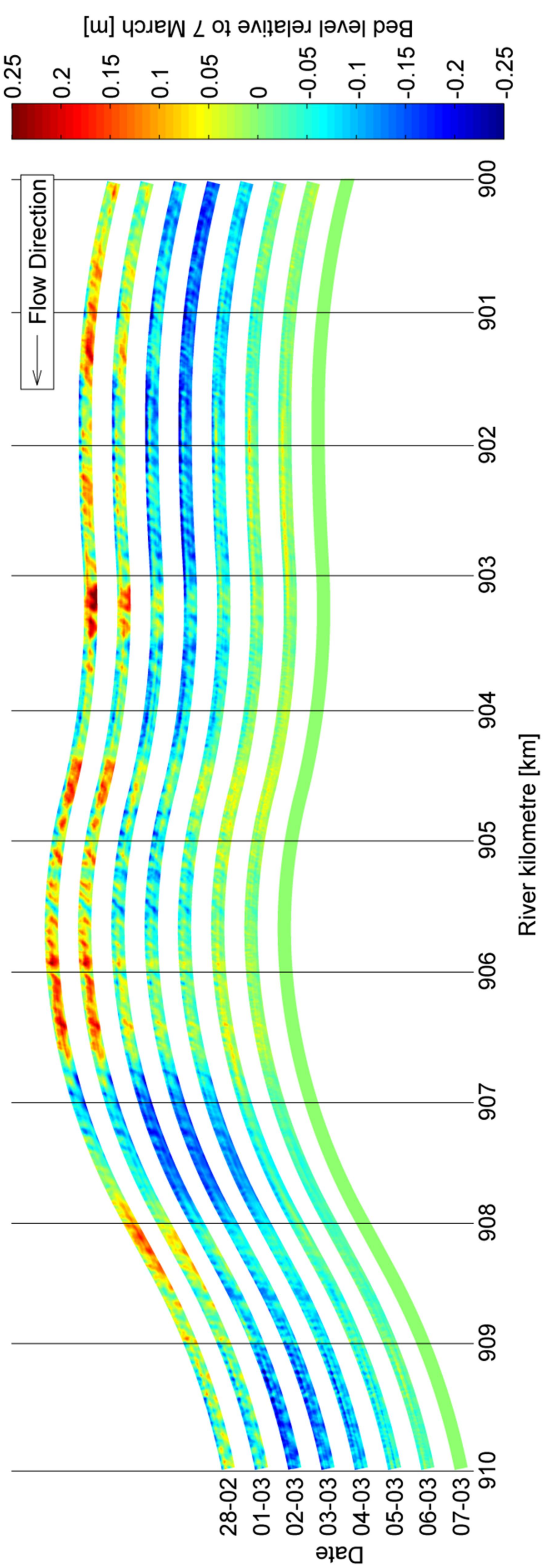

Figure 1.11 Bed level at each date subtracted by the bed level on the 7 March.

1.2 Variable sediment load layers

During a flood the flow conditions rapidly change which has an effect on the sediment load of the flow. The sediment load is the amount of sediment stored in the water column and because of mass conservation this means that the bed level is affected by a change of the sediment load in time. This effect is normally assumed to be very small, but could explain a large-scale decrease of the bed level during a flood. Figure 1.12 makes a distinction between two sediment load layers: the suspended load layer and the bed load layer. In this figure z_b [m] is the bed level, h_s [m] is the height of the suspended load layer, c_s [-] is the concentration of sediment moving in suspension, δ_b [m] is the height of the bed load layer and c_b [-] is the concentration of sediment moving as bed load.

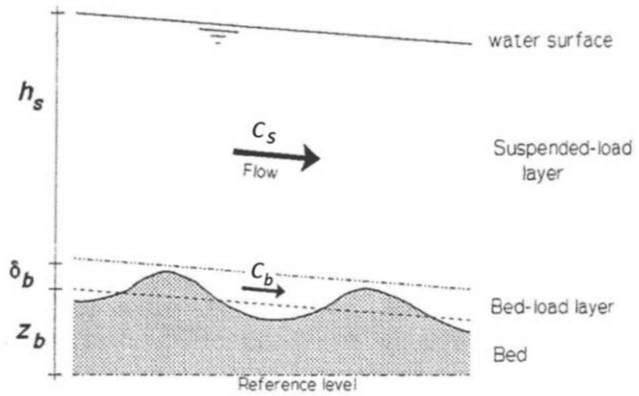

Figure 1.12 A schematization of the layered model for sediment flow (Sloff, 1993). The height of the transport layers multiplied with the concentration is a measure for the amount of sediment in transport.

The thicknesses of the sediment load layers are a defined as $a_b = \delta_b c_b$ and $a_b = \delta_b c_b$ with a_b [m] the thickness of the bed load layer and a_s [m] the thickness of the suspended load layer. The bed load layer thickness (a_b) is defined as the thickness of the bed load layer in the water column multiplied by the concentration of sediment in the bed load layer. In other words, the thickness of this layer is defined as a volume of sediment without pores divided by a surface area.

The suspended load transport was measured during the 1997 flood. From these measurements follows that the suspended load transport was in the order of 16 m^3/mday and the flow velocity was 1.2 m/s during the peak (Kleinhans, 2002). This results in a suspended load layer (a_s) of about $1.6*10^{-4}$ m if one assumes that the suspended particle velocity approaches the flow velocity (Van Rijn, 1984b). From this it may be concluded that the suspended load is not the cause of the large bed elevation drop (Sieben, 2006).

The influence of the unsteady bed load layer was studied by De Vet (2012) using a 1D model. In the model the bed load layer thickness is included in the sediment-mass balance and is calculated as a function of the bed load transport and the bed particle velocity. For the calculation of the bed particle velocity an empirical relation proposed by Van Rijn (1993) was used. Basset (2013) showed that the application of Van Rijn to the particle velocity is valid under the conditions of the Waal. The results of De Vet's experiments show that in case of the 1995 flood in the Bovenrijn the influence of the variable bed load layer thickness on the bed level is relatively small. However, De Vet only tested this for one hydrograph (i.e. the 1995 Rhine flood). A more general description of the bed load layer thickness is studied here.

1.3 Measuring errors

Several measuring errors can explain a large-scale bed level decrease during a flood. Each of these errors shows a time varying inaccuracy during the flood and could have contributed to the large decrease of the average bed level during the 1997 flood. The water level is expected to be the most inaccurate. A single-beam echosounder measures the flow depth and to convert this depth to a bed level the vertical position of the single-beam echosounder is required. This position is a function of the vertical position of the measuring vessel and the vertical position of the echosounder on the vessel. The vertical position of the vessel is estimated by the water level. During the 1997 flood the water level was not measured on the vessel but estimated from the surrounding water level measuring stations. Wiegmann et al. (2002) showed that this could be responsible for a varying error in the bed levels in the order of 5 cm. The vertical position of the echosounder is assumed to be constant.

A second possible error is caused by the sailing velocity of the measuring vessel. When a vessel moves the vessel sinks deeper into the water due to a pressure decrease below the vessel. This sinkage is called squat. The amount of the squat depends on the sailing velocity of the vessel relative to the current and is therefore different when the vessel is sailing upstream and downstream. In the past the effect of squat was often ignored (Wiegmann, 2002).

Other potential errors are a change over time of the propagation velocity of sound in the water and a bias in the bed level measurements. The velocity of sound could change during a flood due a large sediment concentration change which follows from a large change in the flow conditions. A bias in the bed level measurement could, for example, be caused by an underestimation of the dune trough. If this underestimation is related to the dune height, this can lead to an average bed level change during a flood.

1.4 Research questions

Based on the issues, described in the previous sections, the following general research question is formulated:

Which processes affect the average bed elevation during floods in lower course rivers like the Waal?

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

1. What are the effects of the bed load and the suspended load on the average bed levels during a flood?
2. Which measuring errors could result in a large-scale decrease of the average bed level, revealed by the field measurement, in the Waal during the 1997 flood?
3. What is the quality of a morphodynamic prediction of the bed level changes during the 1997 flood?
4. What is the effect of a flood on the average bed level at the Pannerdensche Kop?

1.5 Methodology

Research question 1:
The effects of the bed load layer and the suspended load layer are studied by estimating the maximum thickness of these layers during a flood. Both layer thicknesses are estimated using empirical relations and for each layer multiple models are used. Based on these results the influence of the sediment load on the bed level during the 1997 flood is estimated. The results of this analysis are presented in Chapter 3.

Research question 2:
Several possible measuring errors were mentioned in section 1.3. There are two large contributors to a potential error in the water level: an error in the water level estimation at station Dodewaard and an error due to the linear interpolation between the stations Dodewaard and TielWaal. Both errors are estimated in Chapter 4 using results from a WAQUA computation of the 1997 flood and water level measurements during a flood in 2011.

In Chapter 5 the remaining potential errors are estimated. The effects of squat, sound velocity and a bias in the bed level measurements are taken into account. The propagation velocity of sound is sensitive to errors due to changes in temperature and dissolved material (Hampton, 1967). Estimates of the influence of suspended sediment on the velocity of sound are made on the basis of the results published by Hampton (1967). The bias in the bed level measurements is estimated by expert judgement since there is insufficient data available to compare the single-beam measurements with other datasets.

Research question 3:
Based on the results of research questions 1 and 2 the measured bed levels are corrected to better represent the real bed levels during a flood in Chapter 6. The results of this correction are compared to the results of a Delft3D model. Chapter 7 presents the results of the Delft3D computation.

Research question 4:
Bed level measurements were carried out at the Pannerdensche Kop during the 1997 and the 1998 floods. Unfortunately the bed level data from the 1997 flood is unavailable and therefore the bed level is studied on the basis of the data presented by Wilbers (1998). Sieben (2004; 2006) presented the dataset of the 1998 flood and showed a decrease of the bed level in the order of 10 cm. The data is reanalysed and processed in Chapter 8 to find measuring errors and the source of the large decrease of the bed level.

Conclusion:
The main research question is addressed based on the answers to the previous questions including a brief overview of possible errors in single-beam and multi-beam measurements in Chapter 9. This analysis is based on the results of Wiegmann (Wiegmann, et al., 2002; Wiegmann, 2002) and on the new quality law for bed level echosoundings by the Dutch government (NHI, 2009).

2 Analysis of the Waal

The Waal is the most important shipping route between Rotterdam Harbour and Germany. Moreover, the Waal needs to transport water from the Bovenrijn to the sea during flood. For these reasons a lot of research has been done to keep the river navigable and to reduce the flood risk. This chapter focusses on the characteristics of the Waal during a flood. The first part focusses on water levels and discharges during flood conditions. The second part focusses on the river morphodynamics, the dune formation and the evolution of dune characteristics during floods.

2.1 Floods in the Waal

To study and predict floods in a river, information about water levels and discharges is important. Figure 2.1 presents the main water level measuring station in the upstream part Waal. At Lobith, Pannerdensche Kop and TielWaal the daily averaged discharges are recorded. These discharges are estimated based on a regression analysis as a function of the water level (Van Vuuren, 1998). Figure 2.1 also shows a measuring station Dodewaard but the water level at this station is calculated with a regression relation which is explained in section 2.1.2. Section 2.1.1 presents a comparison of different floods in the Waal.

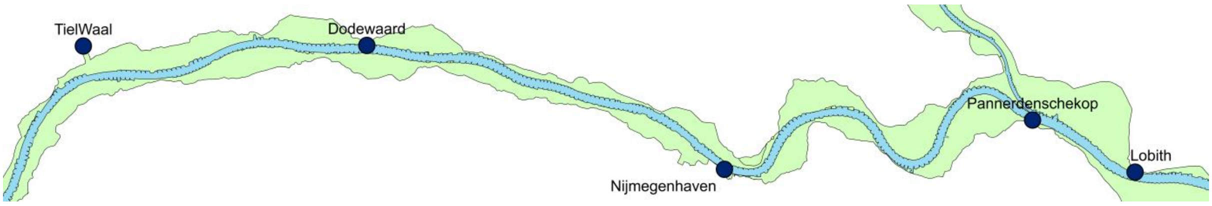

Figure 2.1 A schematized map of the Waal with the locations of the water level measuring stations.

2.1.1 Measured floods

The height and the shape of each flood is different. In thesis three different floods are discussed: the 1997, 1998 and 2011 flood. Figures 2.2a and b present the discharges and the water levels at TielWaal for the three floods. The 1998 flood was largest with a peak discharge of 6158 m^3/s on 4 November 1998. The flood of 2011 has two large peaks of which the second peak is slightly larger than the first with a peak discharge of 5794 m^3/s. The 1997 flood is the lowest of the three with a peak discharge of 4660 m^3/s on 3 March. Figure 2.2c presents the Qh-relations of the three floods. The Qh-relation of the 2011 flood shows a loop at the peak of the flood. This loop is caused by the two flood peaks which are more or less similar in size. Figures 2.2a and b show these two peaks. The 2011 flood is the steepest during the rising period and therefore the Qh-relation is lowest during the rising flood compared to the other floods. This is explained with the Jones equation given by Equation 2.1 which can be derived from the Saint-Venant equations.

$$Q = Q_e \sqrt{1 + \frac{1}{c_{HW} i_b} \frac{\partial h}{\partial t}} \qquad 2.1$$

with Q [m^3/s] the discharge, Q_e [m^3/s] the discharge corresponding to the water level in case of uniform flow, c_{HW} [m/s] the propagation velocity of the flood wave, i_b [-] the slope of the bed and h [m] the water level. Assuming that c_{HW} and i_b are similar for each flood, it is shown that for the same water depth the rising period of the 2011 flood presents higher discharges due to the steeper flood wave. The opposite occurs during falling of the 1997 flood when the $\frac{\partial h}{\partial t}$ is much smaller than during the other floods. This results in a lower discharge for the same water level during the falling of the 1997 flood.

For both the 1998 flood and the 2011 flood a large change of the slope is seen in the Qh relation and in the water level around a water level of 8.5 m. The change of the slope is caused by a large inundation of the floodplains upstream of station TielWaal. An inundation of a large flood plain is expected to cause a temporary lowering of the discharge. However, this lowering is not visible in Figure 2.2a which is most likely caused by the low frequency of the discharge data. The discharges are daily averaged and therefore small and short deviations are not visible.

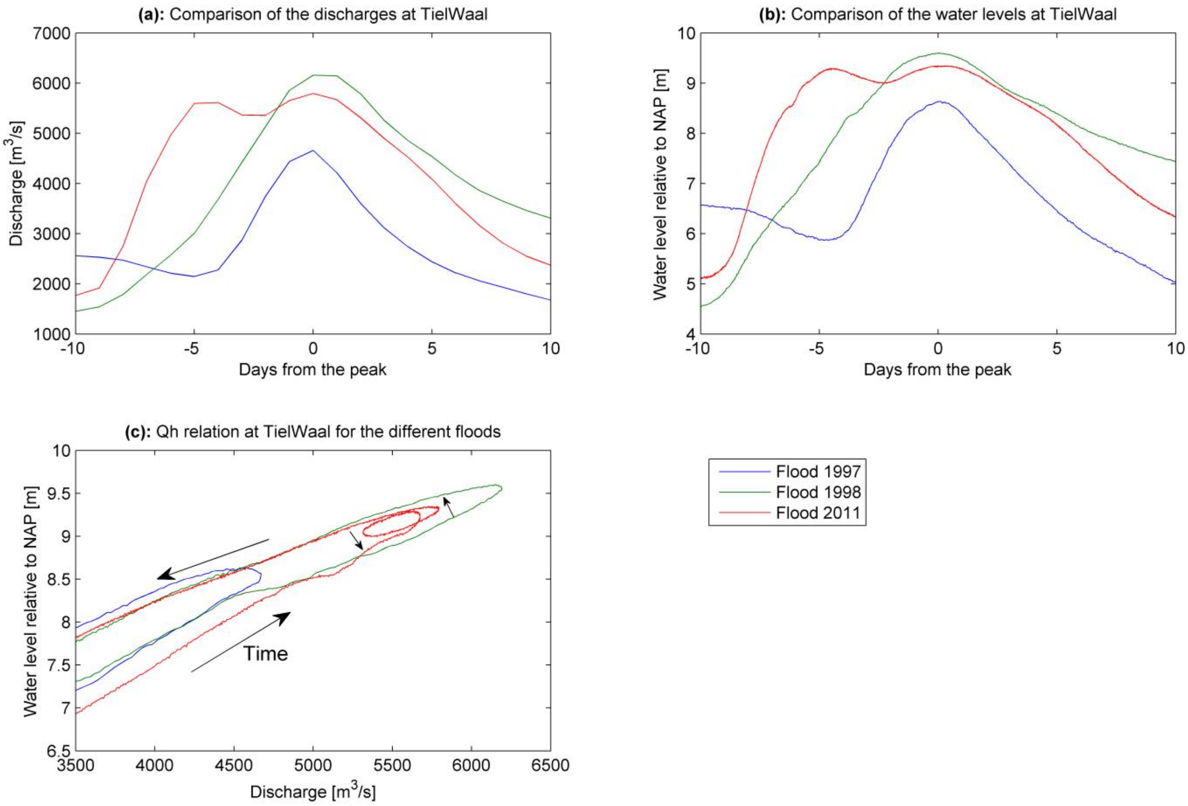

Figure 2.2 (a) A comparison of the discharges during the three floods with the reference time the peak of the flood. (b) The water levels during the three floods with the reference time the peak of the flood. (c) The Qh-relations for each of the three floods

2.1.2 Water level station Dodewaard

Station Dodewaard is an important station for estimating the water level during the bed level measurements. However, the station was removed and replaced by a regression relation in the 1980s. This was done after a measuring optimisation which concluded that it was possible to predict the water level at station Dodewaard on the basis of the water levels at stations Nijmegenhaven and TielWaal with the same accuracy as a measured water level. However, after 5 years the inaccuracy of this regression relation was already in the order of 5 to 10 cm mainly due to changes of the riverbed (Van Rutten, et al., 2003).

During the 1997 flood the water level at station Dodewaard was estimated using a regression relation. The regression relation is based on a 2D-model computation and gives the water level at station Dodewaard as a function of the water level at stations Nijmegenhaven and TielWaal. Table 2.1 presents this regression relation. In between the given values, the water level is interpolated.

Table 2.1 Water level at Dodewaard in cm as a function of the water levels at the measuring stations Nijmegenhaven and TielWaal.

[cm]		Water level at TielWaal										
		182	262	353	448	546	644	748	861	980	1084	1190
Water level at Nijmegenhaven	462	300	350	400								
	560	350	400	450	500							
	662	400	450	500	550	600						
	766		500	550	600	650	700					
	866			600	650	700	750	800				
	972				700	750	800	850	900			
	1080					800	850	900	950	1000		
	1200						900	950	1000	1050	1100	
	1310							1000	1050	1100	1150	1200
	1410								1100	1150	1200	1250
	1520									1200	1250	1300

2.2 River dunes

River dunes are hills on the riverbed and develop depending on the bed material and flow conditions. In the following sections the change of dunes during floods is first described in general and after more specifically for the Waal and the Pannerdensche Kop during the 1997 flood.

2.2.1 Bed forms during a flood

The understanding of the formation of bed forms and the change of their characteristics during floods are essential to be able to predict water levels. Bed forms can have a large influence on the riverbed roughness and during a flood the characteristics of the bed forms change. Figure 2.3 shows the bed state as a function of the flow conditions and the grain size. The main bed states are ripples, dunes and antidunes. Ripples occur in low flow conditions with small grain sizes. At higher values of the flow velocity and the grain size, the riverbed forms dunes which increase in size. At higher Froude numbers the dunes are washed away and the riverbed flattens. At even higher Froude numbers antidunes start to appear.

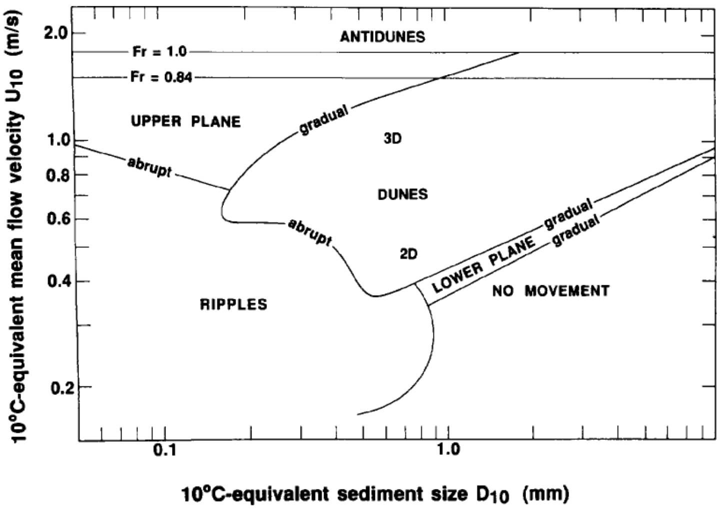

Figure 2.3 Different classifications of the bed state as a function of the flow conditions and the grain size (Southard & Boguchwal, 1990).

Depending on the river, different bed states can occur during a flood. Figure 2.4 shows an example of a change of the bed form regime during a flood based on vertical-2D-model results. The river starts with a flat bed and during the rising stage dunes start to appear and dunes start to grow. Until the Froude number gets too high and the bed flattens. During the falling stage dunes start to reappear.

During a flood, the dune characteristics often show a lag compared to the flow conditions. This lag is a consequence of the response time of the dune to the change of the flow conditions and causes a hysteresis in the dune height as a function of the flow conditions. The reason for this lagged response is that if dunes are large, a large volume of sediment has to be transported to make the dune change of shape. The transport of the sediment takes time and causes a lagged response to the flow conditions (Kleinhans, 2002). Such hysteresis effect has been replicated by the physics based modelling as well (Shimizu, et al., 2009).

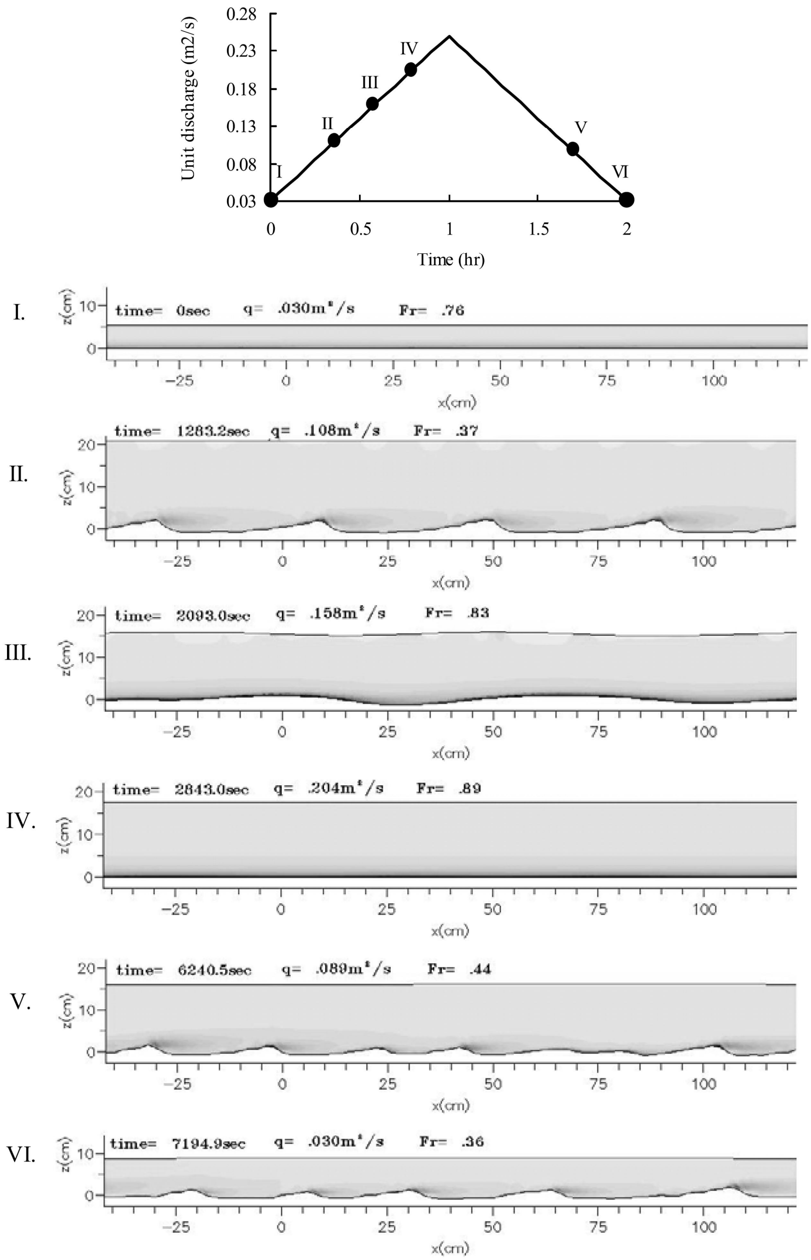

Figure 2.4 Bed form evolution during different stages of a flood from vertical-2D-model calculations. The top figure shows the time and unit discharge of each bed form state (Shimizu, et al., 2009).

2.2.2 Dunes in the Waal during floods

In this thesis the average bed level at two different locations in the Waal are analysed. These locations are a reach between stations Dodewaard and TielWaal and a reach near the Pannerdensche Kop.

Waal between stations Dodewaard and TielWaal

Wilbers (2004) studied a 1 km reach between stations Dodewaard and TielWaal and estimated the dune height, dune length and the dune migration celerity. Figure 2.5 shows the reach which runs from east to west and Wilbers found that the differences between the northern and southern part are large. Due to the curvature of the river, the southern part of the river is deeper than the northern part and this has effect on the dune height during a flood. During average flow conditions is the dune height in the northern part of the river in the order of 90 cm. During the flood the dune height increases to 110 cm as shown in Figure 2.6. In the southern part the dunes are much smaller during the lower flow conditions (35 cm). During the flood the dune height increases to 55 cm. Wilbers (2004) explains that the differences between the northern and southern part are caused by a difference in the availability of fine sediments. In the northern part more fine sediment is available since it is the inner bend of the river. This makes it possible for dunes to grow much larger. In the southern part the sediment is much courser and the bed can even show armouring which restricts the dune growth. Figure 2.6 clearly shows a time lag of the dune height compared to the discharge. The peak of the discharge at TielWaal was on 3 March and the maximum dune height occurred between 4 and 6 March.

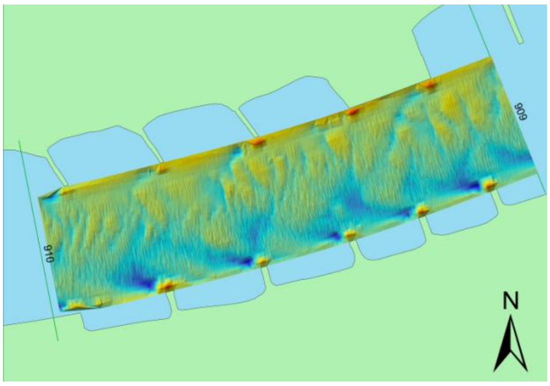

Figure 2.5 Bed level measurements during the 1997 flood between the 909 and 910 river kilometre. This area was used by Wilbers (2004) to study the variation of the dune height in Waal during a flood.

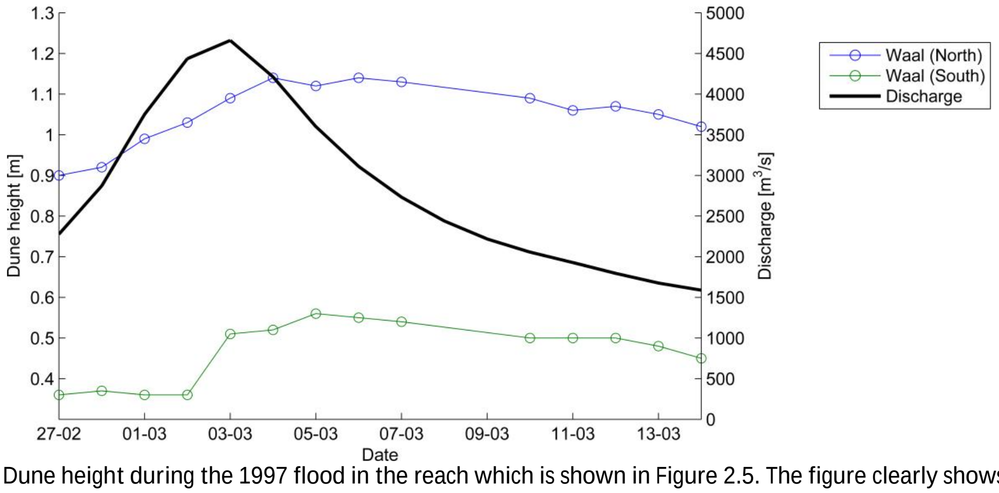

Figure 2.6 Dune height during the 1997 flood in the reach which is shown in Figure 2.5. The figure clearly shows a peak of the dune height which is lagged compared to the discharge peak.

Pannerdensche Kop

The dunes at the Pannerdensche Kop show a similar behaviour during the flood. During average flow conditions is the dune height very small (10 cm). During the flood the dune height increases to 50 cm which is shown in Figure 2.7. The maximum dune height shows a lagged response to the flow. This lagged response causes a hysteresis with the discharge which is shown in Figure 2.8. At the Pannerdensche Kop is the variation of the dune height much larger than in the reach between stations Dodewaard and TielWaal. Figure 2.9 presents an example of the large changes in the dune height and in the bed level during a flood. The figure presents the bed level and the discharge over three months. During the three months the maximum discharge was measured on 7 March 2013 with a discharge of 6000 m^3/s at station Lobith. The figure shows a bed which has a large difference in the dune height between average and flood conditions.

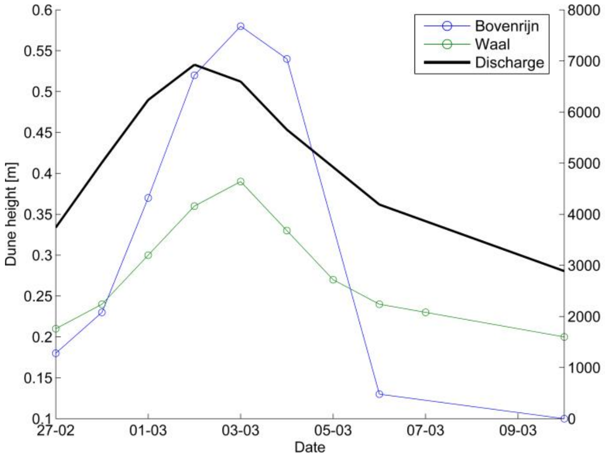

Figure 2.7 Dune height during the 1997 flood in the Bovenrijn and the Waal at the Pannerdensche Kop (Wilbers, 2004).

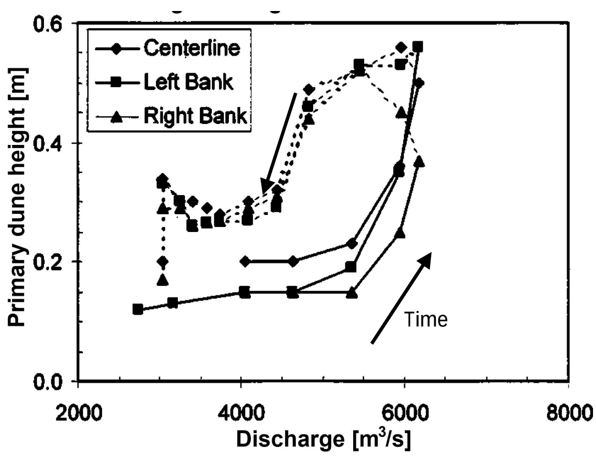

Figure 2.8 Dune height during the 1998 flood in the Waal at the Pannerdensche Kop as a function of the discharge (Julien, et al., 2002).

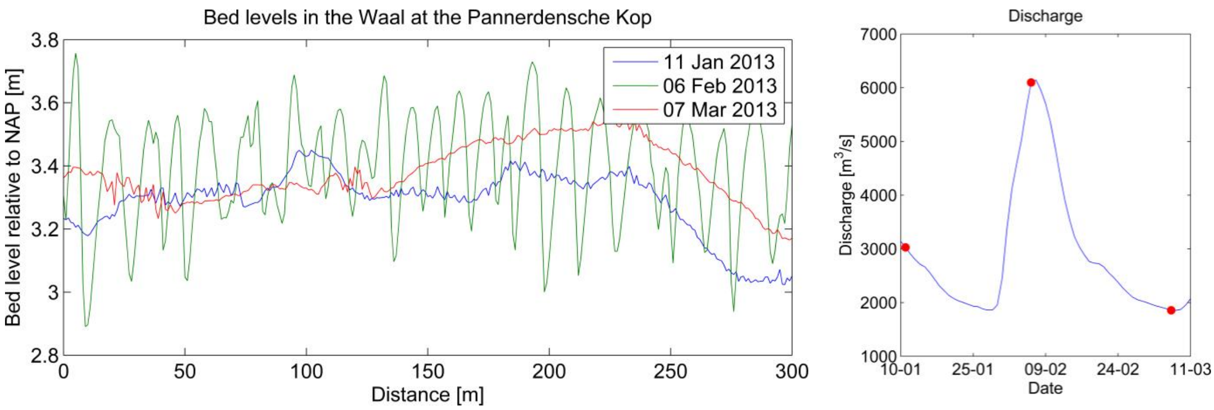

Figure 2.9 Left: Bed level in the Waal at the Pannerdensche Kop over 3 months. Right: Discharge at measuring station Lobith during the 2013 flood with a peak discharge of 6000 m3/s on 7 February 2013.

Conclusion

At both locations in the Waal are the flow conditions not strong enough to show a flatting of the bed but the dune height does increase during the flood. The increase of the dune height is relatively small in the reach between stations Dodewaard and TielWaal. At the Pannerdensche Kop the increase of the dune height is relatively much larger. At both locations the dune height shows a time lag compared to the discharge. This time lag results in a hysteresis in the relation between the dune height and the discharge which was shown in Figure 2.8.

3 Bed level changes due to the transport layer thickness

The effect of the transport layer thickness is often ignored in the current morphodynamic models to simplify the sediment-mass balance. The transport layer thickness is defined as the volume of sediment without pores divided by a surface area and in the sediment-mass balance it accounts for the amount of sediment in the water column. The full sediment-mass balance is given in Equation 3.1 (Sloff, 1993).

$$(1-\varepsilon_b)\frac{\partial z_b}{\partial t} + \frac{\partial(a_s + a_b)}{\partial t} + \frac{\partial q_{tot}}{\partial x} = 0 \qquad 3.1$$

with ε_b [-] the porosity of the riverbed, z_b [m] the bed level, a_s [m] the thickness of the suspended load layer, a_b [m] the thickness of the bed load layer, q_{tot} [m^2/s] the total sediment transport per unit of width. Equation 3.1 shows that a change in the transport layer thicknesses can have an effect on the average bed level. During a flood the flow conditions rapidly change which also affects the transport layer thickness. The time variation of the transport thickness may therefore become more important during a flood. In this chapter the maximum transport layer thicknesses are estimated using empirical relations. This is done to study whether the transport layer thicknesses can have any significant influence on the bed level during a flood.

3.1 Method

The maximum effect of the transport layers is calculated during the peak of the 1997 flood. During the peak the flow velocities and the water levels are largest which will result in the maximum transport layer thickness during the flood. A few assumptions are made for the flow conditions, the friction and the grain sizes. First a general description of the transport layer thickness is calculated for different flow conditions and grain sizes. After that, the transport layer thicknesses are estimated for the 1997 flood in the Waal.

3.1.1 Input parameters

Several assumptions are made to be able to study the variation of the transport layer thickness during a flood. The thicknesses of the transport layers are calculated as a function of the Shields grain stress. This stress is an important parameter in the calculation of the sediment transport. The equation to calculate the Shields grain stress is given by

$$\theta' = \frac{{u'_*}^2}{\Delta g D} \qquad 3.2$$

where u'_* [m/s] is the grain shear velocity, Δ is the relative density $\Delta = (\rho_s - \rho)/\rho$ and D [m] is the grain size.

The first parameter which is varied is the specific discharge. However, the empirical relations require a flow depth and a flow velocity which means that a friction coefficient is needed to find the ratio between the flow depth and flow velocity. The Manning/Strickler relation is used to estimate the friction coefficient. To simplify the problem, the bed form roughness height is ignored and only the grain roughness height is taken into account which is a function of the grain size.

The second parameter which is varied is the grain size. The available empirical models for the suspended load transport were validated for much smaller sediment particles than the models for bed load transport. This means that the ranges in between which the models are valid differ. The transport layer thicknesses are therefore not tested for the same grain sizes.

3.1.2 Bed load layer thickness

The bed load layer thickness is defined as a volume of sediment without pores divided by a surface area. The following equation is derived:

$$a_b = \frac{q_b}{u_p} \qquad 3.3$$

with q_b [m^2/s] the bed load transport per unit width and u_p [m/s] the velocity of the bed load sediment particle. Both the sediment transport and the particle velocity are estimated using empirical relations which are described in the following sections.

Bed load sediment transport

The bed load transport is estimated using the empirical models by Van Rijn (1984a) and Meyer-Peter Müller (1948). These two models are often used in practise to calculate the bed load transport. Bed load transport consists of three types of transport: rolling, sliding and saltation motion. The rolling and sliding of the particles occurs for shear velocities just larger than the critical value. In this case the particles have a continuous contact with the bed. When the shear velocity increases the particles start to make jumps and have less regular contact with the bed. This is called the saltation motion. The formulations of the two bed load transport models are presented below.

Van Rijn (1984a)

The empirical relation for the bed load transport by Van Rijn is only valid for particles in the range of 0.2-2 mm. The bed load transport follows from:

$$\Phi_b = 0.053\frac{T^{2.1}}{D_*^{0.3}} \qquad T < 3 \qquad 3.4$$

$$\Phi_b = 0.1\frac{T^{1.5}}{D_*^{0.3}} \qquad T \geq 3 \qquad 3.5$$

with

$$\Phi_b = \frac{q_b}{\sqrt{g\Delta D_{50}^3}} \qquad 3.6$$

Φ_b [-] is defined as the bed transport parameter, T [-] is the transport stage parameter, D_* [-] is the dimensionless particle parameter. The transport stage parameter and the particle parameter are defined as follows:

$$T = \frac{(u_*'^2 - u_{*,cr}^2)}{u_{*,cr}^2} \quad 3.7$$

$$u_*' = \frac{u\sqrt{g}}{C'} \quad 3.8$$

$$u_{*,cr} = \sqrt{\theta_c \Delta g D_{50}} \quad 3.9$$

$$D_* = D_{50} \left[\frac{\Delta g}{\nu^2}\right]^{1/3} \quad 3.10$$

$$\theta_c = \begin{cases} 0.24/D_* & if\ D_* \leq 4 \\ 0.14 D_*^{-0.64} & if\ 4 < D_* \leq 10 \\ 0.04 D_*^{-0.10} & if\ 10 < D_* \leq 20 \\ 0.013 D_*^{0.29} & if\ 20 < D_* \leq 150 \\ 0.055 & if\ 150 < D_* \end{cases} \quad 3.11$$

Meyer-Peter Müller (1948)

The bed load transport relation of Meyer-Peter Müller has been experimentally defined for rivers with coarse bed material ($D \geq 0.45$ mm) and therefore without large influence of suspended load. Other restrictions of the Meyer-Peter Müller relation are $w_s/u_* > 1$ and $\mu\theta < 0.2$.

$$\Phi_b = 8(\psi - 0.047)^{\frac{3}{2}} \quad 3.12$$

$$\psi = \mu\theta = \mu \frac{u^2}{C^2 \Delta D} \quad 3.13$$

$$\mu = \left(\frac{C}{C'}\right)^{3/2} \quad 3.14$$

In these equations ψ [-] is the flow parameter; μ [-] is the ripple factor.

Particle velocity

The particle velocity is also estimated by using two empirical relations. Basset (2013) compared five empirical relations and collected their validity ranges for particle diameter and shear velocity. Based on his results two models are chosen. These models are Van Rijn (1984a) and Sklar & Dietrich (2004). From the report of Basset (2013) it follows that both models perform well under the considered conditions and that both models are based on different datasets. However, the model of Sklar & Dietrich is only valid for a grain size of larger than 1.36 mm and is based on a dataset with a large variation in grain sizes. The model by Van Rijn is valid for a smaller range and is focussed on smaller particles.

Van Rijn (1984a)

The particle velocity mode by Van Rijn model was calibrated on a limited amount of data and is therefore only valid in the following ranges: 0.9 mm $\leq D \leq$ 2.2 mm and 0.0233 m/s $\leq u_* \leq$ 0.0812 m/s (Basset, 2013). Within these ranges the particle velocity is given by Equation 3.15.

$$u_p = u_*(9 + 2.6\log(D_*) - 8\sqrt{\frac{\theta_c}{\theta}}) \qquad 3.15$$

Sklar & Dietrich (2004)

The model by Sklar & Dietrich has been developed to describe abrasion of bedrock by saltating bed load as a function of particle velocity. The particle velocity model has been tested for a wide range of particle diameters (1.36 mm $\leq$D$\leq$31 mm) and a wide range of shear velocities (0.0362 m/s $\leq u_* \leq$0.184 m/s). Equation 3.16 describes the particle velocity within these ranges:

$$u_p = 1.56\sqrt{\Delta g D_{50}}\left[\frac{\theta}{\theta_c} - 1\right]^{0.56} \qquad 3.16$$

3.1.3 Suspended load layer thickness

The suspended load layer thickness also changes during a flood. Suspended load transport consists of particles which do not have regular contact with the bed. Suspended load becomes important when the particles are relatively small and the flow shear velocity is relatively high. The suspended load transport is described by

$$q_s = \int_{\delta_b}^{h} c(z)u(z)dz \qquad 3.17$$

where δ_b [m] is the height of the bed load layer with pores (Figure 1.12), c [-] is the concentration as a function of the elevation and u [m/s] the flow velocity as a function of the elevation. To calculate the suspended load layer thickness (a_s) the depth-averaged concentration is needed, Equation 3.18:

$$a_s = h\bar{c_s} = \frac{q_s}{\bar{u}} \qquad 3.18$$

Two different methods are used to calculate the average concentration: the simplified method by Van Rijn (1984b) and a model by Camenen and Larson (2007; 2008). Both methods require different reference concentrations and use different integration techniques. For the model of Van Rijn the reference concentration (c_a) is calculated at the height $z = a_{ref}$. The model by Camenen and Larson uses the reference concentration (c_R) which is calculated at the height $z = 0$.

Van Rijn (1984b)

Van Rijn calculates the concentration profile as a function of the reference concentration (c_a). Multiple relations were developed to describe this reference concentration and each relation assumes a different reference height (a_{ref}), which makes it difficult to compare the results. A comparison of the different reference concentrations was made by Garcia and Parker (1991). They compared multiple models for the reference concentration and tested the models for the same dataset. They concluded that the relations of Van Rijn (1984b) and Smith & McLean (1977) performed best. Garcia and Parker also proposed a new relation but this relation was created from the same dataset as the comparison and it is therefore unknown if it performs well on a different dataset. Figure 3.1 shows different relations for the reference concentration for different values of D_{50}. In this figure the relation of Wright and Parker (2004) is the corrected relation of Garcia & Parker (1991). The graph shows that the reference concentration easily varies by a factor ten depending on which relation is used. However, the curves are not directly comparable due to the different reference heights, Table 3.1. Van Rijn (1984b) states that a reference height smaller than 0.01h leads to large errors in the concentration profile, Equation 3.21. Based on this statement and on the results of Garcia & Parker the reference concentration model by Van Rijn is chosen.

Table 3.1 The reference heights of the reference concentrations as shown in Figure 3.1.

Author	Reference height	
Engelund and Fredsøe (1976)	$a_{ref} = 2D_{50}$	3.19
Smith and McLean (1977)	$a_{ref} = \alpha_0(\theta' - \theta_c)D_{50} + k_s$	3.20
Van Rijn (1984b)	$a_{ref} = 0.5\Delta_b \; or \; a_{ref} = k_s$ with $\min(a_{ref}) = 0.01h$	3.21
Wright and Parker (2004)	$a_{ref} = 0.05h$	3.22

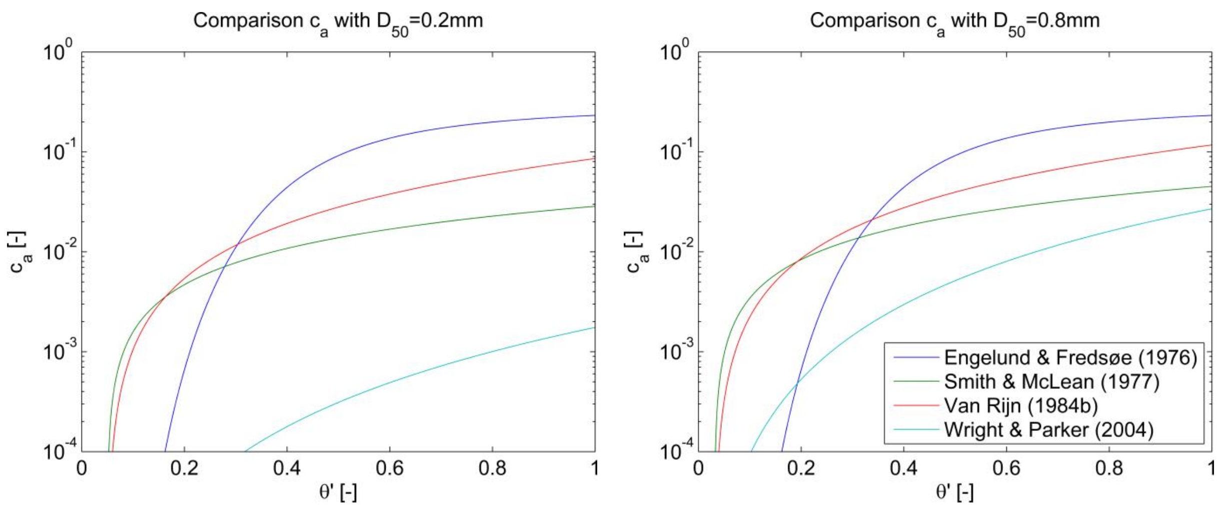

Figure 3.1 Comparison of relations for c_a with different reference heights ($\mathbf{a_{ref}}$) and two different grain sizes. The curves are however not directly comparable due the different reference heights, Table 3.1.

The reference concentration was calibrated on measuring data for the following ranges: $0.1\, m \leq h \leq 25\, m$, $0.4\, m/s \leq u \leq 1.6\, m/s$ and $0.18\, mm \leq D_{50} \leq 0.7\, mm$. Within these ranges the reference concentration is described by

$$c_a = 0.015 \frac{D_{50}}{a_{ref}} \frac{T^{1.5}}{D_*^{0.3}} \quad 3.23$$

To calculate the average concentration profile Van Rijn derived a relation which can only be solved numerically. Therefore Van Rijn also created a simplified description of the concentration profile for practical use. This simplified relation is given by

$$q_s = F\bar{u}hc_a \quad 3.24$$

$$F = \frac{\left[\frac{a_{ref}}{h}\right]^{Z'} - \left[\frac{a_{ref}}{h}\right]^{1.2}}{\left[1 - \frac{a_{ref}}{h}\right]^{Z'} [1.2 - Z']} \quad 3.25$$

$$Z' = \frac{w_s}{1 + 2\left(\frac{w_s}{u_*}\right)^2 \kappa u_*} + 2.5\left(\frac{w_s}{u_*}\right)^{0.8}\left(\frac{c_a}{0.65}\right)^{0.4} \quad 3.26$$

with Z' as the modified suspension parameter and κ = 0.4 as the Von Karman constant. This model is valid for the following conditions: $0.1 \leq w_s/u_* \leq 1$.

Camenen and Larson (2007;2008)

The method proposed by Camenen and Larson is based on an exponential profile for the sediment concentration. This exponential profile is a function of the reference concentration (c_R) at z = 0. Camenen and Larson (2008) compare several models for this reference concentration and propose a direct relation between the bed load transport (Camenen & Larson, 2005) and c_R. The resulting equation is given by

$$c_R = A_{cR}\theta \exp\left(-4.5\frac{\theta_c}{\theta}\right) \quad 3.27$$

where coefficient A_{cR} is assumed constant with a value of $5 \cdot 10^{-4}$. This relation for the reference concentration has been tested for $1 \leq D_* \leq 18$ and $0.01\ m/s \leq u_* \leq 9.14\ m/s$.

An exponential concentration profile is assumed which results in Equation 3.25. By integrating Equation 3.28 over the depth the depth-averaged concentration is found which is given in Equation 3.29.

$$c(z) = c_R \exp\left(-\frac{w_s}{\varepsilon_v} z\right) \quad 3.28$$

$$\bar{c} = \frac{c_R}{h}\frac{\varepsilon_v}{w_s}\left[1 - \exp\left(-\frac{w_s h}{\varepsilon_v}\right)\right] \quad 3.29$$

In Equation 3.29 ε_v is the vertical sediment diffusivity which is given by

$$\varepsilon_v = \sigma \kappa u_* h \quad 3.30$$

with

$$\sigma = 1 + 2\left(\frac{w_s}{u_*}\right)^2 \ for\ 0.1 < \frac{w_s}{u_*} < 1 \quad 3.31$$

3.2 Results

3.2.1 Bed load layer thickness

As described in the previous section, the bed load layer thickness is calculated from the bed load transport and the particle velocity. First the influence of these parameters is presented and discussed after which the bed load layer thickness is presented as a function of the Shields grain stress.

Bed load transport

The bed load transport has been calculated using the models by Van Rijn (1984a) and Meyer-Peter Müller (1948). There are large differences between the two models which are presented in Figure 3.2. The transport rate predicted by Meyer-Peter Müller increases faster with increasing grain size than the model by Van Rijn. For the Waal during the 1997 flood this results in a much larger bed load transport for the model by Meyer-Peter Müller.

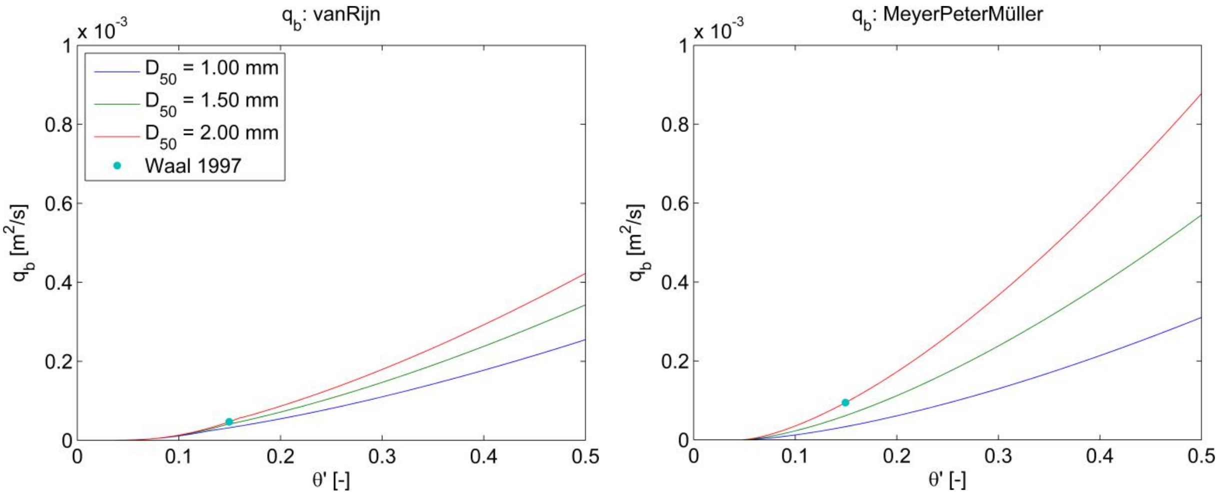

Figure 3.2 Results of the bed load transport models as a function of the Shields grain stress.

Particle velocity

Figure 3.3 shows the results of the particle models within the validity ranges. The model by Van Rijn (1984a) shows a slight increase of the particle velocities with increasing grain size. The model by Sklar & Dietrich (2004) does not show an increase at even larger grain sizes. The increase shown by the model by Van Rijn is possibly a result of the limited amount of measuring data at larger shear velocities. The model by Sklar & Dietrich presents lower values for the particle velocity than the model by Van Rijn. This is confirmed by the results of Basset (2013).

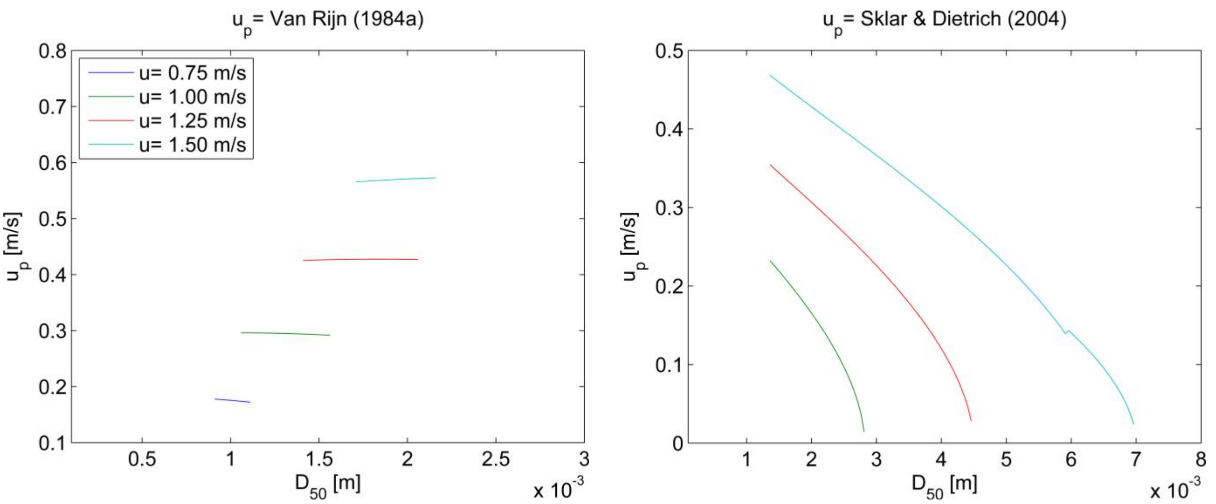

Figure 3.3 The particle velocity predicted by Van Rijn (1984a) and Sklar & Dietrich (2004) as a function of grain size and flow velocity.

In the results of Sklar & Dietrich a discontinuity is shown for a flow velocity of 1.5 m/s. This discontinuity is caused by the model for the critical shear stress, Equation 3.11. With different model for the critical shear stress, for example Soulsby & Whitehouse (1997), this discontinuity disappears but the results remain similar.

Bed load layer thickness

Figure 3.4 presents the results of the bed load layer thickness for each combination of the four models. The main differences in the results are caused by the bed load models (Figure 3.2). The particle velocity model by Sklar & Dietrich was not validated for particle sizes smaller than 1.36 mm but the results are comparable to the other particle sizes. Based on Van Rijn's bed load model the maximum bed load layer thickness in the Waal is more or less 0.1 mm. The model of Meyer-Peter & Müller presents a bed load layer thickness in the order of 0.2 mm. The particle velocity model by Sklar & Dietrich presents slightly higher values for the bed load layer thickness than the model by Van Rijn, which is confirmed by the results of Basset (2013) and the results presented in Figure 3.3.

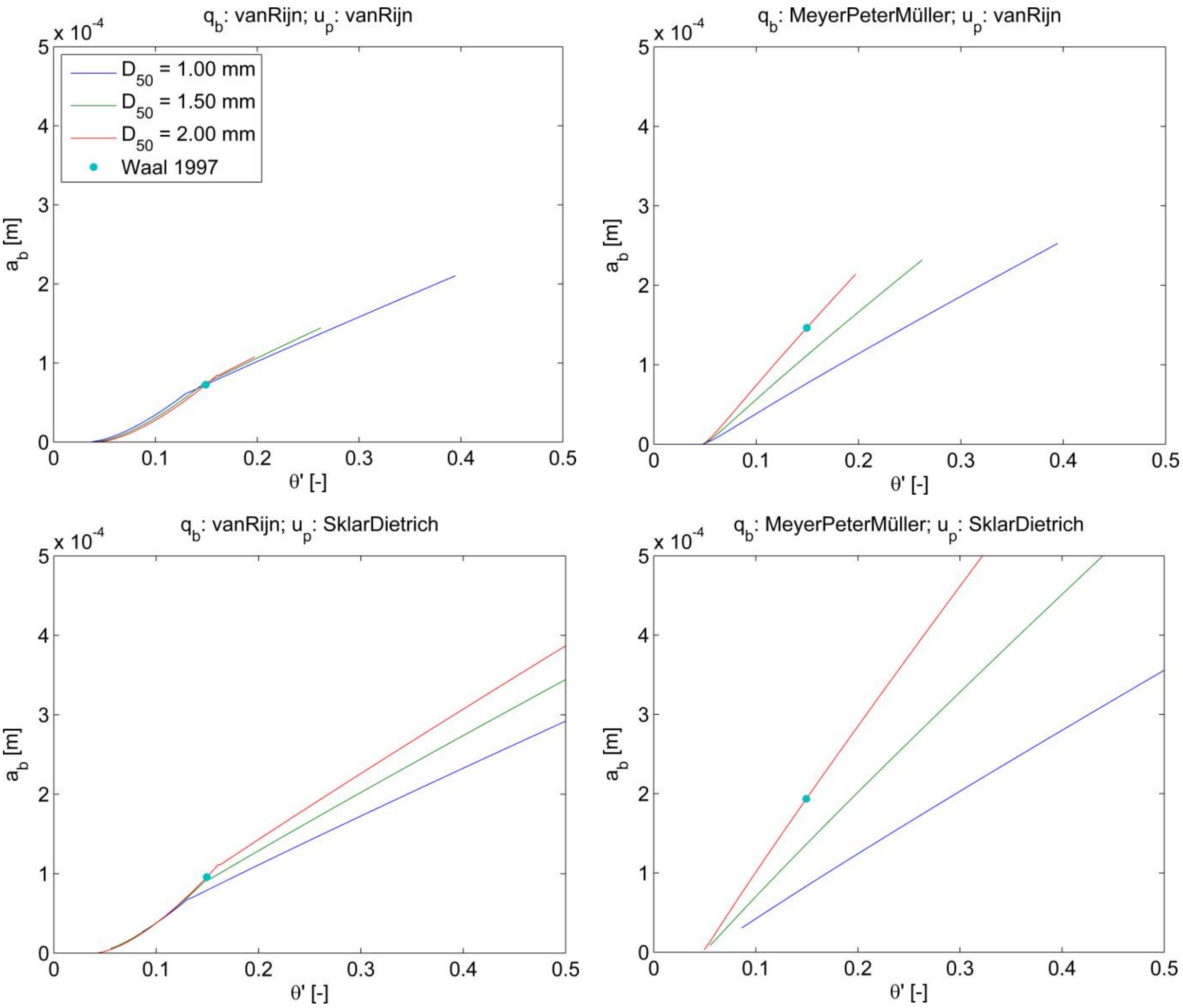

Figure 3.4 Results of the analysis of bed load layer thickness with multiple models for the bed load transport and the particle velocity.

3.2.2 Suspended load layer thickness

The results of the two models for the suspended load layer thickness are presented in Figure 3.5. The suspended load model of Van Rijn (1984b) gives lower results for the suspended load than the model of Camenen & Larson (2007; 2008). This is in agreement with the model comparison by Camenen and Larson. They showed that both models underestimate the sediment transport but that the underestimation is larger for the model by Van Rijn. Both models show however the same order of magnitude for the suspended load layer thickness. The suspended load layer thickness for the

Waal is calculated while neglecting the validity ranges of the models. This results in a suspended load layer thickness in the order of 0.2 mm.

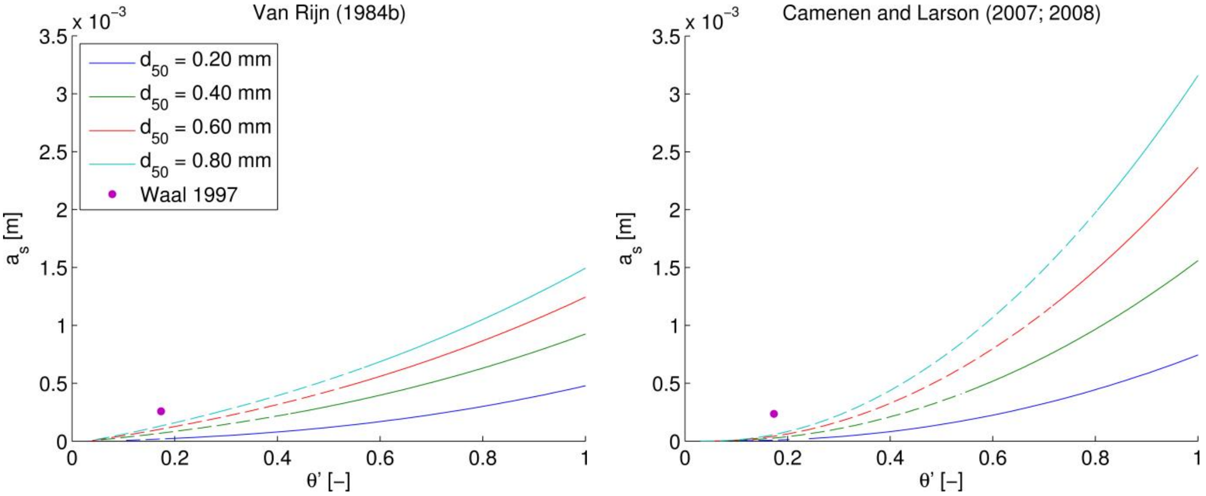

Figure 3.5 Results of the suspended load layer thickness. The dashed lines present results outside the validity ranges of the used models.

3.3 Discussion and conclusions

The results presented in the previous section were calculated while neglecting the form drag of the bed. In reality bed forms are present in the Waal which grow during the flood and decrease in size after the flood. Including the effects of dunes increases the bed roughness value and therefore increases the sediment transport. However, the particle velocity is not affected since it is a function of the Shields grain stress. Both transport layers increase in thickness with a larger friction value due to the increase of the sediment transport. For the Waal 1997 the roughness including dunes was calculated based on velocity and water level measurements. For both layers it is concluded that even though the thickness increases, the order of magnitude does not change.

This analysis shows that the maximum change of the transport layer thickness during a flood in river like the Waal is in the order of 0.5 mm. Assuming a porosity of 0.3, this results in a maximum change due to the unsteady sediment load in the order of 0.7 m. The models show a large variation for the bed load transport, particle velocity, and suspended load transport. Even when the uncertainty of these models is included, the transport layer thicknesses remain small. Therefore it is concluded that neither the bed load layer thickness nor the suspended load layer thickness nor a combination of the two are large enough during the peak of the 1997 flood to significantly affect the bed level in the Waal and to explain a 10 cm decrease in bed elevation.

4 Bed level changes due to inaccurate water level measurements

The single-beam echosounder measures the distance from the measuring device till the bottom. To then calculate the bed level, the water level and the location of the device in the water column are required. In this chapter the accuracy of the water level and its influence on the measured bed level is discussed.

An error responsible for the large decrease in bed level has to be caused by an inaccuracy which varies in time and space. Figures 1.7 and 1.9 show the features of this variation and if it is caused by an inaccuracy in the water level then it needs to show a similar trend. Figure 4.1 presents the effect of an underestimated water level. From this figure is concluded that the water level would have to be underestimated during the peak of the flood to cause a large decrease of the bed level. Two possible sources for errors caused by the water level are identified: the estimation of the water level at station Dodewaard and the linear interpolation of the water levels between measuring stations Dodewaard and TielWaal. The size of these errors is estimated by comparing the water level used to calculate the bed level with two other datasets: water level measurements during the 2011 flood and a WAQUA-simulation of the 1997 flood. These datasets are discussed in the next section.

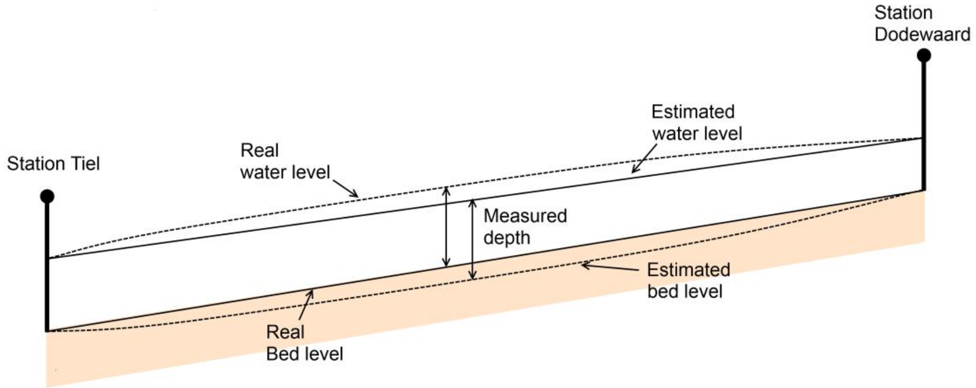

Figure 4.1 Schematisation of the effect of an incorrect estimation of the water level. In this case the water level is underestimated which results in an underestimation of the bed level.

4.1 Reference data

Additional data is needed to be able to compare the water level used to calculate the bed level and to estimate an error in this water level. The WAQUA-simulation of the 1997 flood makes it possible to study the spatial variation of the water level and the water level at station Dodewaard in more detail. However, inaccuracies in the computation should be taken into account. During the 2011 additional water level measurements were carried out in between the permanent measuring stations. These additional measurements give insight into the variation of the water level over the reach and give an estimation of the water level at station Dodewaard. The measurements and the WAQUA-model are discussed in the following sections.

4.1.1 Water level measurements of the 2011 flood

During the 2011 flood in the Waal additional water level measurements were carried out in between the permanent measuring stations using divers to study the variation of the water level over the reach. Divers are pressure meters and when the atmospheric pressure and the location of the diver are known, the water levels are calculated. These measurements were done at 13 locations over a 75 km reach. Figure 4.2 shows the locations of the divers around the bed level measuring reach and Figure 4.3 presents an example of the results between the stations Nijmegenhaven and TielWaal. In between the measuring points the water level is estimated using a spline interpolation and from the spline interpolation the water level at station Dodewaard is estimated.

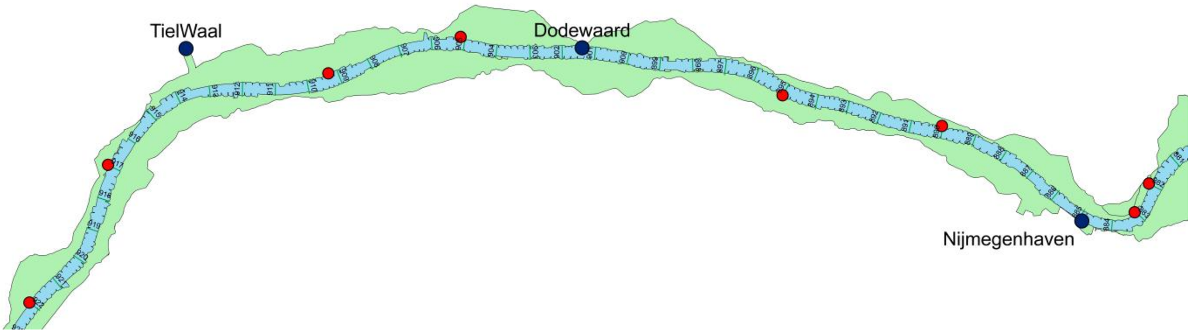

Figure 4.2 Part of the Waal with the locations of the divers indicated with the red dots.

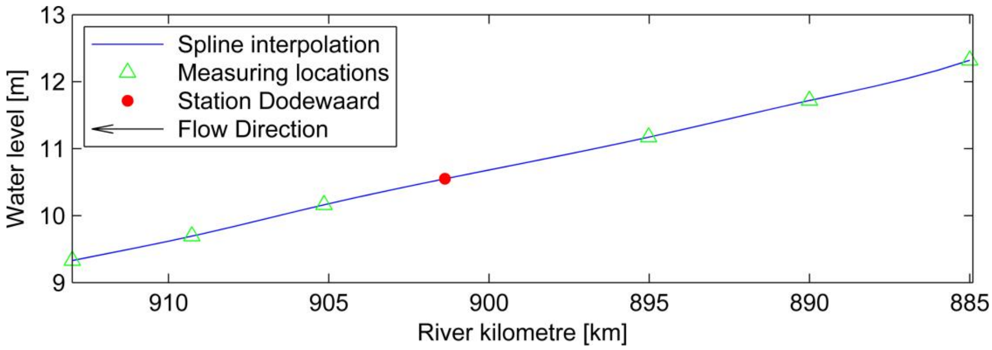

Figure 4.3 Water level over the reach between stations Nijmegenhaven (km885) and TielWaal (km913) during the peak of the 2011 flood.

The diver measurements give a more detailed description of the variation of the water level over the reach. The water level measurements were only made for the largest water levels during the 2011 flood. Figure 4.4 presents the time and spatial variation of the high water and shows that just before the first peak the gradient of the water level in time changes. This was also visible in Figure 2.2b and is strongest around the 905 river kilometre. The gradient change is caused by the inundation of several large floodplains which causes a temporarily lower water level in this area.

The spline interpolation of the diver measurements gives a better estimation of the water level at station Dodewaard than, for example, a linear estimation. However, there are too little measuring locations to show local water level variations and therefore the estimation of the water level at station Dodewaard with the spline interpolation can show an inaccuracy of a few centimetres.

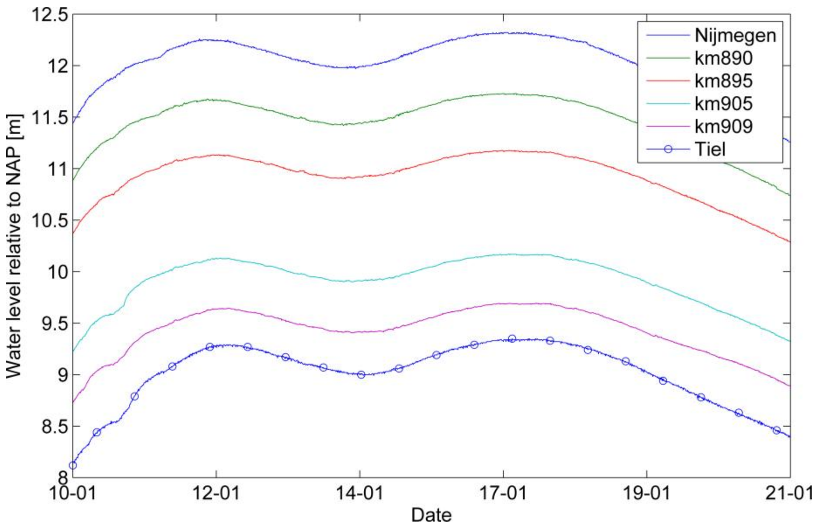

Figure 4.4 Water level from the diver measurements in the river reach between stations Nijmegenhaven and TielWaal during the 2011 flood.

4.1.2 WAQUA-model for the 1997 flood

A WAQUA-model is used to estimate the water level at station Dodewaard and to study the water level variation over the reach during the 1997 flood. WAQUA is a 2D hydrodynamic model and is used to study and estimate water levels and flow velocities during floods. The WAQUA-model used here describes the state of the Rhine branches in 1995. The model was used to calibrate the main channel roughness in the river branches and forms the basis of a second model which describes the expected state of the Rhine branches in 2017. This second model uses the calibrated values of the 1995 model and is used calculate the water levels in the Rhine branches during extreme conditions like a discharge at station Lobith of 16,000 m^3/s. In this study the Waal branch of the 1995 model is used to estimate the water levels during the 1997 flood.

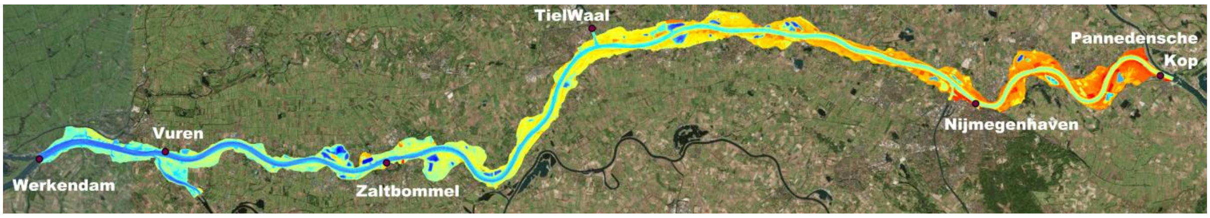

Figure 4.5 Overview of the WAQUA model domain from the Pannerdensche Kop to Werkendam.

Calibration procedure

The 1995 model was calibrated on the water levels during the 1995 flood by adjusting the main channel roughness. The main channel roughness is based on a simplified version of the roughness height predictor in a dune regime by Van Rijn (1984c). The calibration was done between two measuring stations and between those stations the main channel roughness has a constant calibration parameter. The floodplain is categorized in ecotopes which relate to certain roughness values. The water levels were calibrated for three different flow levels: the low level, which is equal to an average discharge of the Rhine (Waal 1850 m^3/s), the medium level, which is the bankfull discharge (Waal 3000 m^3/s), and the high level, which is equal to the flood peak of 1995 (Waal 7450 m^3/s). In between these levels, the calibration parameter is interpolated (Becker, 2012). The verification of the model on the 1993 flood shows a mean absolute error (MAE) in the order of 7 cm.

Boundary conditions

The upstream boundary of the model is located at the Pannerdensche Kop and is represented by a daily averaged discharge. The downstream boundary is given by a Qh-relation where the river bifurcates in the Beneden Merwede and the Nieuwe Merwede. The Qh-relation is based on average conditions and can therefore not correctly represent the hysteresis in the Qh-relation which was shown in Figure 2.2c. Figure 4.6 shows a comparison between the measured water level at station TielWaal and the calculated water level from the WAQUA-model. The figure shows that there are both differences in the amplitude and the phase of the flood wave.

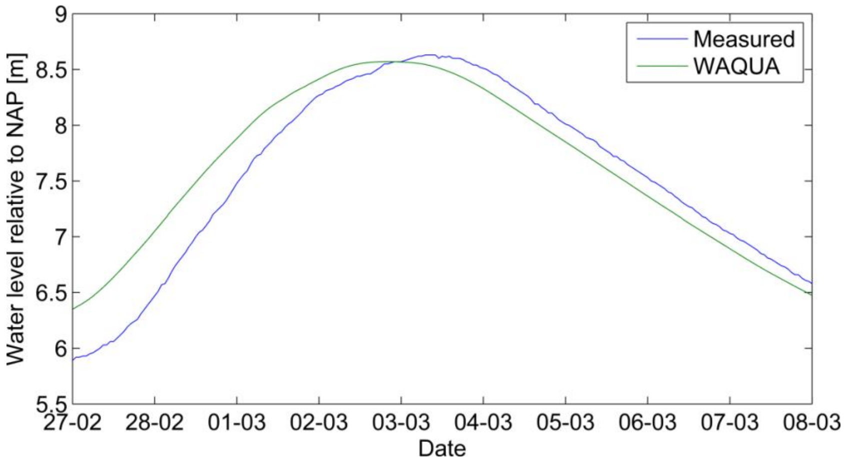

Figure 4.6 A comparison of the measured water level at station TielWaal and the water level which follows from the WAQUA-computation of the 1997 flood.

Accuracy of the WAQUA-model

The accuracy of the WAQUA-model for the 1997 flood is difficult to determine. The time shift of the measured and calculated flood wave is in the order of 11 hours and is therefore most likely a consequence of the daily averaged discharge at the upstream model boundary. The Qh-relation at the downstream boundary causes an overestimation of the water level during the rising flood and an underestimation of the water level during the falling flood due to the ignored hysteresis. The downstream boundary lies 50 km downstream of station TielWaal and since the backwater curve has a half-length of about 25 km, the water level at TielWaal is affected by the ignored hysteresis.

There are also other contributions to the inaccuracy of the WAQUA-model. The WAQUA-model assumes a constant bed level which means that morphological effects are not taken into account. Ignoring these effects can cause large errors in the water level. For example, Room for the river measures like flood plain lowering and secondary channels give additional space to the river during floods but cause a deceleration of the flow which causes sedimentation and a rising bed level in that area. The effects of these bed level changes are not taken into account in the WAQUA-model but do have an effect on the flow conditions in the reach (Mosselman, 2012).

The main channel and the floodplain roughness are also large contributors to uncertainties. The floodplains are divided in ecotopes and each ecotope is related to a roughness value. The effects of the uncertainties in these roughness values are mitigated by calibrating the water level on the main channel roughness and therefore the main channel roughness includes both the uncertainty of the main channel roughness and the floodplain roughness. The main channel roughness is calibrated between two measuring stations and distance between these stations is in the order of 25 km. This means that the calibration parameter is constant between the two stations and that the roughness is more or less averaged over the reach. Local variations of the roughness accuracy can therefore cause inaccuracies in the water level at that location. Field observations showed that the main channel roughness has an uncertainty of 5 $m^{1/2}/s$ for the Chézy value during flood conditions (Mosselman, 2009). For the Waal during the 1997 flood this corresponds to an uncertainty of the water level in the order of 0.2 m.

The WAQUA-results can contain large inaccuracies. The boundary conditions are not accurate and the estimation of roughness values also adds uncertainty. The WAQUA-model should therefore mainly be used to estimate relative differences of the water level over the reach.

4.2 Water level at station Dodewaard

The regression relation which was used to estimate the water level at station Dodewaard can contain large inaccuracies. To estimate these inaccuracies the water level is compared with the measurement during the 2011 flood and the WAQUA-results of the 1997 flood. Figure 4.7 presents the effect of an error in the water level at station Dodewaard. In this figure the water level is underestimated at station Dodewaard which causes an underestimation of the bed level. This underestimation linearly decreases towards station TielWaal since the water level is linearly interpolated between stations Dodewaard and TielWaal.

Previous research shows that five years after the closure of the measuring station Dodewaard in the 1980s, the regression relation was unable to estimate the water level at station Dodewaard accurately and errors occurred in the order of 5 to 10 cm (Van Rutten, et al., 2003). Although the regression relation was later updated and the error is partly structural, it does show that the use of a regression relation to calculate the water level can give significant errors. To estimate these errors, the regression relation is compared to the water level measurements during the 2011 flood and the WAQUA-results for the 1997 flood.

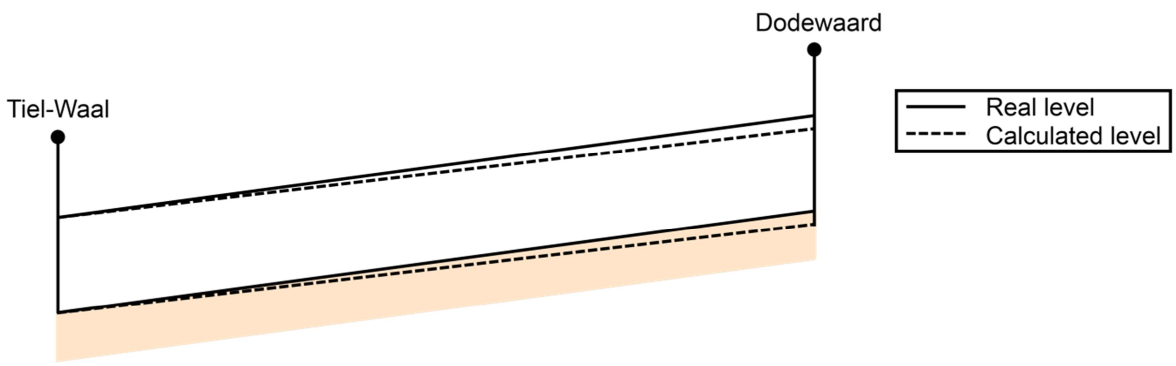

Figure 4.7 The effect of an error in the water level at station Dodewaard on the bed level and the linear decrease of this error towards station TielWaal.

4.2.1 Measurements of the 2011 flood

The water level at station Dodewaard is estimated using a spline interpolation of the diver measurements during the 2011 flood. The results of this interpolation are presented in Figure 4.8. The calculated line in this graph represents the water level at station Dodewaard calculated from the regression relation. The figure shows that the measurements were only carried out during the peaks of the flood and during this period the water level is constantly underestimated by the regression relation. This can be better seen in Figures 4.9 and 4.10 where a more detailed plot is given and the difference between the measured and the calculated water level is presented. The difference between the two water levels shows a variation from 10 to 18 cm.

The sudden jump around 11 January is caused by the inundation of a large floodplain and is in seen in Figure 4.9 as a change of the gradient of the water level. Figure 4.11 shows that the floodplain lies between river kilometre 895 and 905, and station Dodewaard is located at river kilometre 901. It is likely that the water level at Dodewaard is affected by the inundation of the floodplain. Figure 4.11 also shows that the effect of the floodplain inundation is not visible at station Nijmegenhaven and is diffused at station TielWaal which makes it impossible for the regression relation to show this effect correctly. The jump can cause an error in the water level estimate in the order of 8 cm but cannot explain the bed level decrease over multiple days since it only occurs during the filling of the floodplain.

Apart from the jump the water level difference varies between 9 and 15 cm. Moreover, at the beginning of the graph the gradient is positive and at the end of the graph the gradient is negative. This suggests that the difference decreases towards the beginning and the end of the flood. In other words, Figure 4.10 illustrates an error in the order of 6 cm in the water level at station Dodewaard which is largest around the peak and suggests that this error is even larger if the analysis could be extended to lower water levels in the rising and falling period of the flood.

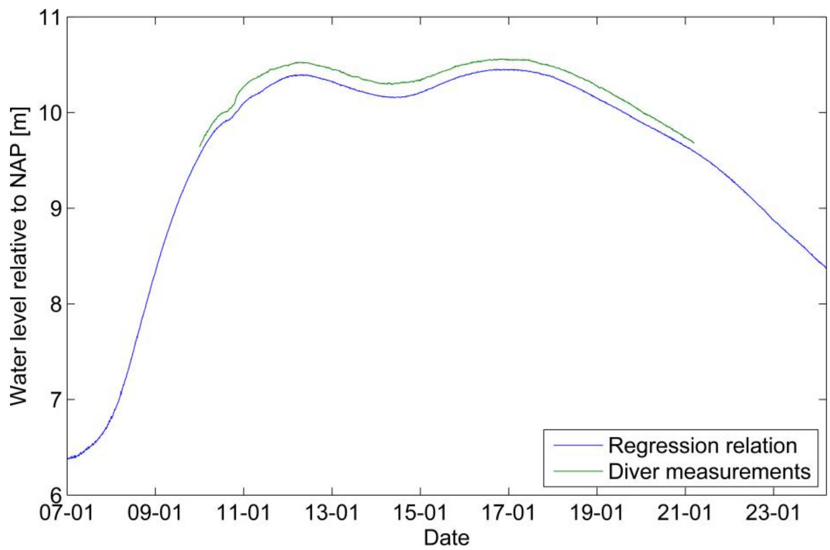

Figure 4.8 Water level at station Dodewaard during the 2011 flood calculated from the regression relation and the measured water level.

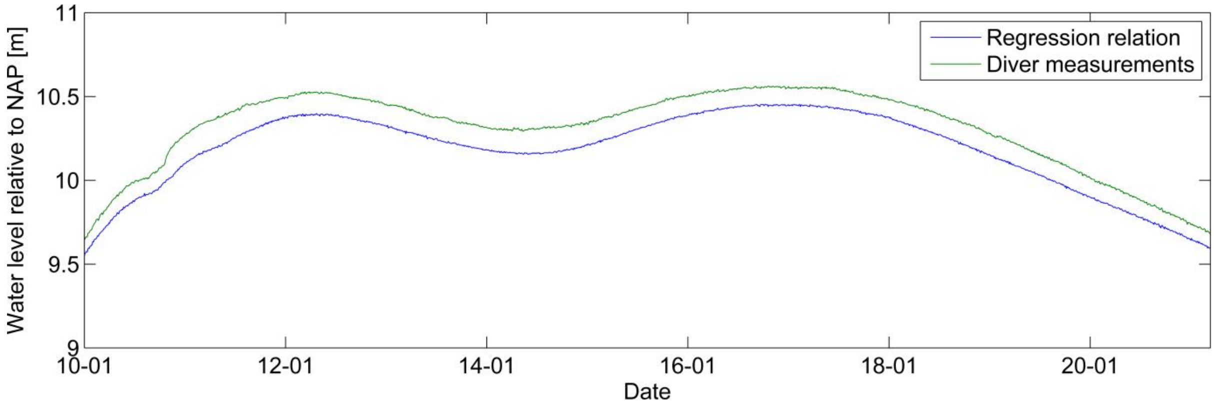

Figure 4.9 Fragment of Figure 4.8 which shows the water level at station Dodewaard based on the calculation from the regression relation and the measured water level with divers.

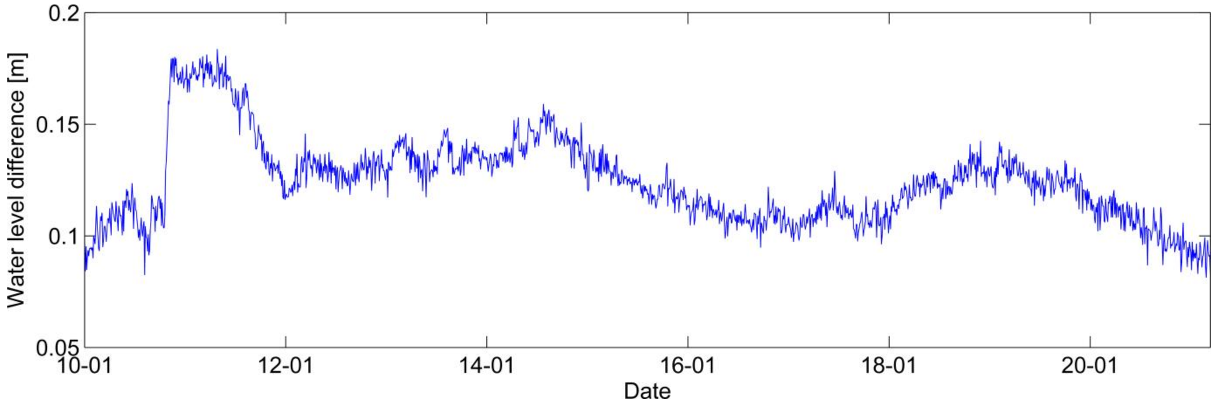

Figure 4.10 The difference in the water level at station Dodewaard during the 2011 flood: Measured from divers – calculated from the regression relation.

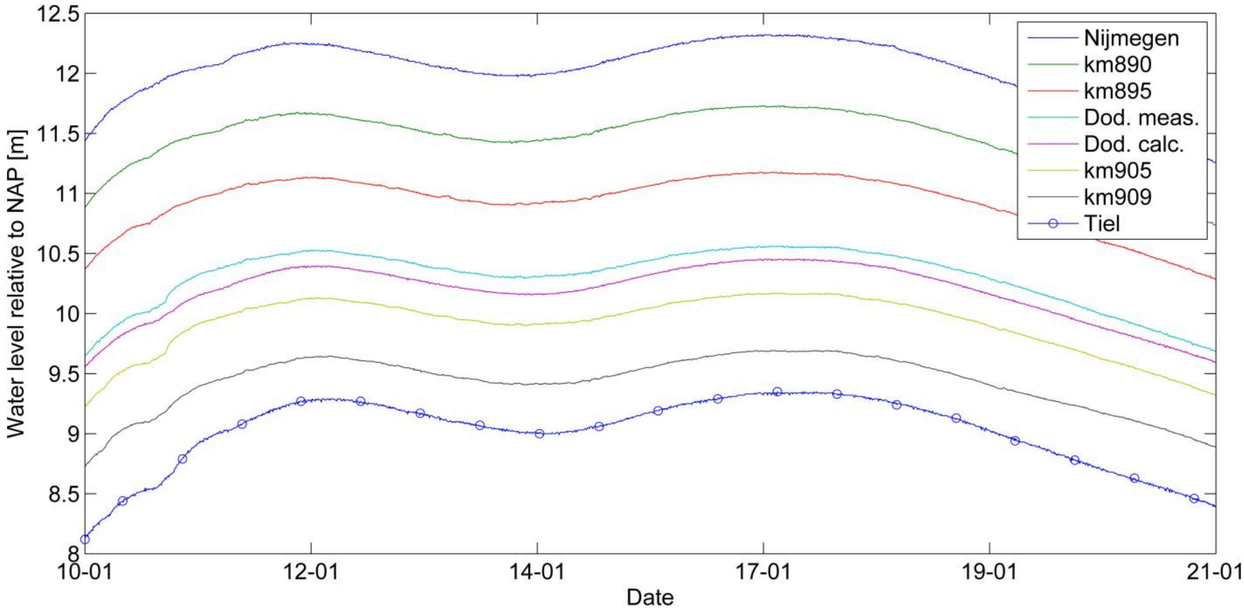

Figure 4.11 Water level in the river reach between stations Nijmegenhaven and TielWaal during the 2011 including the two estimations of the water level at station Dodewaard.

4.2.2 WAQUA-model results for the 1997 flood

The analysis of the 2011 water level shows that there is too little data available to estimate the error correctly over the whole flood peak. Therefore a WAQUA-model is used to estimate the water level at station Dodewaard and to compare this estimation with the calculated water level from the regression relation. However, in Section 4.1.2 was shown that the WAQUA-simulation does not compute the correct water level at the stations TielWaal and Nijmegenhaven. In other words, if the water level of the WAQUA-model is compared with the water level from the regression relation with input values of measurements, then an additional error occurs which is caused by inaccuracies of the WAQUA-model. To reduce the effect of these inaccuracies, the water level at station Dodewaard is calculated using the regression relation based on the water levels at stations TielWaal and Nijmegenhaven calculated from the WAQUA-model. This allows for a direct comparison of the WAQUA-results with the regression relation.

Figure 4.12 presents the water levels from the WAQUA-model and from the regression relation. Similar to the 2011 flood the water levels are underestimated by the regression relation during the peak of the flood. However, it can be seen that before and after the peak the water level is overestimated by the regression relation. In other words, the regression relation seems to give a much more diffused flood wave than the WAQUA-model, which results in a lower amplitude and a larger length. The difference between the two water levels is presented in Figure 4.13. This figure shows that the difference between the two water levels varies from -13 to 4 cm which corresponds with a bed level decrease during the 1997 flood of 17 cm at station Dodewaard.

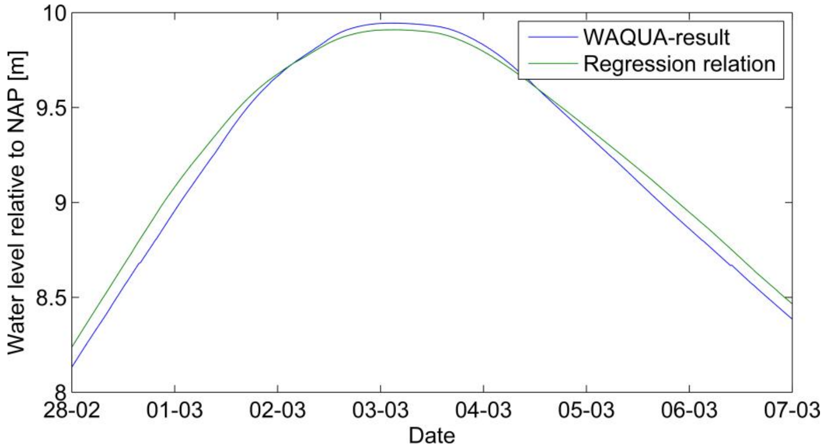

Figure 4.12 Water level at station Dodewaard: comparison between the WAQUA-result and the regression relation during the peak of the 1997 flood.

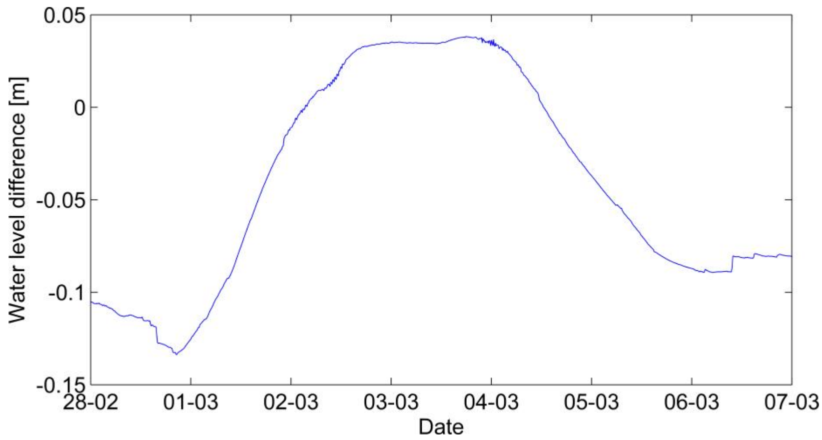

Figure 4.13 Water level difference between the WAQUA-result and the regression relation at station Dodewaard for the peak of the 1997 flood.

In the previous section it was shown that during the 2011 flood the inundation of a floodplain had a large effect on the water level. In the water level graph for the 1997 flood (Figure 4.12) the large floodplain inundation is not visible. However, the temporary lower water level could be caused by an outflow from the main channel to the floodplain. This means that the discharge at station TielWaal was temporary lower than the discharge at station Dodewaard which could result in an underestimation of the water level by the regression relation. The WAQUA-computation makes it possible to compare the discharge at the two stations. Figure 4.14 presents the discharge at station Dodewaard and TielWaal with the phase difference between the two stations filtered out. Figure 4.15 presents the difference between the two discharges and shows that during the rising flood water flows into the storage area of the floodplains. The maximum outflow is the order of 50 m^3/s on 2 March and last more or less one day. From the Qh-relation (Figure 2.2c) is found that this corresponds with a water level change in the order of 5 cm. The outflow to the floodplains is therefore too small and too short to be responsible for the large bed level decrease but can be partly responsible for the water level difference which was shown in Figure 4.13.

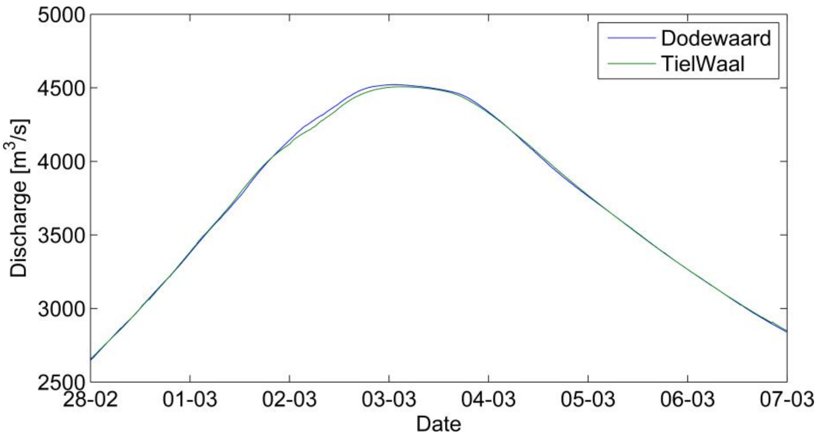

Figure 4.14 Discharge at stations Dodewaard and TielWaal from WAQUA-results without the time lag which is caused by the travel time of the flood wave between the stations.

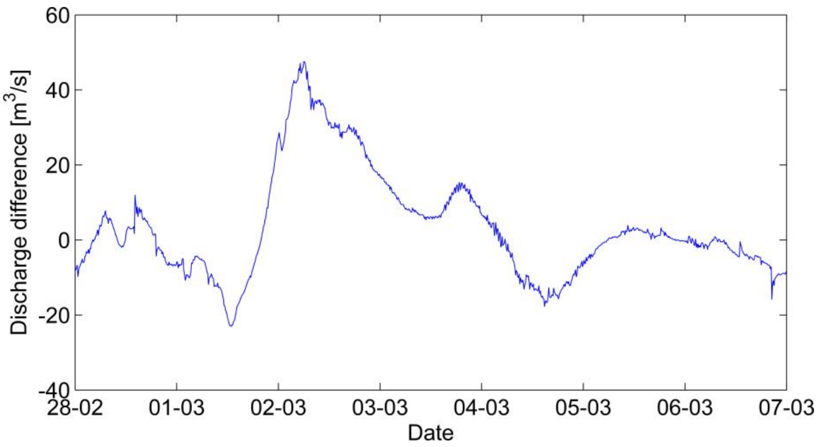

Figure 4.15 Difference between the discharge at stations Dodewaard and TielWaal from WAQUA-results without the time lag.

4.2.3 Water level difference station Dodewaard and TielWaal

The previous sections showed that the regression relation underestimates the water level at station Dodewaard during the peak. The WAQUA-model has, however, boundary conditions which are inaccurate, i.e. the discharge at the Pannerdensche Kop is underestimated due to the daily averaging and the downstream boundary is given by a Qh-relation which does not include a hysteresis. A comparison of the WAQUA-results with measurements can validate the usage of the WAQUA-model to estimate the error in the water level.

Figure 4.16 shows the water level difference between stations Dodewaard and TielWaal as a function of the discharge at station TielWaal during the 2011 and the 1997 flood. The water level at station Dodewaard is estimated in different ways. The left figure presents the water level difference during the 2011 flood and shows that the difference is underestimated during the whole flood with the regression relation. This corresponds with the underestimation of the water level which was presented in Figure 4.9. The WAQUA result fits the measured water level difference much better at the peak of the flood but underestimates the effect of hysteresis.

The right figure of Figure 4.16 shows the difference between the regression relation and the WAQUA results for the 1997 flood. The water level at station Dodewaard from the regression relation is based on the water level at station Nijmegenhaven en TielWaal which were retrieved from the WAQUA results. The effect of an error in the WAQUA model is therefore mitigated. The graph shows that the regression relation has a trend similar to the 2011 flood. During the rising flood the water level difference decreases and during the falling flood the difference increases. The WAQUA-result does not show this trend.

The WAQUA-model predicts the water level at station Dodewaard during the 2011 flood better than the regression relation. Although the WAQAU model underestimates the hysteresis, the model shows better results than the regression relation. From the results of the 1997 flood can be seen that the WAQUA model does not show the expected trend but that the regression relation does show this trend. The results of the 2011 flood present the WAQUA-result better represents the water level at station Dodewaard than the regression relation. Therefore it is concluded that the WAQUA model gives a good estimation of the water level at station Dodewaard but that inaccuracies in the model are to be expected.

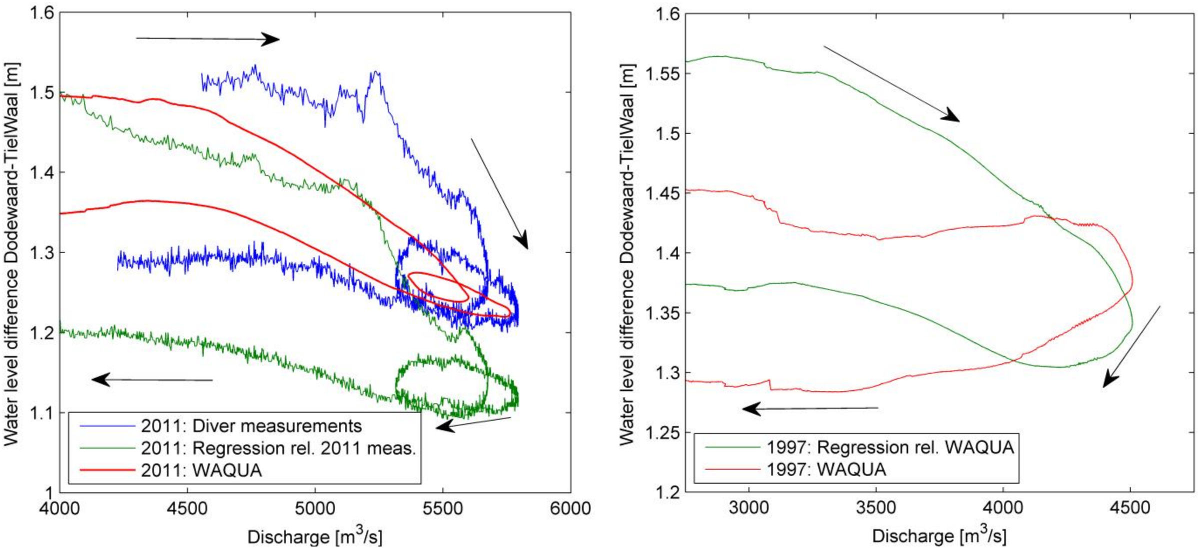

Figure 4.16 The water level difference between station Dodewaard and TielWaal during the 2011 (left) and the 1997 (right) flood as a function of the discharge at station TielWaal. The water level at station Dodewaard is estimated in different ways. The arrows show the direction of the variation in time.

4.2.4 Conclusion

The diver measurements show that the error in the water level at station Dodewaard is at least 6 cm. The measurements suggest that the error is even larger when the full flood wave is considered. With the WAQUA-model it is possible to estimate the error for the full flood wave but inaccuracies due to the WAQUA schematization are likely. Both the measurements and the WAQUA-results show a similar trend: the regression relation underestimates the water level during the peak of the flood and during the rising and falling of the flood this underestimation becomes smaller. The WAQUA-results suggest that the water level at station Dodewaard calculated from the regression relation contains a maximum error of 17 cm at the peak of the flood.

4.3 Linear interpolation of the water level

The bed level can only be correctly estimated if the water level is known at every measuring location and at every measuring time. During the 1997 flood the water level between stations Dodewaard and TielWaal was not measured, but afterwards calculated by a linear interpolation between the two stations. Wilbers (1998) expected an error due to this linear interpolation to be the main contributor to the bed level decrease. This is supported by Wiegmann (2002; 2002) who recognises a variable error in the order of 5 cm. The water level is in reality not linear due to, for example, local width variations. Local width variations can cause a deviation from the linear water level and thus an error in the bed level as shown in Figure 4.17. The error caused by the linear interpolation is estimated by comparing the linear water level with the measurements during the 2011 flood and the results of the WAQUA computations.

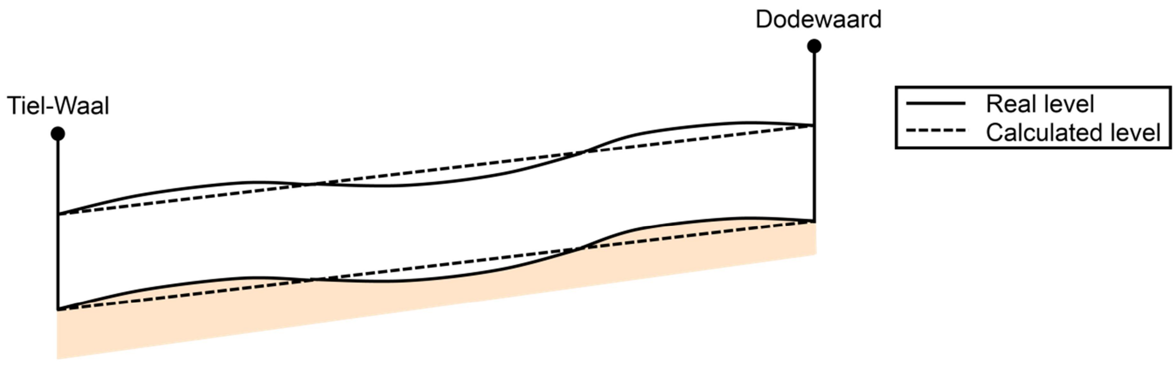

Figure 4.17 The effect of an error caused by assuming a linear water level between stations Dodewaard and TielWaal.

4.3.1 Measurements of the 2011 flood

The measurements of the 2011 flood are compared with the linear interpolation of the water levels between the stations Dodewaard and TielWaal. The water level at station Dodewaard follows from a spline interpolation of the diver measurements (Figure 4.2) and the water level at station TielWaal was measured. Based on these measurements Figure 4.18 is made. This figure shows the difference between the linearly interpolated water level and the measured water level which corresponds to an error in the bed elevation data. The graphs show that the difference is smallest at station Dodewaard, since this is one of the points from which the water level is linearly interpolated, and in the downstream part the difference is largest. From these graphs it follows that before the peak of the flood the water level is underestimated, during the peak the water level is overestimated and after the peak the water level is underestimated. This would correspond to an increase of the bed level during the flood in the downstream area of the reach in the order of 10 cm.

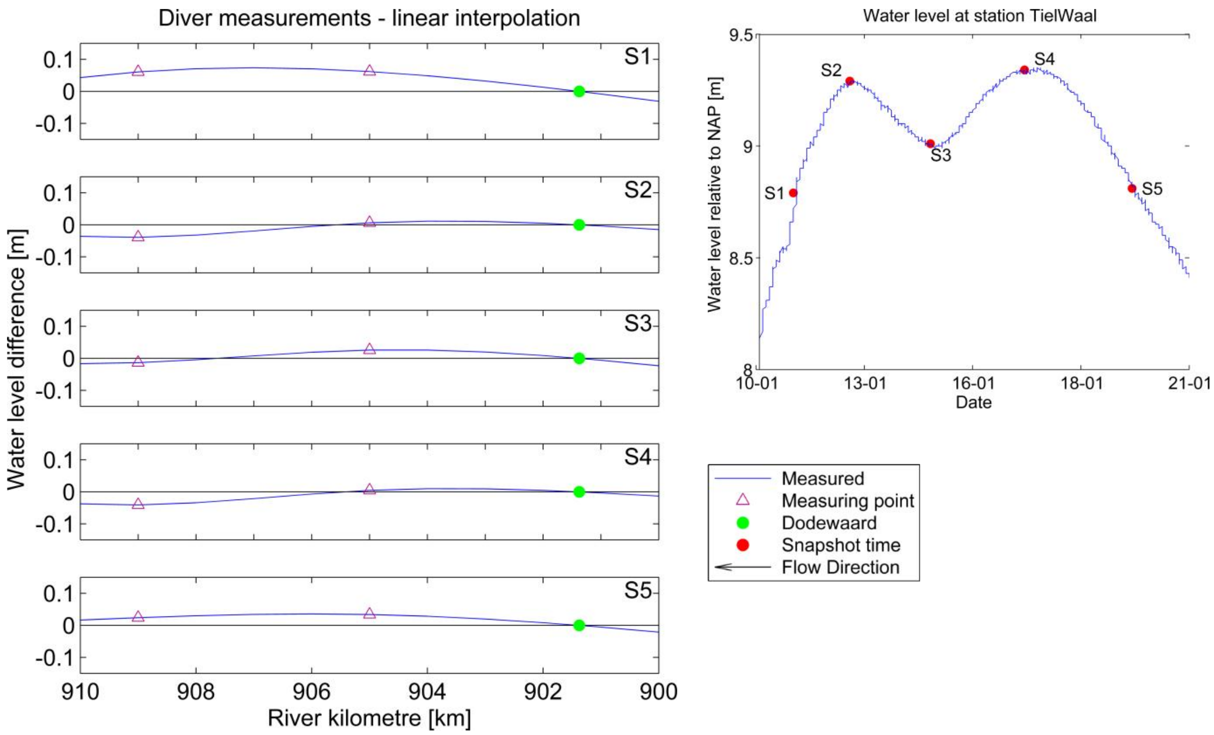

Figure 4.18 Left: The difference between the measured water level and the linear interpolated water level for different moments in time during the 2011 flood. Right: The water level at station TielWaal with red dots which indicate the different moments in time corresponding to the five graphs on the left.

4.3.2 WAQUA-results for the 1997 flood

The results of the WAQUA-model for the 1997 flood give a more detailed water level variation over the reach. The result is presented in Figure 4.19 which shows the difference between the WAQUA-result and the linearly interpolated water level. The interpolated water level is based on the water level at stations Dodewaard and TielWaal retrieved from the WAQUA-simulation. In the upstream area the difference between the two water levels is relatively small because it is close to station Dodewaard. In the middle part of the reach the difference decreases and in the downstream part the difference increases. The variation in the downstream part is in the order of 8 cm and the difference is largest at the peak. This variation could explain a bed level decrease in the order of 8 cm in the downstream part of the reach during the 1997 flood.

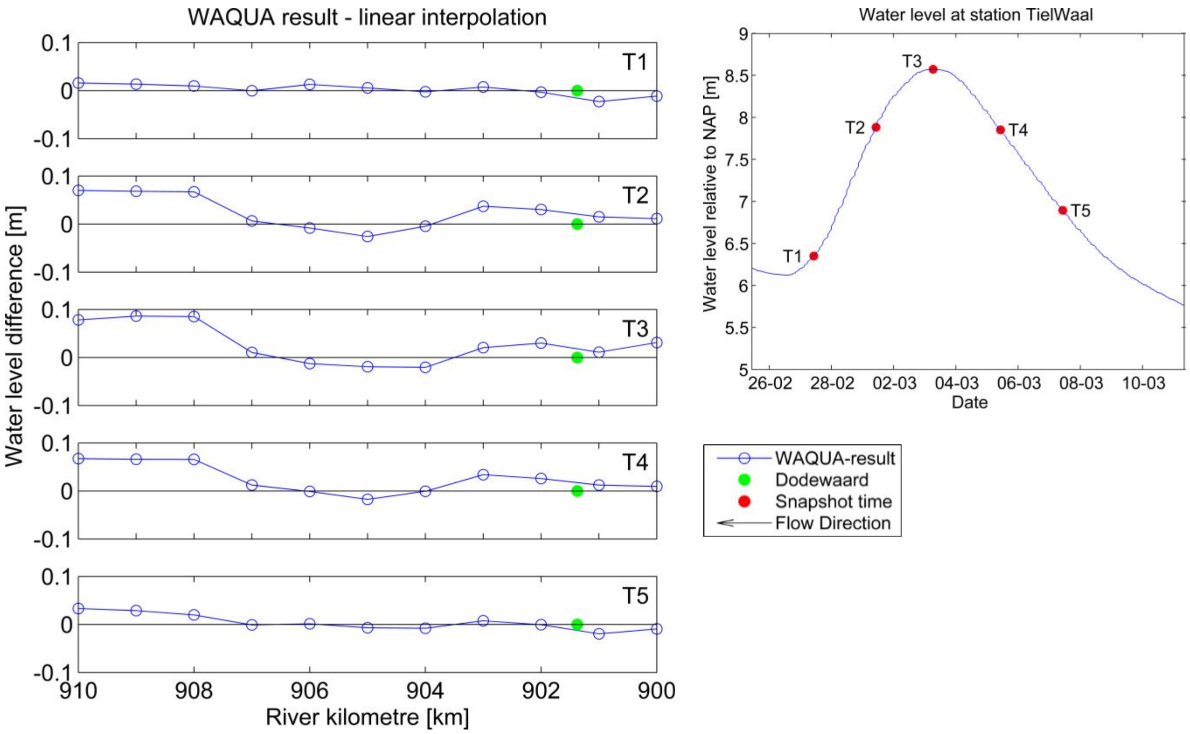

Figure 4.19 Left: The difference between the WAQUA-result and the linear interpolated water level for different moments in time during the 1997 flood. Right: The water level at station TielWaal with red dots which indicate the different moments in time corresponding to the five graphs on the left.

4.3.3 Comparison of the results

The results of the linear interpolation of the water level during the 2011 and the 1997 flood show opposite results for an error in the bed level due to the linear interpolation. The measurements of the 2011 flood suggest a bed level increase during the peak of the flood while the WAQUA-result for the 1997 flood suggests a bed level decrease during the peak of the flood. First of all it is noted that the measurements during the 2011 flood were carried out during high water levels and only a few measurements during the rising and falling of the flood are available.

Figure 4.20 shows the variation of the flow-conducting cross-sectional area during the two floods. The data was retrieved from a 1D schematization of the Waal and related to the water levels of the WAQUA-computation. In the figures each line corresponds to a snapshot time of the Figures 4.18 and 4.19. Figure 4.20b shows that between river kilometre 907 and 908 the flow-conducting cross-sectional area increases significantly more than the surrounding areas with increasing water level. This is caused by a small side channel which is formed in the floodplain. Due to this large increase of the flow-conducting cross-sectional area, the water level is locally lowered which is shown in Figure 4.21. This lowering still has a significant effect on the water level at station Dodewaard since the half length of the backwater curve is in the order of 25 km. The water level is therefore underestimated with the linear interpolation in the part of the reach unaffected by the widening of the river. The difference in the flow-conducting cross-sectional area between river kilometre 907.5 and the surrounding locations is largest during the 1997 flood and therefore the effect is largest as well. During the 2011 flood the change of flow-conducting cross-sectional area at river kilometre 907.5 is much smaller than the surrounding areas which results in the mitigation of the local water level decrease. Another reason for the difference between the two floods could be that due to the limited amount of measuring points during the 2011 flood, the variation of the water level over the reach is not well represented. Moreover, the water level at station Dodewaard during the 2011 flood was estimated based on the spline interpolation which could easily cause an inaccuracy of a few centimetres.

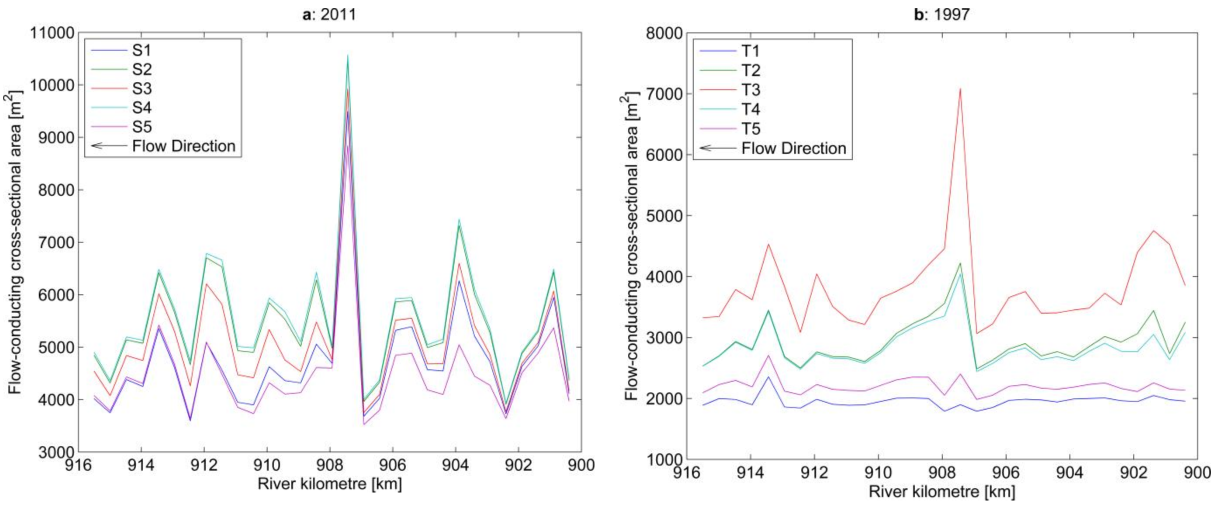

Figure 4.20 a: The flow-conducting cross-sectional area for different water levels in the river during the 2011 flood as presented in Figure 4.18. b: The flow-conducting cross-sectional area for different water levels in the river during 1997 flood for different water levels which was shown in Figure 4.19.

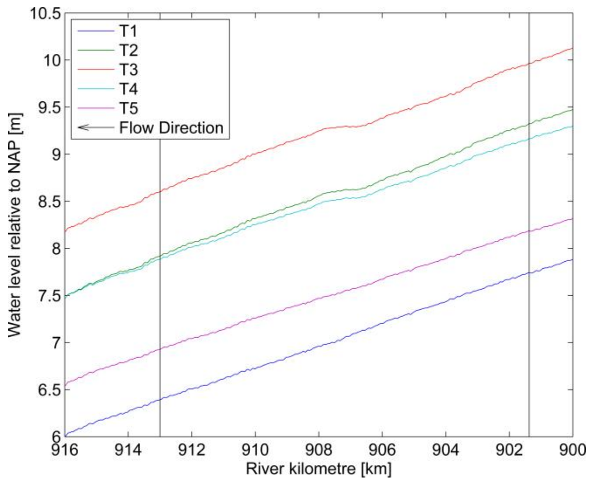

Figure 4.21 Water level over the reach during the 1997 flood retrieved from the WAQUA-result. Each line corresponds to water levels in Figure 4.19. The vertical black lines indicate the location of the measuring stations Dodewaard (upstream) and TielWaal (downstream) in between which the water level is linearly interpolated.

4.3.4 Conclusion

A comparison of the 2011 measurements with the linearly interpolated water level shows different behaviour than the results of the WAQUA-model. The 2011 flood is much larger than the 1997 flood which can explain the differences. Moreover, only limited data is available during the 2011 flood which makes it difficult to compare the two results accurately. During both floods the inaccuracy due to the linear interpolation is largest at the downstream part of the reach. From the WAQUA-results it is concluded that the linear interpolation contributes to a bed level decrease in the order of 8 cm in the downstream part of the reach.

4.4 Combined water level error

From the previous two analyses it is concluded that both the water level at station Dodewaard and the linear interpolation of the water level contribute to an error in the average bed levels. The contributions from both errors are summed as seen in Figure 4.22 since the water level at station Dodewaard is linearly decreasing towards the downstream part (Figure 4.7) and the spatial variation of the error from the linear estimation (Figure 4.17) is known from the WAQUA-model. The effect caused by small instabilities in the results is mitigated by averaging the results for every day between 8 am and 15 pm which is the part of the day during which the measurements were carried out.

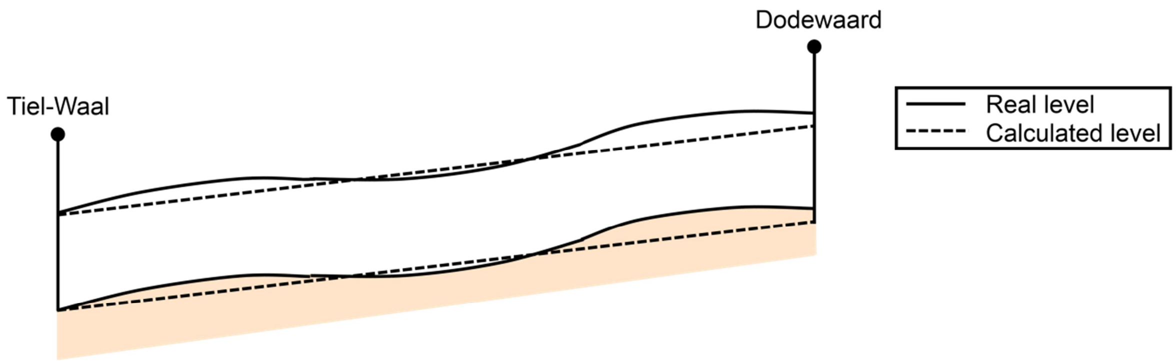

Figure 4.22 A combination of the effect of an error in the water level at station Dodewaard and an error due to the linear interpolation.

Figure 4.23 shows the result of the summation of the two errors. The blue line presents the error in the water level at station Dodewaard which is calculated from the difference in water level between the WAQUA-result and the regression relation (Figure 4.13). The green line follows from the difference between the linearly interpolated water level and the WAQUA-result as presented in Figure 4.19. The summation of these two lines is presented by the red line. This line suggests that the bed level decrease is largest at the beginning of the reach, smallest in the middle of the reach and larger again at the end of the reach. A comparison between Figure 1.9 and the red line in Figure 4.23 shows that the same trend is visible in the measurement. This means that the estimated error in the water level explains both a time and spatial varying bed level decrease in the Waal during the 1997 flood.

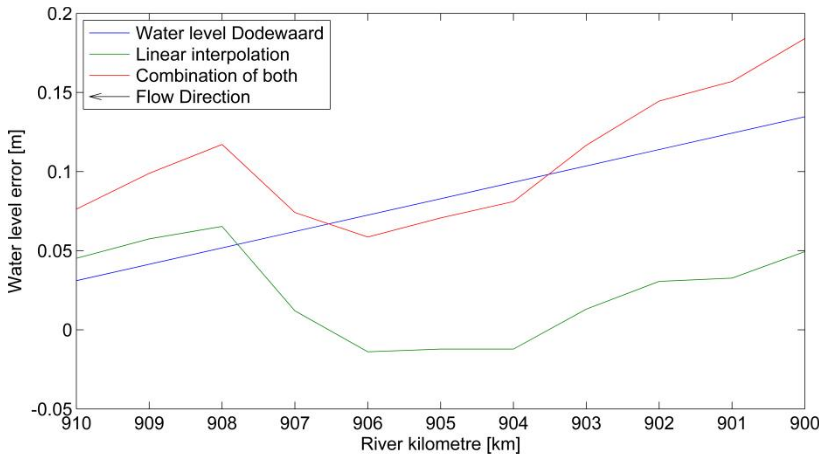

Figure 4.23 Variation of the maximum change of the error over the reach which is created from the difference between the error on 3 March and the error on 7 March. A positive error corresponds to a decrease in the bed level during the peak of the flood.

5 Bed level changes due to other potential errors

There are several other potential errors which could lead to large bed level changes during a flood. In the following sections the contributions and the relevance of several errors are discussed. Each of these errors is influenced by the variability of the flow conditions and could possibly cause a large decrease of the bed level.

5.1 Squat

Squat is the amount of sinkage of a vessel in the water. A variation of the amount of squat during the flood causes a different vertical position of the vessel relative to the water level and could therefore explain a variation of the bed level. Squat is caused by a pressure decrease below the vessel when it moves in shallow water. The amount of squat depends on the vessel, the sailing direction and the sailing velocity. During the measurements three different vessels were used. The first measured from river kilometre 900 to 905, the second from 905 to 909 and the last from 909 to 910. On each of the days each the measuring vessels measured the same area and all the measurements were taken while sailing from upstream to downstream. During bed level measurements in the past, squat was often not taken into account which could lead to a variable error in the order of 5 cm (Wiegmann, 2002). However, the effect of squat does not seem to be related to the peak of the flood and therefore it is not expected to be a large contributor to the lowering of the average bed level.

5.2 Propagation velocity of sound

One of the important parameters to calculate the depth from an echosounding is the propagation velocity of sound. The propagation velocity of sound changes with the density of the water and with the amount of particles in the water. Especially in areas with strong stratification large errors can occur because the different layers have different propagation velocities of sound. This means that the depth has to be calculated based on a depth varying velocity of sound. A second problem of stratification is that refraction of the beams occurs. Refraction is the change of the beam angle caused by a difference in velocity between two layers. The amount of refraction is described by Snell's Law and especially in case of multi-beam echosounders the measurements have to be compensated for this effect (Dinn, et al., 1995; Kammerer, 2000). At the location in the Waal where the single-beam echosoundings were made, stratification did not occur. However, a large change over time in the sediment concentration during the flood could lead a change of the propagation velocity of sound.

The effect of the change in sediment load on the propagation velocity of sound during the flood can only cause a large bed level decrease if a large change of the suspended load concentration occurs. The bed load is assumed to have only a small influence since the layer thickness is very small. The suspended load concentration is calculated from measurements (Kleinhans, 2002). During the peak of the 1997 flood the suspended load was measured to be in the order of 16 m^3/mday with a flow velocity of 1.2 m/s at the Pannerdensche Kop. From these measurements it follows that the sediment concentration was in the order of $1.7 \cdot 10^{-5}$. In Chapter 3 the suspended load concentration was calculated for the Waal with two empirical relations. Both resulted in an average concentration in the order of $2.7 \cdot 10^{-5}$ (Van Rijn, 1984b; Camenen & Larson, 2007; 2008). With these concentrations the maximum influence of the suspended sediment concentration on the propagation velocity of sound is estimated.

Hampton (1967) describes the effect of sediment concentration and acoustic frequency on the propagation velocity of sound in the mixture. With increasing sediment concentration the propagation velocity of sound first decreases till the point of maximum attenuation after which the propagation velocity of sound in the mixture increases. The tests were done using Kalinite, which is a certain type of clay, as the sediment mixture but Hamilton (1956) found a similar behaviour for sand. Assuming an inaccuracy of 10 cm, Hampton (1967) showed that this corresponds to a sediment concentration increase of about 0.05. In case of the Waal the maximum change of concentration is in the order of $2.7 \cdot 10^{-5}$ and therefore the inaccuracy of the propagation velocity of sound cannot explain the decrease in bed level in the Waal during the 1997 flood.

5.3 Bias in the bed level measurements

Variations of the bed level, e.g. river dunes, can have a large influence on the accuracy of the bed level measurements. The reflection of a pulse as seen in Figure 1.4 returns multiple signals which corresponds to multiple depths at the same location. One part of the beam reflects at the peak, one in the trough and some in between. Choosing the correct height is therefore important to be able to calculate the correct mean bed level. Taking the smallest depth will underestimate the troughs and taking the largest depth will underestimate the peaks. These effects are schematized in Figure 5.1. The single-beam data of the Waal was processed using the mean value. Therefore both the peaks and the troughs are underestimated, but for the average bed level the effects of these errors are expected to cancel each other out.

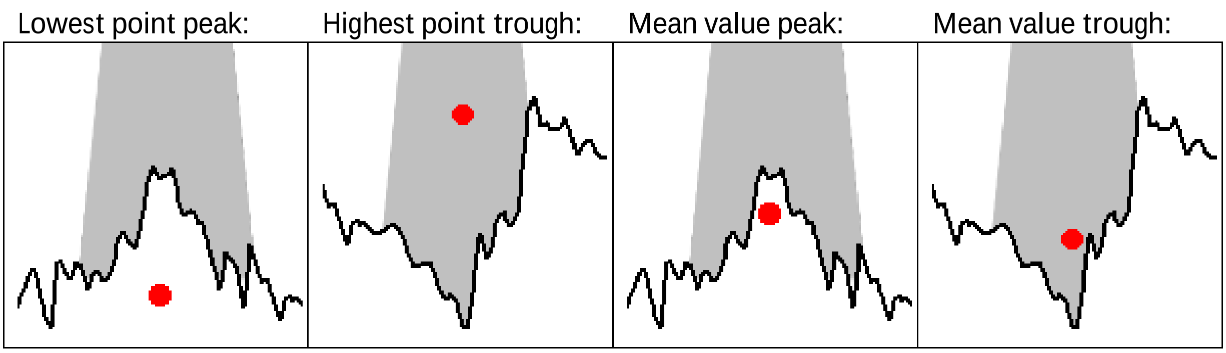

Figure 5.1 The effect of choosing an incorrect method to estimate the bed level from multiple return signals.

The size of an error made by the processing of the data is dependent on the beam width and the local slope of the bed. During the 1997 flood a single-beam echosounder was used with a beam angle of 9.8 degrees (Wiegmann, et al., 2002) and with a water depth in the order of 10 m this results in a footprint with a diameter of 1.7 m. However, the beam angle depends strongly on how the echosounder has been calibrated by the manufacturer and therefore is in reality a larger beam angle expected (Wiegmann, et al., 2002). The effect of the local slope is clear from Figure 5.1. A steeper bed form means that more surrounding values are included in the averaging of the depth values which leads to larger errors. In case of an averaged bed level this effect should be limited since both the troughs and the peaks are affected in the same way.

From a conversation with A. Sieben (2014) it followed that in practice the dune troughs are often underestimated. If this underestimation increases with increasing dune height, it could be responsible for an increase in the average bed level during the flood. Moreover, due to the lagged response of the dune height to the flow conditions, the maximum dune height was measured to be on 5 March (Figure 2.6). A bias could therefore result in an increase of the average bed level with a peak on 5 March. The bed level measurements do not show these characteristics and therefore the effect is most likely small.

5.4 Conclusion

The large-scale bed level change which occurred during the 1997 flood in the Waal was caused by the incorrect estimation of the water level. The other contributions which are described in this chapter have a small contribution or do not have a correlation with the peak of the flood. These inaccuracies did therefore not cause the large-scale bed level decrease.

6 Corrected bed level profiles

Chapters 3 to 5 showed that an inaccuracy in the water level is most likely the cause of the large-scale decrease of the bed level. Other possibilities were investigated but could not explain an average bed level decrease in the order of 10 cm during the peak of the 1997 flood. The incorrect water level is therefore assumed to be the main problem. The WAQUA-model seems to estimate the error relatively well and therefore the bed level is corrected based on the errors found in Figures 4.13 and 4.19. The error is averaged between 8 am and 15 pm to avoid the influence of small instabilities. The averaging was done after a correction for the phase difference between the measured and the computed flood wave as seen in Figure 4.2.

6.1 Corrected bed levels

Figure 6.1 presents the result of the bed level correction. The figure shows that instead of a lowering during the flood, the bed level increases with a few centimetres. River kilometre 900 to 904 clearly show an increase of the average bed level during the rising flood. During the peak and after the peak the bed level is more or less constant. Figures 6.2 and 6.3 show the same pattern. These two figures clearly present that the WAQUA-model overestimates the error on the 1 and 2 March. Also at other locations these two days seem to be out of place. In Chapter 1 was noted that at river kilometre 907 the bed level increases during the flood. This increase of the bed level is visible in the corrected measurements and is caused by a deceleration of the flow due to a large widening of the flow-conduction cross-sectional area as was shown in Figure 4.20b. The last measurement on 15 April shows at almost all locations a large increase of the bed level. This is possibly caused by inaccuracies in the WAQUA-model.

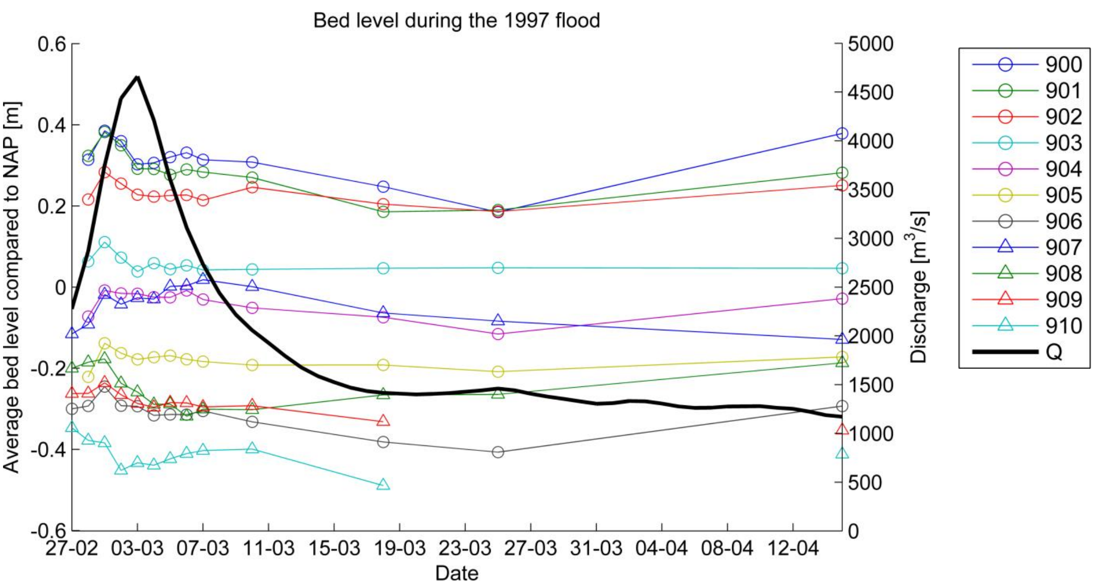

Figure 6.1 Corrected average bed level during the 1997 flood at each river kilometre in the measuring reach. Q is the discharge in the Waal at measuring station TielWaal

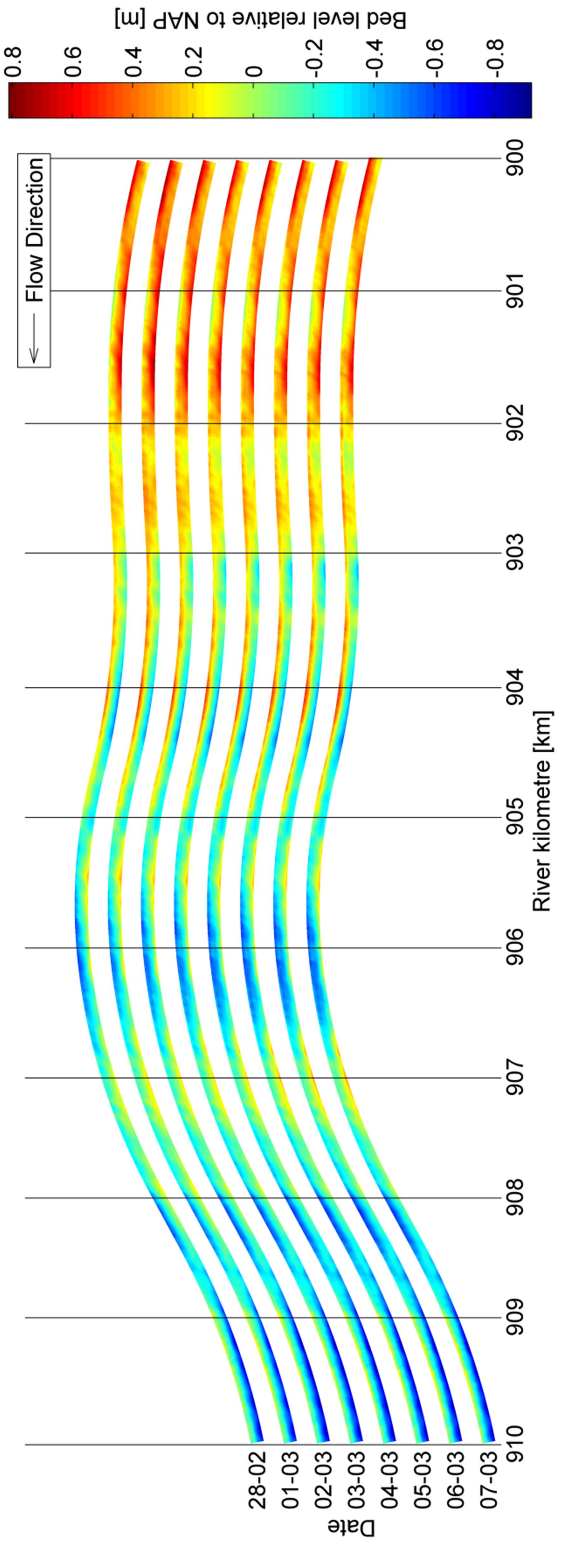

Figure 6.2 Bed level during the 1997 flood averaged over a distance of 390 m and corrected for the water level error.

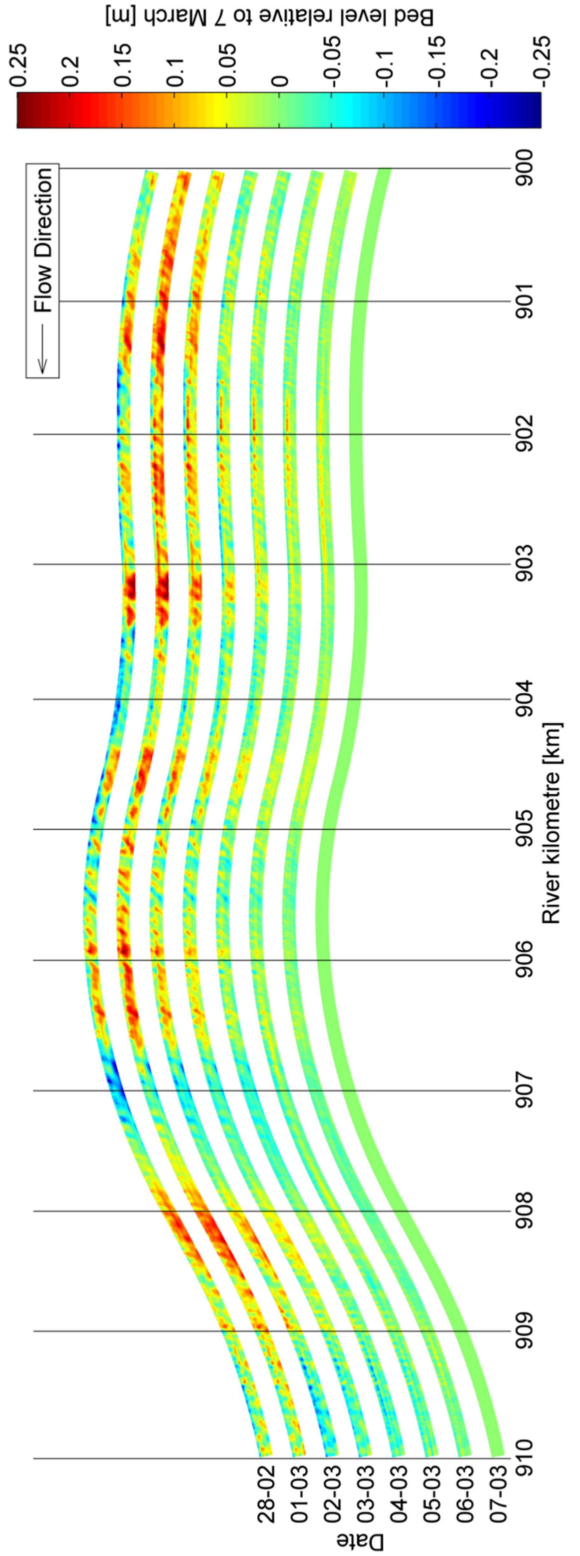

Figure 6.3 Bed level during the 1997 flood subtracted by the bed level on 7 March and corrected for the water level error.

6.2 Variation of the river geometry

The corrected bed level measurements show that a large-scale bed level change does not occur but local variations of the river geometry show large effects. Two locations are discussed in more detail: the area downstream of the 903km and the reach between 906 and 908 km. These river geometry variations can only have a large effect if the average flow conditions of the river counteract the bed level changes during a flood. The time it takes to restore the riverbed after a flood is therefore important to predict the bed level changes in case of multiple floods. In this thesis this time is referred to as the refilling period which is discussed in Section 6.2.2.

6.2.1 Measured bed level changes

The main bed level changes are caused by local variations in the river geometry. As mentioned in the previous section, the bed level increases at the 907 river kilometre due to a large increase of the flow-conduction cross-sectional area. However, further downstream at the 908 river kilometre this cross-sectional area decreases as was seen in Figure 4.20b. This decrease of the cross-sectional area causes an acceleration of the flow which results an erosion at the 908 river kilometre as explained in Figure 6.4. In this figure the large increase of the flow-conduction cross-sectional area corresponds to the withdrawal of water from the main channel and the decrease of the cross-sectional area corresponds to a resupply of water. Upstream of the withdrawal the velocity decreases due to the decreasing water level which results in erosion (between 906 and 907 km). The velocity is much lower between the withdrawal and the resupply due to the lower discharge in the main channel which results in deposition (907 km). Downstream of the resupply the velocity increases again causing an erosion of the bed (908 km).

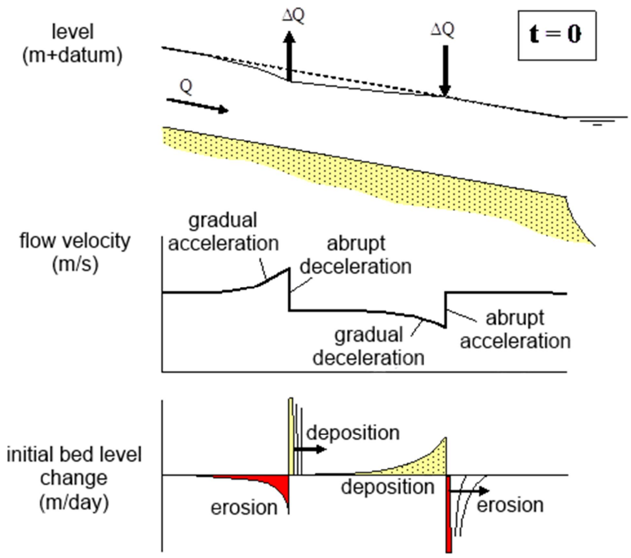

Figure 6.4 Initial morphological response to a local increase of the flow-conducting cross-sectional area. From top to bottom: Immediate effect on the water level; immediate effect on the flow velocities; initial morphological response (Mosselman, 2012).

A second location where large erosion occurs is just downstream of the 903 river kilometre. A detailed look at the height of the riverbank reveals a harbour at this location with a high pier. The pier is the same size as the surrounding groynes but the crest level of the pier is much higher. The effect of the pier is therefore negligible at lower flows. At higher water levels the flow goes over the groynes but not over the pier due to the higher crest level. This causes a local narrowing of the main channel during a flood which results in higher flow velocities and a lowering of the bed level at this location.

6.2.2 Refilling period

The previous section shows that the river geometry has a large effect on the bed level changes during a flood. It is shown that the bed level changes only occur during flood conditions and that during low flows these effects are mitigated. A previous flood can therefore have a large effect on the bed level and the bed level changes (Bolla Pittaluga, et al., 2014). Bolla Pittaluga et al. found that the spatial variation of the river width in combination with floods can cause a large deviation of the riverbed from the equilibrium profile. In case of multiple floods over a short period of time the bed level changes are therefore affected by the previous flood conditions. The time it takes for the bed to restore itself after a flood is therefore important to predict the effect of floods on the bed level.

The corrected bed level measurements can suggest the refilling period. Figure 6.2 shows that on 15 April the bed level is more or less similar to the starting bed level. At the 907 kilometre aggradation occurs during the flood and on 15 April this aggradation has eroded. At the 908 kilometre degradation occurred during the flood and on 15 April this degradation is mitigated. The bed level measurements therefore suggest that the refilling period is at most 1.5 month. However, the correction on the measurements is considered to be uncertain which could result in both a longer and a shorter refilling period.

6.3 Conclusion

The bed level changes which occurred are mainly caused by variations of the river geometry during the flood. Bolla Pittaluga et al. (2014) showed that the bed level still has a memory of the previous floods which disturbed the equilibrium profile. For the Waal the period of refilling is estimated 1.5 months from the measurements but there is insignificant data available to confirm. Simulations with a morphological model should be able to give better estimation of the refilling period.

The corrected bed level measurements clearly show that the WAQUA-model does not predict the error correctly. The large and short increase of the bed level before the peak of the flood is not correct. The three main reasons for this inaccuracy in the WAQUA-model are:

- The model was not calibrated on the 1997 flood and in section 4.1.2 was shown that this leads to a difference in the absolute water level at station TielWaal in the order of a few centimetres which could lead to an incorrect estimation of the error.
- The WAQUA-model was calibrated for the 1995 flood. The calibrated roughness value is constant between the measuring stations TielWaal and Nijmegenhaven. This value most likely approaches the average roughness value in this area and therefore it is possible that locally the roughness values are over or underestimated.
- The boundary conditions contain errors. The Qh-relation downstream does not contain the hysteresis effect which most likely has a large influence at station TielWaal. The discharge at the upstream boundary is daily averaged and does underestimate the real discharge. The effects of these errors are however mitigated by the use of the WAQUA-results as input for the regression relation.

7 Morphodynamic simulations of the 1997 flood

The previous chapter showed that large-scale bed level changes in the Waal do not occur during a flood. However, local variations of the river geometry cause bed level changes during floods. A morphodynamic model like Delft3D should be able to simulate the bed level variations caused by the geometry changes and with the model it should be possible to make a better estimate of the refilling period. In this chapter the morphodynamic changes during the 1997 flood in the Waal are simulated using a Delft3D model.

7.1 Model setup

The effects of the 1997 flood are studied with a Delft3D model of the Waal which is shown in Figure 7.1. The model domain includes the part of the Waal from the Pannerdensche Kop to Vuren (Van Vuren, et al., 2006) and bed levels are based on multi-beam measurements from 2011 (Sloff, et al., 2013).

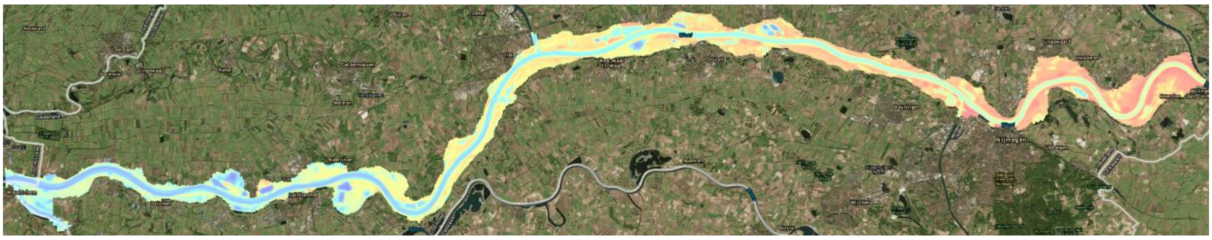

Figure 7.1 Overview of the Delft3D model domain from the Pannerdensche Kop till the measuring station Vuren with the initial bed level.

7.1.1 Initial conditions

The single-beam measurements of the Waal during the 1997 flood cannot be used as the bed level in the model because the 10 km reach is too short and has to be extended. Moreover, Wiegmann et al. (2002) showed that the single-beam measurements also contain a constant error. The bed level can be corrected for this constant error, but it will most likely cause discontinuities in the bed. The initial bed level used shows patterns which are similar to the measured bed level measured during the 1997 flood. The initial grain size is given by a spatial varying D_{50} and the sediment transport is calculated using Van Rijn (1984a). The main channel roughness is estimated based on a dune predictor. The dune height is calculated using the predictor by Fredsøe (1982). The dune length and the roughness height are calculated using Van Rijn (1984c).

7.1.2 Model calibration

The model was calibrated both on the hydrodynamic and the morphological changes. The hydrodynamics calibration is done by changing the roughness height in the main channel. The main channel roughness is estimated using the dune height predictor by Fredsøe, the dune length by Van

Rijn and the roughness height by Van Rijn. The water levels of the river are calibrated at the water level stations by adjusting the roughness height. The morphological calibration is done on 1D and 2D morphological processes.

The 1D-morphological calibration was based on the annual sediment transport rates, the celerity of bed disturbances, annual bed level changes and period-averaged bed level gradient. These parameters were calibrated by adjusting the bed load and suspended load transport, the critical Shields parameter and the spatial distribution of bed material (Yossef, et al., 2007). The 2D morphological calibration focusses on transverse slopes in river bends and the position of crossing between two opposite bends. These patterns are changed by adjusting parameters which affect the intensity of the spiral motion due to the curvature of the flow and the effect of the transverse bed slope. Overall performs the model reasonably well for both the 1D and the 2D morphological behaviour.

7.1.3 Boundary conditions for the 1997 flood

Three boundary conditions have to be defined: An upstream hydrodynamic condition, a downstream hydrodynamic condition and an upstream sediment transport condition. The upstream hydrodynamic condition is given by the daily averaged discharge at the Pannerdensche Kop during the 1997 flood. The downstream hydrodynamic condition is estimated with the measured water level at station Vuren. The upstream sediment transport is given by the equilibrium sediment transport in the first cell and is therefore similar to a Neumann boundary condition.

Preliminary computations show that the bed is unstable when the morphological changes of the 1997 flood are computed. This is caused by the 2011 bed level which does not fit the flow conditions. The bed level has to adjust to the flow conditions. The best solution would be to run a cycle of low and high flow conditions, but this would mean that the model would have to simulate an entire year. Instead the computation is made for twice the 1997 flood with in between a lower discharge as seen in Figure 7.2. During the first peak the bed is able to adjust itself to the flow and during the second peak the bed should show the same trends as the measured bed levels during the 1997 flood. However, the qualitative bed level changes are difficult to determine due to the double flood wave and due to the 2011 bed level.

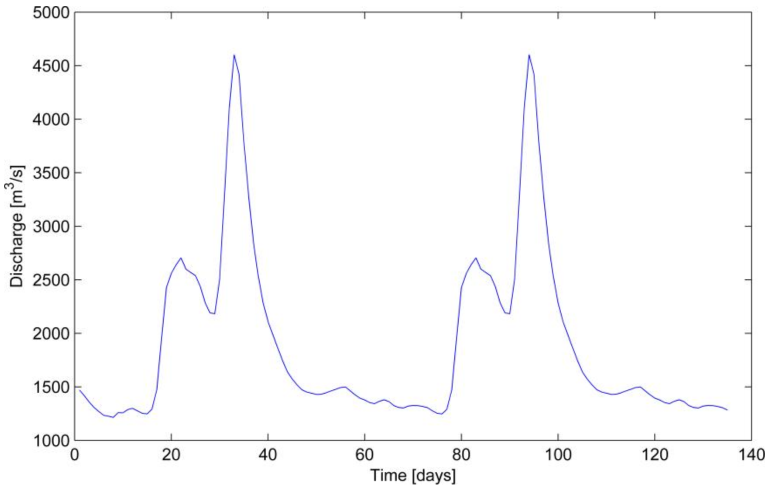

Figure 7.2 The upstream discharge boundary condition for the Delft3D model of the Waal which is located at the Pannerdensche Kop.

7.2 Results

The bed level changes during the 1997 flood calculated from the Delft3D model are presented in this section. Figure 7.3 shows the water level at station TielWaal from measurements and from the Delft3D model. It is clear from this graph that the water level is underestimated by the model. The lower water level could be caused by the daily averaged discharge which underestimates the real discharge and the 2011 initial bed level probably has a large influence. On average the bed level in this part of the Waal decreases with a centimetre per year (Van Vuren & Sloff, 2006). This bed level decrease is not taken into account in the model and therefore an underestimation of the water level is expected. The results of the Delft3D computation are discussed in the following sections.

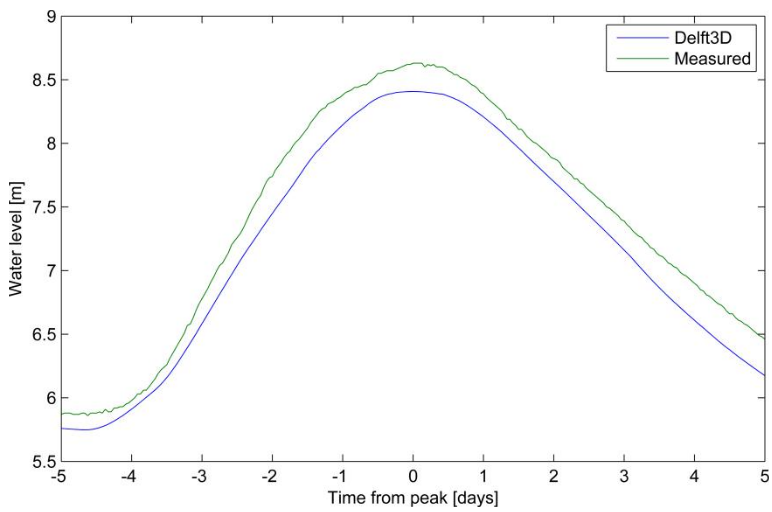

Figure 7.3 Water level at station TielWaal from the Delft3D model and the measured water level during the 1997 flood.

7.2.1 2D simulation results

In Chapter 6 the bed level changes were presented based on the bed level measurements. Figures 7.4 and 7.5 show the bed level during the 1997 flood from the Delft3D computation. A comparison with the measurements (Figure 6.2) directly shows that the bed level is lower in the model. This could be caused by a constant error in the measurements and the average bed level decrease in the Waal. Figure 7.5 shows the bed level relative to the bed level on 7 March and gives therefore an indication of the bed level changes during the flood.

As expected from the measurements sedimentation occurs downstream of the 907 river kilometre where the flow-conduction cross-sectional area increases during the flood. Upstream around km906 and downstream around km908 erosion occurs which was also expected from the measurements, Figure 6.4. However, exactly on the 907 river kilometre erosion occurs which is caused by a narrowing of the main channel at this location. This erosion did not occur in the measurements and is therefore assumed to be caused by a change of the bed level between 1997 and 2011.

A second large change of the bed level occurs downstream of the 903 river kilometre which was also described in the previous chapter. The local narrowing of the main channel during high water levels causes an acceleration of the flow which results in local erosion. Similar erosion was found in the corrected bed level measurements.

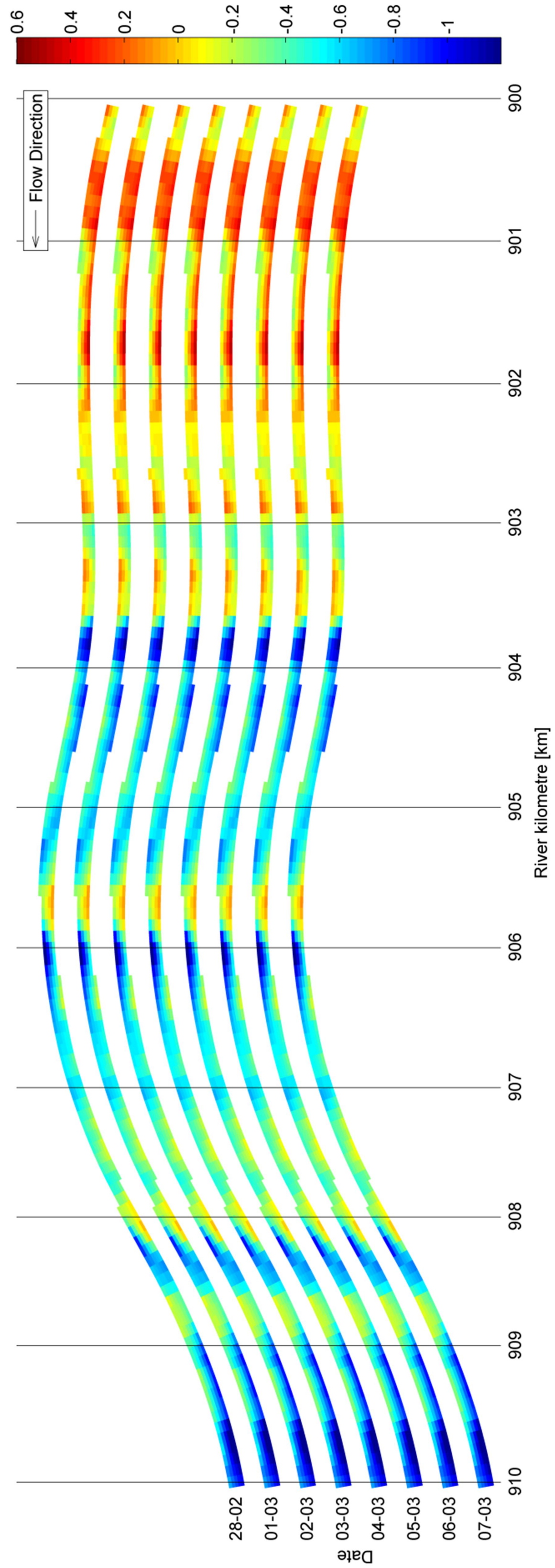

Figure 7.4 Bed levels during the 1997 flood from the Delft3D computation.

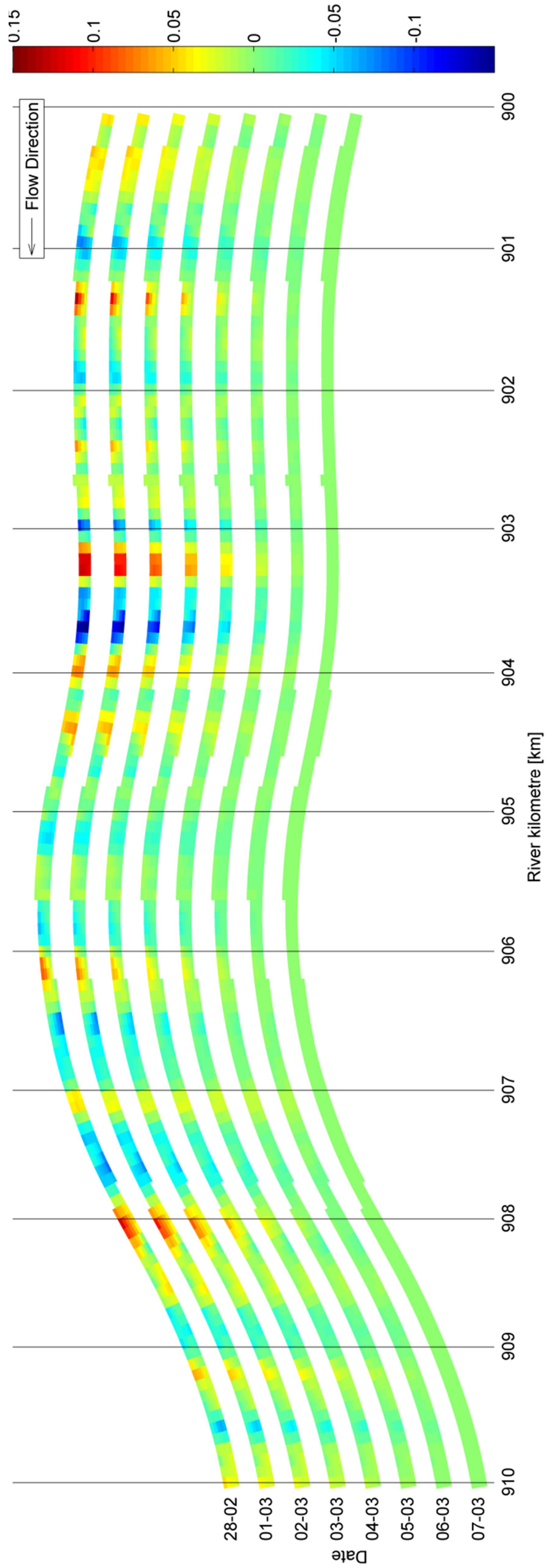

Figure 7.5 Bed level changes during the 1997 flood with the reference level on 7 March.

Overall are the trends between the measured bed level and the computed bed level similar. The important processes near the 903 and the 907 river kilometre which were recognized in the measurements are also visible in the simulated bed level changes. At other locations are the differences large.

7.2.2 Longitudinal profiles

A longitudinal profile gives a better insight into the differences between the measured and computed bed levels. Figure 7.6 shows the bed level during the peak of the 1997 flood from measurements and from the Delft3D results. The measured bed level is averaged over 390 m in length and 100 m in width to filter the effects of dunes. The figure shows that the measured bed level is more or less everywhere larger than the computed bed level. At some locations the difference between the two bed levels is larger than 0.5 m. This is mainly caused by the initial bed level in the Delft3D model which is constructed from 2011 bed level measurements but could also be caused by the inaccuracies in the single-beam echosounder measurements during the 1997 flood.

Figure 7.7 shows the bed level change after the peak of the flood. As presented in the previous section, the computations do not show the same results as were measured but do show similar trends at some locations. The fluctuations which are visible in the measured bed level are caused by small scale bed level variations like dunes. These effects are filtered with a moving average over 390 m but in the graph for the relative bed level changes these small scale bed level variations are still visible. The computed bed level changes are at almost all locations smaller than the measured bed level changes which is caused by the double flood wave in the upstream boundary. The first flood wave allows the bed level to adjust to the flood conditions which results in smaller bed level changes during the second flood wave. The changes of the bed level are in the order of 5 cm which is the same order of magnitude as the difference between the two bed level changes.

Both figures show that the computed and the measured bed levels are significantly different and that a quantitative comparison of the bed level changes is almost impossible due to these differences. The main locations with erosion and sedimentation are also visible in the computed bed levels. The trends are therefore similar but the differences between the two bed level changes are in the order of 5 cm.

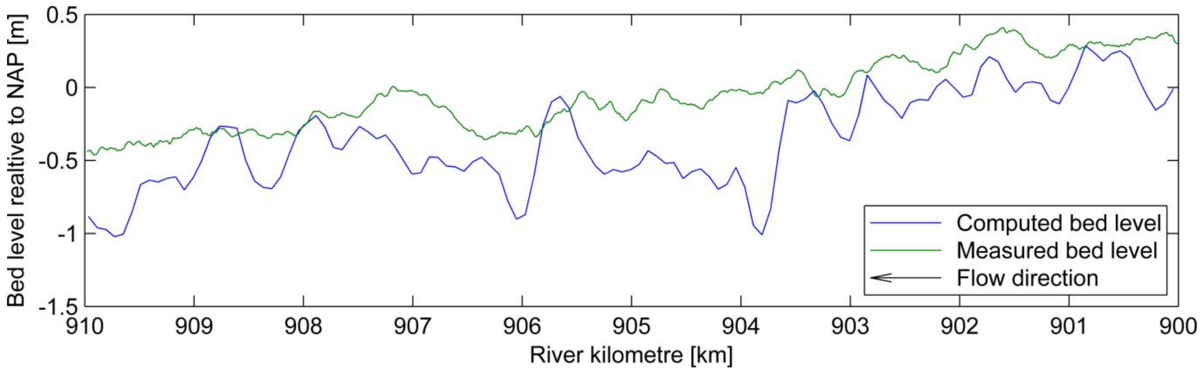

Figure 7.6 Longitudinal profile of the measured and computed bed level at the peak of the 1997 flood.

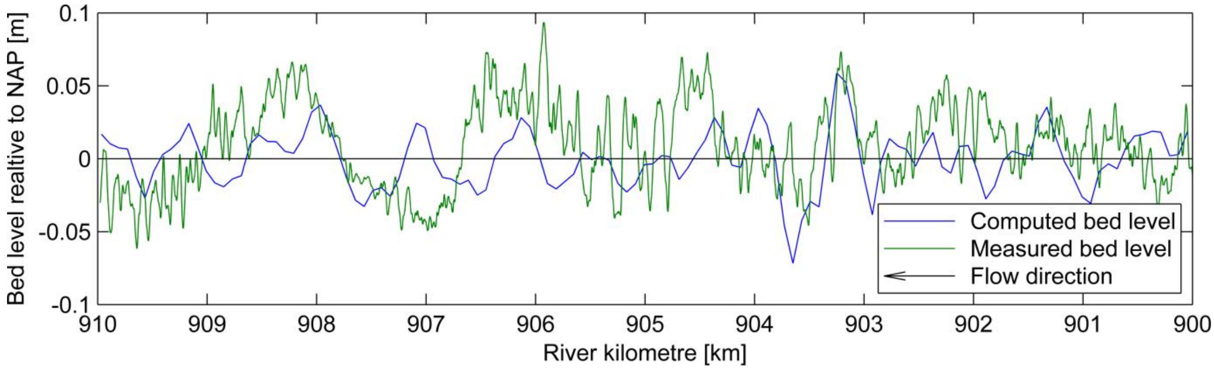

Figure 7.7 The bed level at the peak of the 1997 flood relative to the bed level on 7 March.

7.2.3 Refilling period from computations

Due to the two flood peaks it is difficult to define a refilling period since the effect of the first flood peak is most likely still visible in the bed. The refilling period is defined similarly to the previous chapter where the refilling period was defined as the time it takes to reach the same bed level as was measured at the beginning of the measurements. In other words, at which time is the bed level similar to the bed level on 28 February. This time is different for different locations in the river since the reasons for the local sedimentation and erosion are different.

Figure 7.8 shows the bed level at each river kilometre. From the graph it is visible that at every location the bed behaves differently and that also the refilling period is different at each location. This is related to the reason of the sedimentation or erosion at that location during the flood. For example, the local narrowing of the main channel at the 903 river kilometre starts to have an effect as soon as the water level is high enough to cause a flow over the groynes. In the area around the 907 river kilometre the bed level changes occur as soon as the floodplain starts to flow. Exactly on the 907 river kilometre the bed level decreases during the flood due to the narrowing of the main channel in the model. The increase of the bed level can be seen at this location as a smaller decrease. Downstream at the 908 river kilometre the bed level decreases as soon as the floodplain starts to flow which corresponds to the measurements and Figure 6.4. At other locations the bed level changes are not related to the flood, for example river kilometre 901, 905 and 906. It is likely that at these locations the 2011 bed level still has to adjust to the conditions since the bed level has not reached its equilibrium yet.

The refilling period is estimated from Figure 7.8 based on the results form river kilometre 903 and 908. The reasons for the bed level changes at these locations are different. However, at both locations the refilling time is in the order of one month. For the 903 river kilometre it is 28 days and for the 908 river kilometre 39 days. The difference is most likely related to the amount of erosion. At the 903 river kilometre the bed level decreased with 3 cm while at the 908 river kilometre the bed level decreased with 6 cm. The periods estimated from the model results are most likely underestimations of the real duration since the time between the first and the second peak was about 30 days and therefore the bed level changes which occur during the first peak still have an effect on the bed level during the second one. The refilling period from the model does however agree with the measurements which suggested than the period is smaller than 1.5 month.

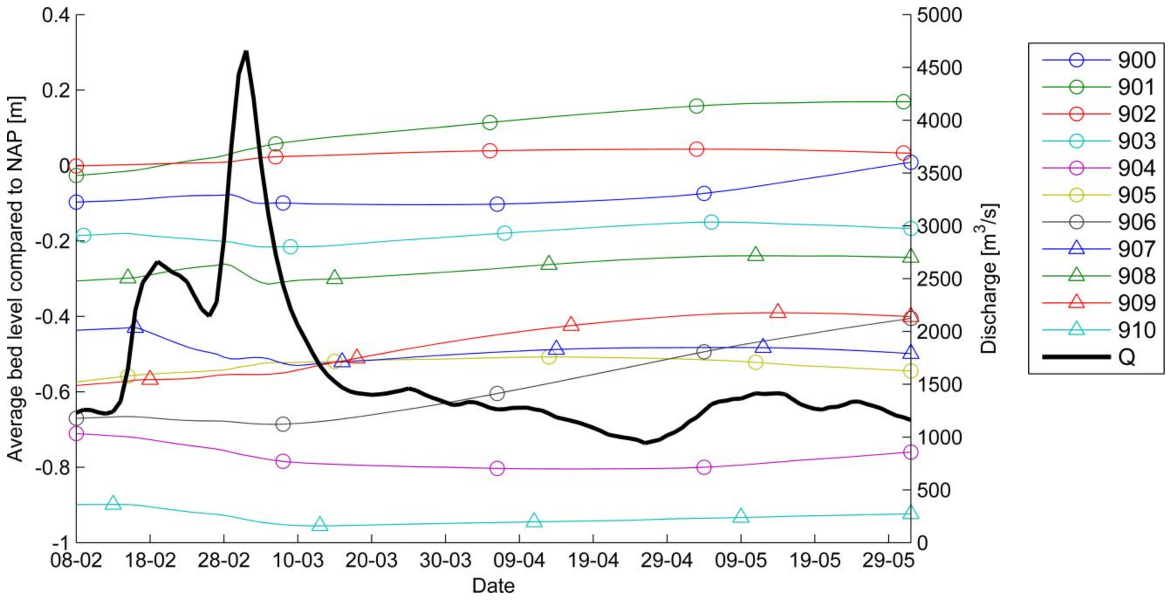

Figure 7.8 Bed level at each river kilometre from the Delft3D simulations. Q is the discharge at station TielWaal. The line markers do not correspond to measuring points but are shown to distinguish between the locations.

7.3 Conclusions and discussion

The differences between the Delft3D computation and the measured bed levels are large compared to the bed level changes. The measurements show a maximum bed level change in the order of 5 cm during the flood. The main trends which are visible in the measurements (around the 903 and the 907 river kilometre) follow also the computed bed level changes. The differences between the computed and the measured bed levels could be caused by the assumptions made to create the Delft3D model but could also be caused by inaccurate measurements or an inaccurate correction of the bed level with the WAQUA-results.

The Delft3D model does not show a large-scale bed level change which was seen in the uncorrected bed level measurements. Giri et al. (manuscript, 2014) studied the bed level changes during similar flood conditions in the Waal with a vertical 2D morphodynamic model (Giri & Shimizu, 2006). They were able to reproduce the changes of the dune characteristics during a flood in the Waal and confirmed that the large-scale average bed level does not change during a flood. The bed level changes which were visible in the Delft3D results are caused by local variations of the river geometry. The local variations of the river geometry have a large effect during a flood when during average flow conditions the effect is mitigated. From the measurements and the Delft3D model is concluded that in case of the 1997 flood it takes 40 days for the river to return to the bed level which is similar to the bed level before the flood. This duration is most likely underestimated due to the two flood waves. This duration also depends on the flow conditions between the two flood waves.

Local width variations have large effects on the bed level changes during floods. The measurements, the model results and Bolla Pittaluga et al. (2014) found that the effect of these width variations do not disappear after the flood but it takes time to refill the erosion holes and to erode the aggraded areas. The Room for the River Programme includes measures which give additional space to the floodplain. This could result in a large spatial variation of the river width. The measurements and the Delft3D results show that if there is additional room in the floodplain that the effect is mitigated by aggradation in the main channel. Ignoring these morphological changes can have a large influence on the flood risk and the navigability of the river (Mosselman, 2012).

A validation of the Delft3D model based on the bed level measurements during the 1997 flood is not possible. Both the model and the measurements contain large inaccuracies due to assumptions. The Delft3D model could be improved by using a more accurate initial bed level. The 2011 bed level is not similar to the 1997 bed level which causes differences in the bed level changes during the flood. The bed level measurements during the 1997 flood were unfortunately not accurate enough and the measuring reach was too small to use in the model computations. A second improvement could be to not use two flood waves to stabilize the bed but to create an initial bed level based on the flow conditions in 1996.

8 Bed level measurements at the Pannerdensche Kop

In the previous chapters was shown that a large-scale decrease of the bed level in the Waal during a flood is not expected. Bed level measurements during other floods could be used to confirm this conclusion. Unfortunately the bed level measurements during the 1998 flood in the Waal are not available anymore. However, Wilbers (1998) and Sieben (2006) present the average bed levels at the Pannerdensche Kop during the 1997 and the 1998 flood. The original data of the 1997 flood at the Pannerdensche Kop is not available anymore and therefore the result of an analysis by Wilbers (1998) is presented here. Sieben (2006) showed an average bed level decrease during the 1998 flood at the Pannerdensche Kop similar to the bed level decrease in the Waal during the 1997 flood. The bed level changes during the 1997 and the 1998 flood will be discussed in the following two sections.

Figure 8.1 shows an average bed level of the Rhine River around the Pannerdensche Kop. The upstream part of the branches shown in Figure 8.1 is called Bovenrijn, the bottom left branch is the upstream part of the Waal and the top left branch is the upstream part of the Pannerdensch Kanaal.

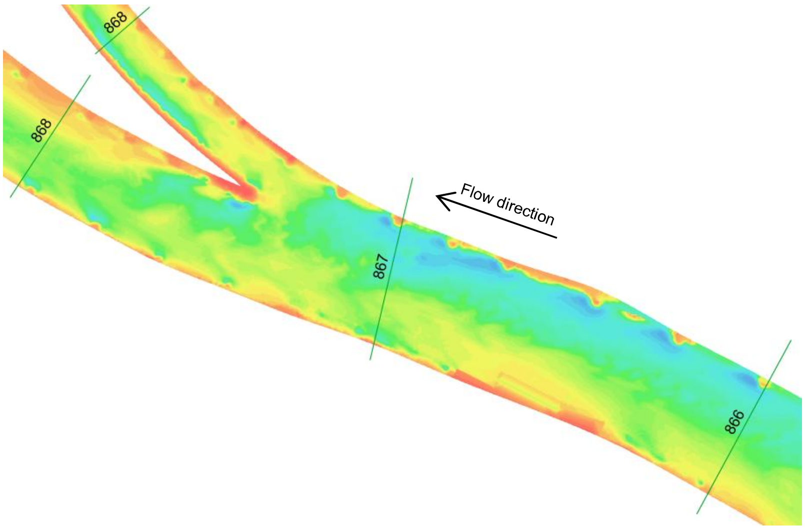

Figure 8.1 Average bed level at the Pannerdensche Kop based on bed level measurements of 1995 which is the basis of the WAQUA-model presented in Chapter 4.

8.1 Pannerdensche Kop 1997

In Wilbers (1998) the average bed level of the Waal and the area around the Pannerdensche Kop during the 1997 flood were published. Even though Wilbers found a bed level decrease of about 10 cm in the middle part of the Waal, at the Pannerdensche Kop the average bed level remained more or less constant during the 1997 flood.

The bed level was measured using a single-beam echosounder and the water level was calculated based on linear interpolation from the surrounding measuring stations. The measurements were made over 1 km in each branch. Figures 8.2 and 8.3 show the variation of average the bed level during the 1997 flood. In both figures Wilbers used the bed level of 2 March as the reference level since this was the peak of the flood at the Pannerdensche Kop. In Figure 8.2 it can be seen that the bed level shows a variation in the order of 5 cm. This variation does however not show a strong correlation with the discharge as seen during the 1997 flood in the Waal. Moreover, a comparison between Figures 8.2 and 8.3 shows that the bed level changes are local and do not show a similar trend over the whole reach.

During the flood the flow velocity increases which causes a deepening of the river between river kilometre 866 and 867. After the flood, i.e. the 10 March, the erosion pit is slowly refilled. In the Pannerdensch Kanaal large erosion is visible after the flood which could be caused by a narrowing of the floodplain at that location. From satellite images it is seen that a factory is located in the floodplain around that location. This factory can cause spatially a variation of the flow-conduction cross-sectional area which in this case could result in erosion of the main channel.

The bed level at the Pannerdensche Kop does not show a similar large-scale bed level decrease as in the Waal. This suggests that the water level was more accurately estimated for the area around the Pannerdensche Kop. The water level was measured at the measuring station Pannerdensche Kop which is located at river kilometre 867. The entire measuring area around the Pannerdensche Kop is therefore within 1 km of the measuring station. An error caused by the linear interpolation of the water level is therefore negligible.

In Figure 8.3 it can be seen that after the flood the bed level erodes at some locations during the flood. This erosion is caused by the deepening of erosion pits during the flood and the propagation of these pits downstream. Wilbers (1998) assumes that a part of these areas with erosion, show erosion due to interpolation and processing errors. Since it is unknown how Wilbers processed the data, the variation shown in Figure 8.2 could be partially caused by the data processing methods. An example of this is that Figures 8.2 and 8.3 are not consistent. In Figure 8.2 the Pannerdensch Kanaal shows an increase of the bed level between 2 and 6 March. However, from Figure 8.3 a large decrease of the bed level would be expected.

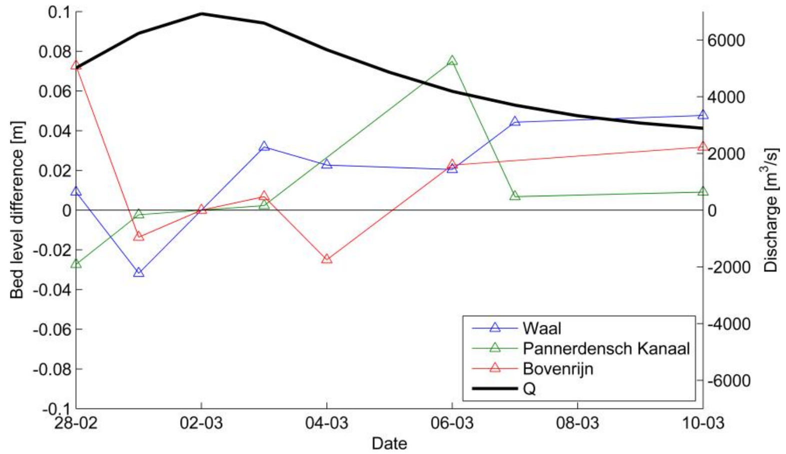

Figure 8.2 Relative bed levels during the 1997 flood for the different Rhine branches at the Pannerdensche Kop (Wilbers, 1998). Q is the discharge at measuring station Lobith which is located in the Bovenrijn.

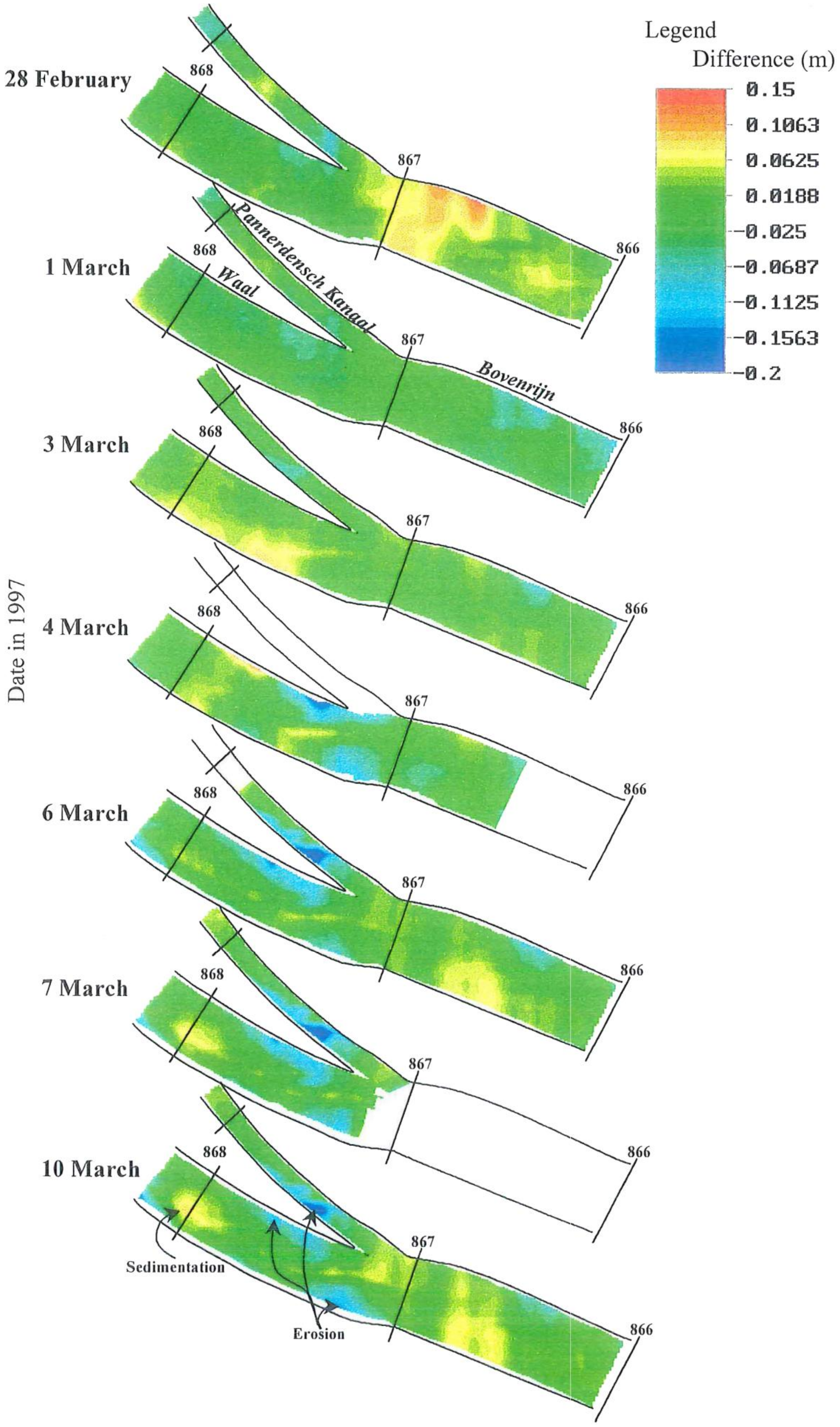

Figure 8.3 Bed level at the Pannerdensche Kop relative to 2 March. The data of 2 March is therefore not shown (Wilbers, 1998).

8.2 Pannerdensche Kop 1998

The second data set of the Pannerdensche Kop was measured during the 1998 flood. Sieben (2004; 2006) found a large decrease of the average bed level just after the peak of the flood. The measurements were made with a multi-beam echosounder in the Bovenrijn and the Waal between river kilometres 866 to 869 during the flood from 29 October to 16 November 1998 and an additional measurement was done on 11 December 1998. In Figure 8.4 the discharge at station Lobith in the Bovenrijn is shown. The peak of the flood is on 4 November with a discharge of 9,413 m^3/s.

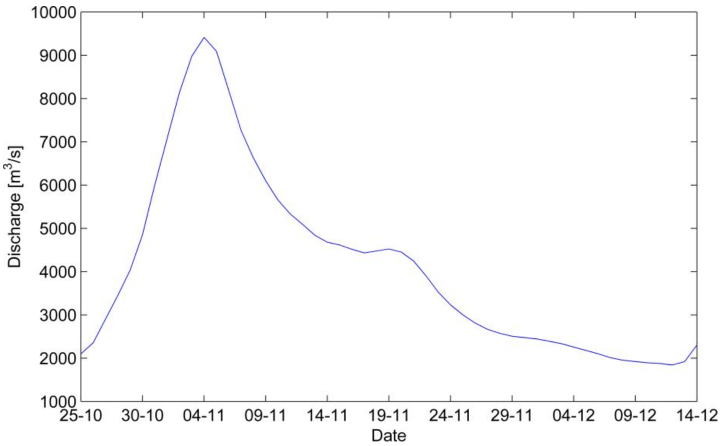

Figure 8.4 Discharge at measuring station Lobith in the Bovenrijn during the 1998 flood with a peak on 4 November of 9413 m^3/s.

8.2.1 Data processing

The point density of the multi-beam measurements is much larger than the single-beam measurements which means that the data has to be processed in a different way. First the data is converted to a 2x2 m raster where each grid cell has a value which is the mean of the measuring points in that cell. As we are using the mean value, the peaks of the bed form and the trough of the bed form are underestimated in the same way and therefore it should give a good estimation of the average bed levels (Van der Mark, 2009). The data are however not covering the full area, as is shown in Figure 8.5 and this can lead to a biased averaging. Therefore the data is interpolated using a triangular irregular network (TIN) to estimate the bed level at the missing locations. From the TIN the bed levels are interpolated to a grid which follows the river axis. Figure 8.6 shows the shape of the grid.

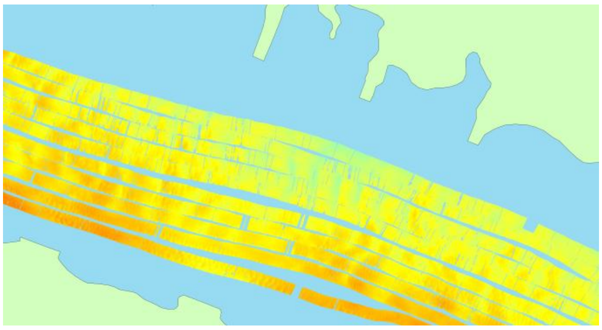

Figure 8.5 Multi-beam data on 12 November in the Bovenrijn.

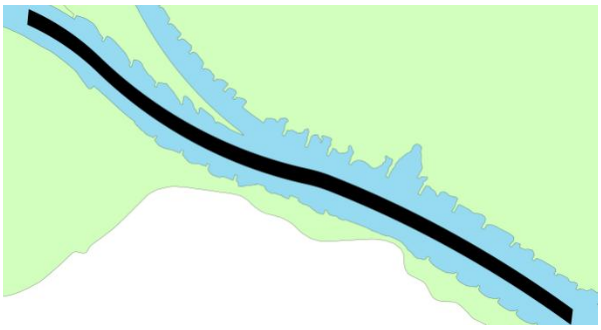

Figure 8.6 The shape of the interpolation grid following the river axis with a width of 100 m.

In Figure 8.8 the bed level for the different days is shown. In this figure it can be seen that the bed level on 29 October, 30 October and 16 November deviates significantly from the ones on the other days. On three measuring days the bed level at a groyne is available and these levels are compared to a set of measured bed levels in the autumn of 2010 and the spring of 2011. Figure 8.7 shows the bed level at the groyne with the distance orthogonal to the river axis. The groyne is located on the right side of the figure and it is shown that the groyne height on 29 October corresponds to the groyne height measured in 2010 and 2011. The other two days show a measured bed level of about 0.8 m lower and this seems to be more or less constant over the considered distance. From Figure 8.7 it therefore follows that the bed levels on 29 October, 30 October and 16 November represent the real bed levels and that on all the other days the bed level is about 0.8 m too low.

The exact reason for this large error is unknown. A possible reason is that during the measurements different multi-beam echosounders were used. On 29 and 30 October a SeaBat 8101 and on all the other days a SeaBat 9001 was used which could explain a difference. It is possible that the software was incorrectly setup or that also a different measuring vessel was used. Rumour has it that during maintenance the DGPS antenna on one of the measuring vessels was incorrectly placed which resulted in an error in the order of 1 m. However, it is unknown which vessels were used to measure the bed level. From Figure 8.7 it is estimated that the error results in a lowering of about 0.8 m and assuming that the error was caused by the misplaced antenna this error is constant. The bed level is corrected for this error which results in the bed level as shown in Figure 8.9. This figure shows that the 0.8 m is a good estimate for the error and the bed level shows on every day more or less the same pattern which suggests that the error is indeed constant.

The bed levels on 29 and 30 October are much smoother compared to the other days. One reason could be that at the Pannerdensche Kop the dune height during non-flood conditions are very small, see Figure 2.9. Another reason could be the change of the measuring device or a different setting of the measuring software. The density of the data points on 29 and 30 October is much lower which means that a lot of dunes are filtered from the data. There are also other issues found in the data which are discussed in the following sections.

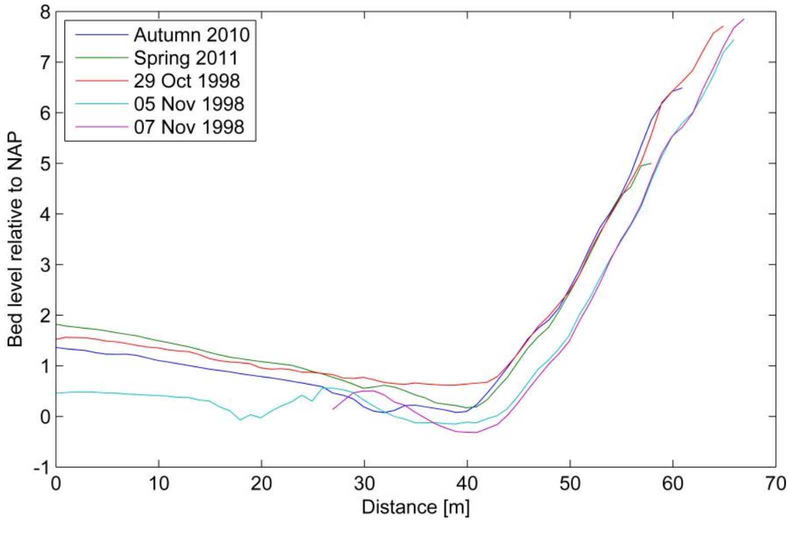

Figure 8.7 The bed level at a groyne in the Bovenrijn with on the left side the main channel and on the right side the groyne.

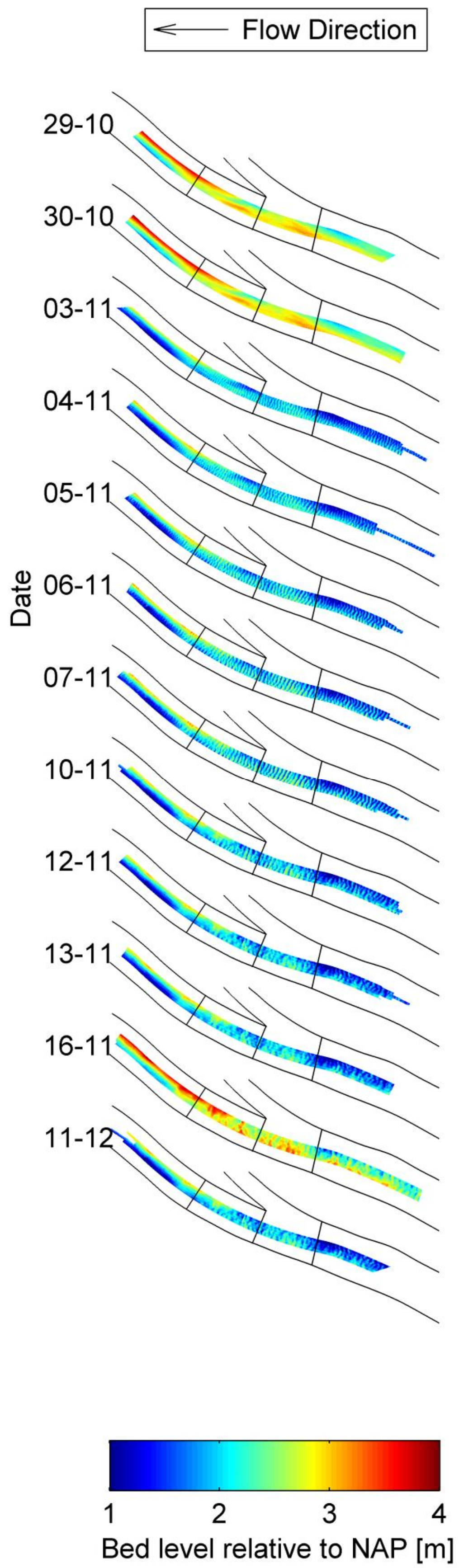

Figure 8.8 Bed level at the Pannerdensche Kop during the 1998 flood.

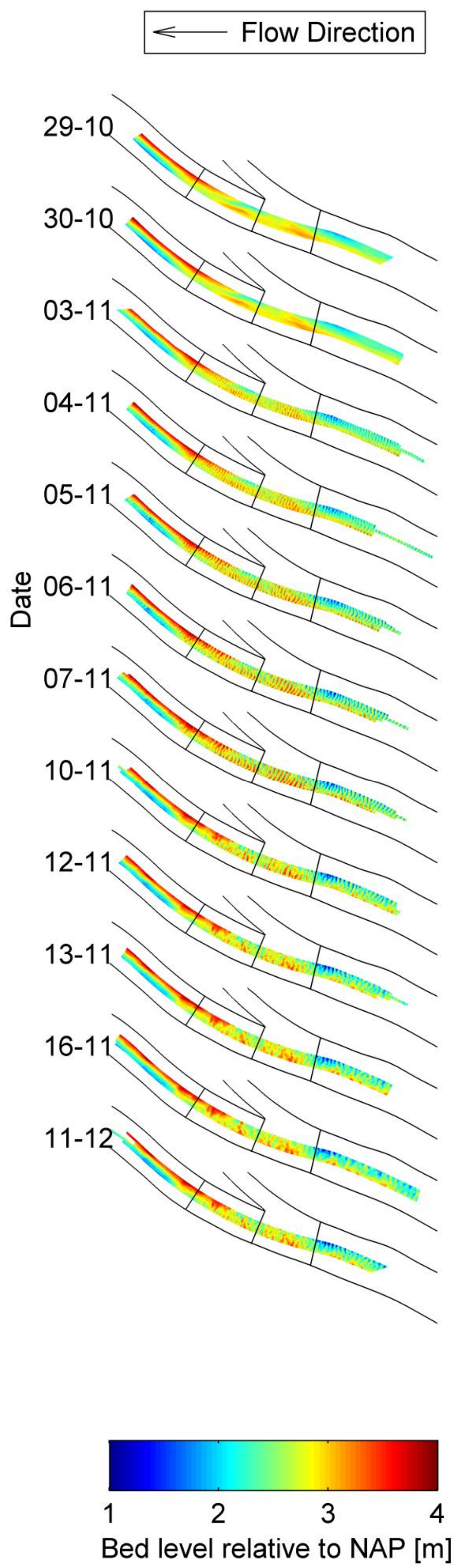

Figure 8.9 Bed level at the Pannerdensche Kop with a correction of 0.8 m for 3 to 13 Nov and 11 Dec.

Inaccuracies in the motion sensor
The measurements contain inaccuracies which are caused by the motion sensor. To be able to accurately estimate the bed level with a multi-beam, the registration of the motion of the vessel is crucial. The long travel distance of the side beams are very sensitive to small changes in roll and pitch of the vessel. Errors in the motion sensors of the vessel result in sudden jumps of the bed level or a sinusoidal pattern in the measurements. The measurements show these sudden jumps which are in the order of a few centimetres. These jumps are however short and therefore the effect on the average bed level is minimal. In the measurements is also a sinusoidal behaviour visible. It is difficult to identify this behaviour in a dune regime but the sinusoidal behaviour shows a much more regular pattern than is expected from dunes. The effect on the average bed level is again small the bed level is averaged.

Inaccuracies in the beams
An inaccuracy in the beams causes ridges at the boundaries of each measuring track, Figure 8.10a. These ridges are caused by a large variation in the data at the boundaries of each track, Figure 8.10b, where the variation is much larger than in the middle of each track. The reason of this larger variation is that the outer beams of the multi-beam echosounder which uses amplitude detection are inaccurate. Nowadays amplitude detection is only used directly below the vessels and for the outer beams a phase detection method is used. The phase detection is more accurate for the outer beam but the SeaBat 9001 does not support this method. In Section 9.4 the different detection methods are discussed in more detail. In the next section the bed level is averaged along the river axis and since the vessel sails along the river axis the ridges at the boundaries have a large effect on the running average.

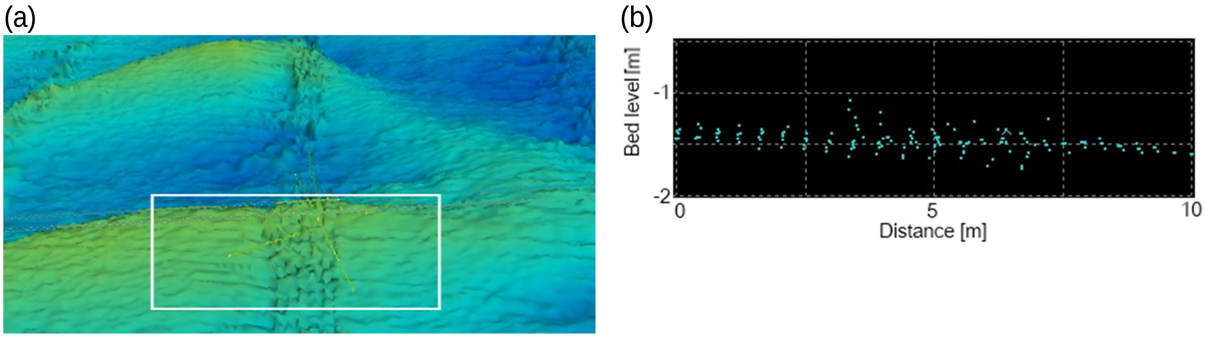

Figure 8.10 (a) A 3D representation of the bed level which shows a large inaccuracy at the borders of each track. (b) A vertical cross-section along the riverbed showing a large variation of the measured bed level at the border of two tracks. The vertical axis shows the bed level in metres and the horizontal axis a distance in transverse direction.

8.2.2 Average bed level

The change of the bed level during the flood can be estimated when assuming that the error which causes a 0.8 m lower bed level is constant. With the corrected values the bed level is averaged using a running average over a length of 200 m. The 200 m length is chosen in such a way that it includes multiple dune lengths. The dune length in the Bovenrijn is estimated to be around 40 m and in the Waal the dune length varies between 5 to 15 m (Wilbers, 2004). An averaging length of 200 m includes therefore more or less 5 dune lengths. A problem occurs when the averaging length is chosen too large. The direction of the ridge shown in Figure 8.10 and averaging direction are the same. If the averaging distance is larger the influence of the ridges is larger too. When the averaging distance is chosen too large, long stripes appear in the result, which affect the average bed level change.

Figure 8.11 presents the average bed level at three locations in the river: one just before the bifurcation, one at the bifurcation and one just after the bifurcation. The figure shows that at the upstream location (km867) the bed level decreases with almost 40 cm during the flood. This effect is also visible in Figures 8.13 and 8.14. Figure 8.14 presents the changes of the bed level relative to the one at the peak of the flood on 4 November. This figure shows that the degradation is local. At km867.5 the bed level stays constant during the flood and at km868 the bed level increases with 8 cm during the flood and decreases afterwards.

The main cause of the large degradation at the upstream location (km867) is the propagation and deepening of an erosion pit in the bed, Figure 8.12. This hole is visible on all the measuring days and during the larger flows it slowly propagates downstream and shows a deepening of about 10 cm which causes a large decrease of the average bed level in Figures 8.11 and 8.14. This decrease is caused by a local narrowing of the main channel at higher water levels which causes local erosion. At the downstream location (km868) a bed level increase was seen during the rising flood and a decrease during the falling flood. The bed level change was in the order of 8 cm. At the bifurcation, the flow width is relatively small and stays more or less constant during the flood. Downstream of the bifurcation (km867) the flow width increases much more during the flood which results in relatively lower velocities and sedimentation.

In Figure 8.14 large stripes are visible in the results. These stripes are a consequence of the running average parallel to the river axis in combination with the measuring inaccuracies at the boundaries of the tracks which were shown in Figure 8.10.

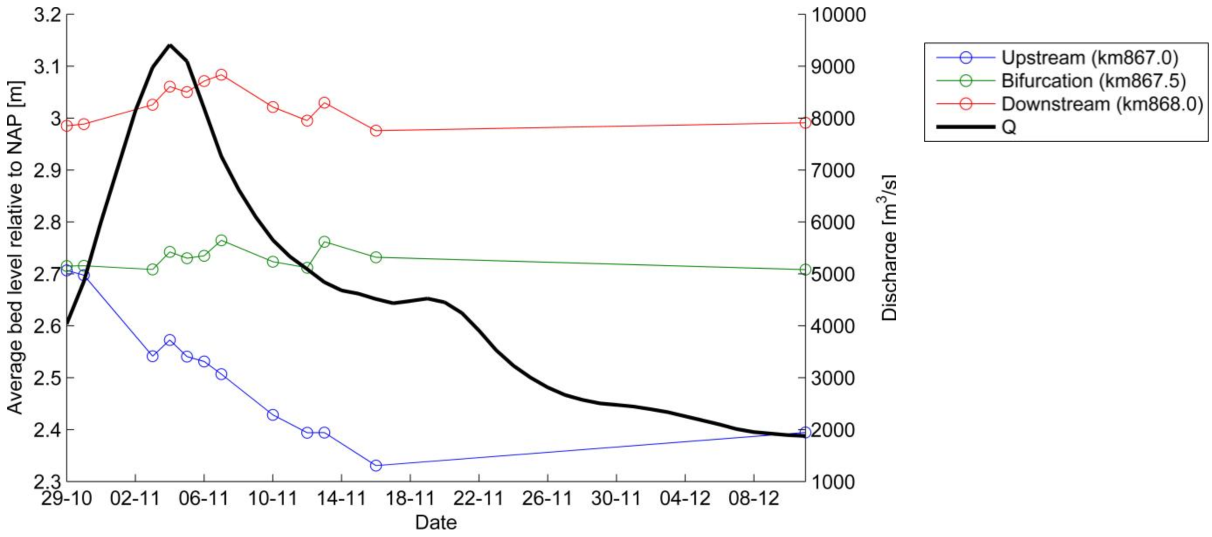

Figure 8.11 Bed level during the 1998 flood at the Pannerdensche Kop averaged over 200 m in length and 100 m in width. The black line represents the discharge at station Lobith.

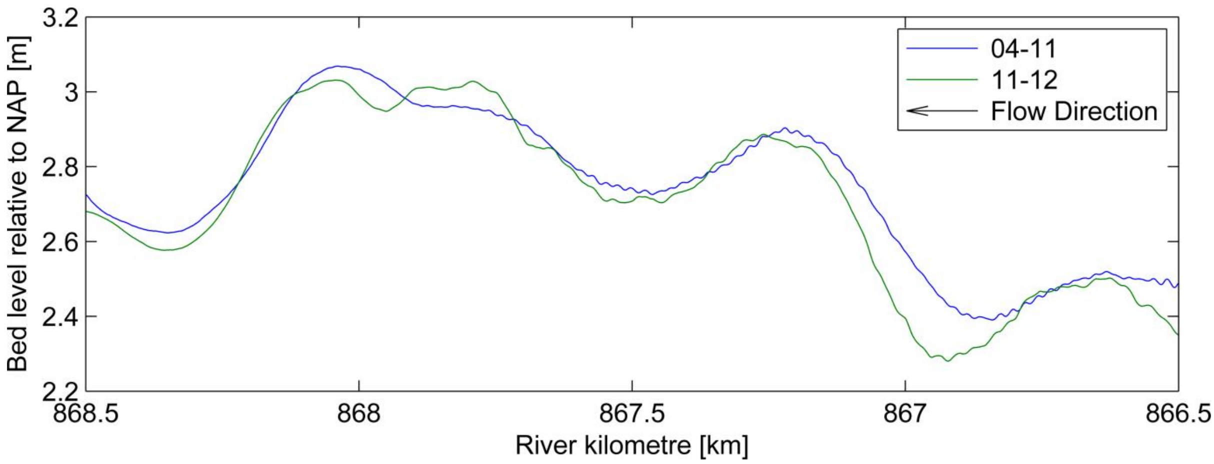

Figure 8.12 Bed profiles of 4 November and 11 December created from a moving average with a window size of 200 by 100 m.

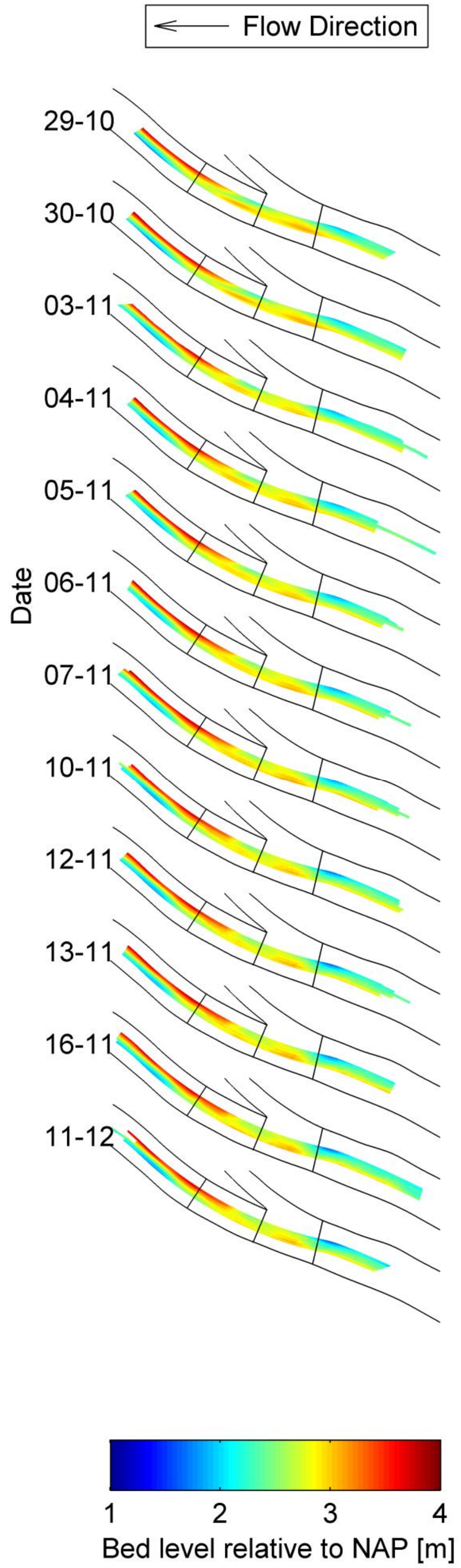

Figure 8.13 Bed level at the Pannerdensche Kop during the 1998 flood averaged in longitudinal direction over a distance of 200 m.

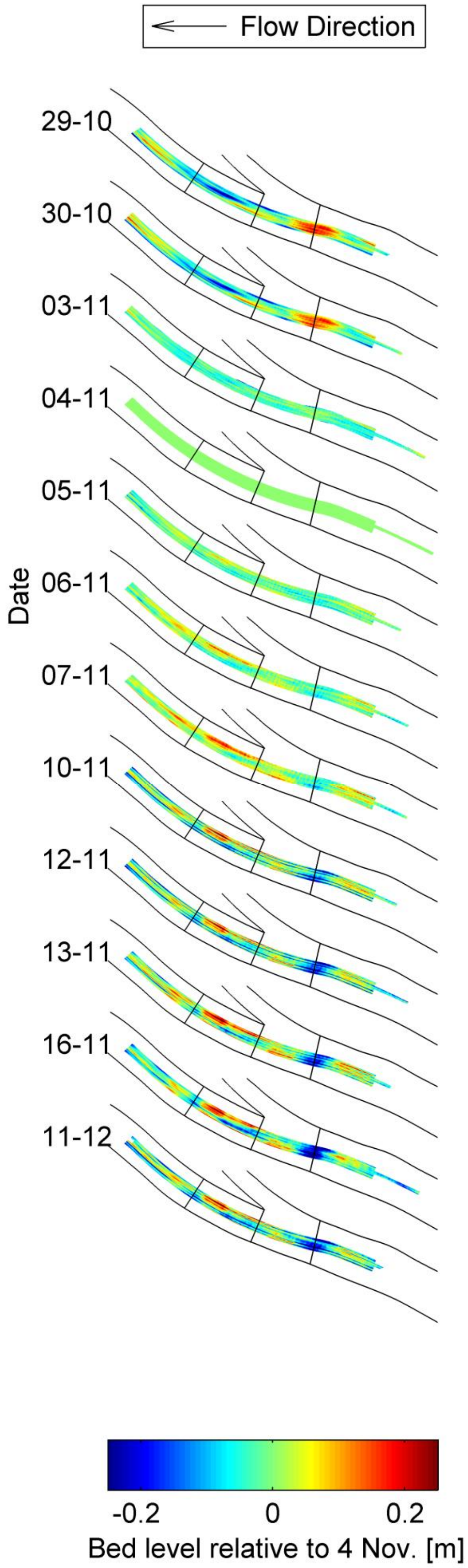

Figure 8.14 Bed level at the Pannerdensche Kop during the 1998 flood relative to 4 November 1998.

8.3 Refilling period

The refilling period is estimated based on the measurements during the 1997 and the 1998 flood. The bed level decreases during a flood at km867 due to a local narrowing of the main channel at high water levels. The measurements of the 1997 flood show that after 4 days the bed level increases again at the 867 river kilometre and that this increase continues. However, during the 1998 flood the bed level does not show an increase even after 12 days. Only on 11 December the bed level increases again but it is still much lower than before the flood. The reason for the difference between the bed level responses after the two floods is that the discharge remains much higher for a longer period after the 1998 flood. Only after 23 November the discharge decreases below 4000 m^3/s which means that during the higher water levels the narrowing of the main channel still has an effect and the erosion continues. On 11 December 1998 the bed level has increased which means that the erosion pit starts to refill. Neither the 1997 measurements nor the 1998 measurements can be used to estimate the refilling period in this area. The measurements do show that flow conditions after the flood in combination with the reason for the erosion are important in estimating the refilling period and the bed level changes after a flood.

8.4 Conclusions

Neither the bed level during the 1997 flood nor the bed level during the 1998 flood show a large-scale bed level change. However, local changes can be large. During both floods a large bed level decrease is seen around km867. This decrease is caused by a local narrowing of the main channel which results in a deepening of an erosion pit during the floods. At km868 sedimentation occurs during the flood. This sedimentation is caused by a large increase of the flow width during the flood at that location. After the flood the flow width reduces which results in a decrease of the average bed level as seen in Figure 8.14. During the 1997 flood (Figure 8.3) the bed level does increase, but after the flood the bed level does not decrease. This is most likely caused by the much shorter measuring period.

9 An overview of the inaccuracies in the echosounder measurements

Several large errors can occur when using echosounders to study the bed levels. During floods flow conditions change rapidly which leads to rapid changes of these errors. In this chapter an overview of inaccuracies in echosounder measurements is given and discussed.

The large bed level change which occurred in the Waal during the 1997 flood would not have happened if multi-beam echosounders were used since the vertical position of the measuring vessel is recorded during the measurements. However, the multi-beam results of 1998 show that large errors still occur when too little attention is paid to the configuration of the multi-beam echosounder. Wiegmann et al. (2002) estimated the inaccuracies of single and multi-beam echosounder measurements which are presented in Table 9.1. In this chapter the values in this table are explained and if needed modified to represent the analysis presented in the previous chapters

Table 9.1 An estimation of the inaccuracies in metres for the single-beam and multi-beam echosounders by Wiegmann et al. (2002).

	Single-beam		Multi-beam	
	Variable	Constant	Variable	Constant
NAP Net			0.00	0.01
Z-reference: LRK			0.03	0.02
Water level	0.03	0.02		
Water level model	0.05	0.10		
Squat	0.05	0.10		
Inaccuracies in acoustic system	0.05	0.03	0.09	0.02
Total estimated accuracy	0.18	0.25	0.12	0.05

9.1 Z-reference

The multi-beam echosounder measures the depth and therefore the vertical location of the measuring vessel is required to find the bed elevation. During the 1998 flood the vertical location was measured using DGPS. DGPS is a system which requires a reference location at which the height is known. Before 2002 these reference locations were often mobile. Every day of the measuring campaign the reference antenna had to be redeployed and the height of the antenna had to be recalculated. This is a large source of uncertainties and in the past this has caused errors of more than a metre (Wiegmann, 2002). The bed level measurements during the 1998 flood resulted in an error in the order of 0.8 m. This was most likely caused by a misplacement of a DGPS antenna on the measuring vessel. Nowadays the reference locations are steady and only a few are needed to cover the Netherlands. This increases the accuracy significantly since the chance of a human error is much smaller. Besides, the measuring service is required to measure a sill with a known height on each measuring day. This reduces the chance of large errors in the z-reference level.

9.2 Water level

Since the implementation of DGPS on the measuring vessels, the water level has become an unimportant parameter in the calculation of the bed level. However, the older single-beam systems which were used during the 1997 measurements are very dependent on a correct estimation of the water level. Table 9.1 shows that inaccuracies at the water level stations can cause variable errors in the order of 3 cm. The errors in the water level model are caused by a linear interpolation between the stations. The effects of the linear interpolation are very dependent on local conditions. The problems which occurred during the 1997 measurements in the Waal were caused by a large local increase of the flow-conduction cross-sectional area during the flood and resulted in a deviation from the linear water level in the order of 5 to 10 cm. The error described by Wiegman et al. (2002) is therefore conservative for the middle part of the Waal. The error is much smaller and can be almost ignored when measurements are carried out close to a water level station. For example, during the measurements at the Pannerdensche Kop the measuring reach was located close to the water level station and measurements were only carried out over a small reach around this measuring station. An error caused by the linear interpolation at the Pannerdensche Kop is therefore minimal.

9.3 Squat

In many cases squat was not taken into account during single-beam measurements and therefore this can be a large contribution to an error in the bed level. It is however very dependent on which vessels are used, the sailing behaviour of the captains and the sailing direction of the vessel. In many cases the effect of squat can be mitigated during the post-processing of the data, but this was also often ignored. Wiegmann et al. (2002) does not take the effect of the vessel's movement into account for multi-beam measurements. However, the 1998 data at the Pannerdensche Kop show that errors in the motion sensor of the vessel can cause large inaccuracies. The data shows a sinusoidal behaviour and small jumps occur in the bed. The inaccuracies due to the motion sensor are therefore estimated in the order of 3 cm and it is assumed to be a variable error. Nowadays the motion sensors are much more accurate and are used for both single and multi-beam measurements. However, certain parameters, like the vessel's geometry, have to be set correctly to make accurate estimations.

9.4 Inaccuracies in the acoustic system

The single-beam echosounder records the return time of all the pulses. Based on this time the water depth is estimated by choosing the maximum, average or the minimum value. Figure 5.1 presents the effect of this choice in a dune regime. The multi-beam is as accurate as the single-beam directly below the measuring vessel. The multi-beam has two detection methods: amplitude detection and phase detection. Amplitude detection calculates the distance on the basis of the travel-time of the return signal and is most accurate for the beams directly below the vessel. Phase detection calculates the travel-time based on a phase difference in the return signal. The beams are reflected with slightly different phase angles from which a travel-time is determined. Directly beneath the vessel, the phase differences are small and therefore it is difficult to determine the travel-time with this method (Dunnewold, 1998). Often a combination of the amplitude and the phase detection is used: amplitude detection for the inner beams and phase detection for the outer beams. Figure 8.10 shows that the bed level becomes inaccurate at the outer beams. During the 1998 measurements only amplitude detection was used. This explains the large inaccuracies at these outer beams.

Nowadays additional rules are set by Rijkswaterstaat to prevent these issues. Each 1x1 m grid cell has to contain a minimal amount of data points, the measurements have to cover the entire area and the 95% confidence interval has to be sufficiently small (NHI, 2009).

9.5 Conclusions

Inaccuracies in the bed level have different contributions. Wiegmann et al. (2002) estimated these contributions as shown in Table 9.1. However, based on the 1998 and the 1997 measurements, the errors are in some cases underestimated. The main contributions are caused by human error due to incorrect placement of the DGPS antenna or ignoring the effects of squat. The 1997 measurements show that an error due to the application of a water level model can cause a variable error in the order of 10 cm, but this effect is strongly dependent on the river geometry and the distance from a measuring station. The current measuring systems are much more accurate than the systems used during the 1997 and the 1998 flood. The main improvement is the use of DGPS to estimate the z-reference which reduces the uncertainty significantly. A second improvement is the new standard which requires a well-covered surface and a strict confidence interval.

10 Conclusions and recommendations

This chapter summarizes the results and the conclusions from the previous chapters. In the first part of this chapter the research questions are answered and in the second part recommendations are made for further research.

10.1 Conclusions

In Section 1.4 the research question was formulated: Which processes affect the average bed elevation during floods in lower course rivers like the Waal? The concluding remarks on the four sub-questions are presented in the following sections.

10.1.1 Transport layers

The effect of the transport layer thickness is very small even during floods. The bed load layer thickness is described with two different models for the bed load transport and two different models for the particle velocity. A combination of these models results in a range from 0.1 to 0.2 mm for the bed load transport layer thickness during the 1997 flood in the Waal. For larger Shields grain stresses the differences between the models becomes larger and there is the bed load layer thickness more uncertain.

The two models which calculate the suspended load layer thickness show similar results for the 1997 flood in the Waal. Both models give a suspended load layer thickness of 0.2 to 0.3 mm. The models are however not valid for the conditions presented by the 1997 flood in the Waal and again large differences between the two models occur for larger Shields grain stresses.

The influence of the transport layers on the bed level is a summation of both layers which results in a total load layer thickness of 0.5 mm. When dunes are taken into account the influence increases but the order of magnitude does not. Neither the bed load layer thickness nor the suspended load layer thickness can explain the large-scale bed level decrease in the Waal during the 1997 flood.

10.1.2 Measuring errors

The largest error contribution comes from the water level. During the single-beam measurements the water level was not measured. The water level was estimated based on a regression relation at measuring station Dodewaard and a linear interpolation between the stations Dodewaard and TielWaal. Results from a WAQUA computation and water level measurements during the 2011 flood show that both the regression relation and the linear interpolation are responsible for a time and spatial varying error. A combination of both contributions shows a similar trend and a similar order of magnitude as the measured bed level changes during the 1997 flood. Errors due to an incorrect water level estimation are therefore a large contributor to the measured bed level decrease during the 1997 flood in the Waal.

Other potential errors which are investigated are: the effect of squat, the uncertainty of the propagation velocity of sound and the possibility of a bias in the measurements. The effects of these errors are small and do not show a time variation as was measured during the 1997 flood. The effect of squat is small if the conditions during the measurements were similar. The uncertainty of the propagation velocity is mainly a problem in areas with strong stratification or large sediment concentrations which is not the case for the Waal. And a bias in the average bed level due to the presence of dunes is not expected to be large. The bias is expected to be related to the dune height which would suggest that the bias has a lagged response to the flood wave. Moreover, it is expected that the dune troughs are underestimated which would suggest an increase during the flood. It is therefore concluded that the effects of these potential errors are relatively small and are not responsible for the large-scale bed level decrease during the flood.

10.1.3 Morphodynamic prediction

The measured bed level during the 1997 flood in the Waal is corrected for the error in the water level estimation on the basis of WAQUA-results. The corrected bed level does not show a large-scale bed level change during the flood. Spatial variations of the river width have however a large influence on the bed level during a flood. These variations cause at multiple locations aggradation or degradation. The correction of the error in the water level is not accurate for each day. On one day the bed level shows a large-scale increase which shows that the water level correction from the WAQUA-results still contains inaccuracies.

A Delft3D model of the same area as the measurements is used to compare the bed level changes during the 1997 flood. The model shows similar trends to the measured data but the differences between the measured bed level and the bed level from the model are large. The model also shows the effect of the river width variations on the bed level during the flood. The reasons for the large differences are that the initial bed level of the model is based on a measured bed level from 2011. This causes bed level changes which are not expected from the measurements.

From the measurement and the model results both show that the local variations of the river geometry are important in predicting the bed level changes during a flood. This was also concluded by Bolla Pittaluga et al. (2014) who found that floods and the memory of the bed for previous floods can cause large deviations of the bed from the equilibrium profile. Measures of the Room for the River Programme which give additional space to floodplain can cause aggradation as was shown in the Waal. Neglecting these effects can give a higher risk of flooding and can cause problems with the navigability of the river (Mosselman, 2012).

The Delft3D model does not show the same bed level changes during the 1997 flood as the measurements. The differences are at some locations in the order of 5 cm which is the same size as the maximum bed level change. However, the model is able to predict the bed level changes at two locations where large bed level changes were found. It is therefore concluded that the model is able to show similar trends but that the local differences are large. The quality of the measurements and the model-results is too low to conclude that Delft3D predicts the bed level changes correctly. More accurate bed level measurements during a flood and a more accurate Delft3D model are required to be able to validate the model.

10.1.4 Pannerdensche Kop
The bed level at the Pannerdensche Kop during the 1997 and the 1998 flood are studied as a reference case to the Waal during the 1997 flood. Neither the bed level during the 1997 flood nor the bed level during the 1998 flood show a large-scale decrease or increase of the bed level. The local bed level changes are large and are cause by river width variations during the flood.

10.1.5 Conclusion
The large-scale bed level change which was measured in the Waal during the 1997 flood is caused by an error in the water level estimation. The bed level changes which do occur are local and are mainly caused by longitudinal changes of the river geometry. With the Delft3D model of the Waal it is possible to show the trends of erosion and sedimentation during floods. However, the differences between the measurements and the model are still large which can be caused by the large inaccuracy of the measurements and the assumptions in the model results. With the current measuring techniques it is possible to measure more accurately which makes it possible to study the bed level changes during a flood in more detail.

10.2 Recommendations
The results of this thesis shows that improvements of the measuring data is needed to study the bed level changes during floods in more detail. In each of the following sections recommendations for the improvement of the knowledge of bed level changes during floods are discussed.

10.2.1 Transport layer thickness
The transport layer thicknesses are relatively small compared to the bed level changes in the Waal during a flood. The effect of these layers is therefore considered negligible. However, the results also show that the layer thickness becomes more important in case of larger Shields grain stresses. Therefore in areas where the particles are smaller and the flow variation is larger it is possible that the effect of the unsteady sediment load becomes more important. It is suggested that rivers which fit these conditions are studied to find a more general description of the significance of the unsteady sediment load layer.

10.2.2 Measurements
The bed level measurements discussed in this thesis contain large errors and the amount of available data is limited. The measurements do give useful information about local bed changes in the river during a flood which has influence on both the navigability and the safety against flooding. The measurements can be improved by studying the effects of the flood over a longer reach and over a longer period. Moreover, the quality of the measurements has to improve. The errors and inaccuracies of the measurements are too large compared to the local bed level changes.

Nowadays, the improved measuring techniques and the measuring guidelines guarantee a more accurate bed level measurement. However, the bed levels were not measured in the Waal over multiple days during a flood since 1998 and therefore any new bed level measurements during a flood should be done while regularly checking of the results. One of the conclusions from the analysis of the measuring techniques is that the incorrect configuration of the measuring devices is often a reason for inaccuracies and errors. A regular check during the measuring, at for example a location with a known bed elevation, can prevent these problems.

10.2.3 Delft3D model

As seen in from the calculation results, the Delft3D model is able to show the same trends in the bed level changes as was found in the measurements. The differences between the model and the measurements are however large. An initial bed level should be used which better represents the bed before the flood. A morphological model which is able to predict the bed level changes more accurately during floods can be used to study the expected bed level changes during design conditions to estimate the effect on the flood risk and the navigability of the river. More accurate measurements are required to be able to validate the bed level changes.

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Nomenclature

A_{cR}	Calibration parameter of the Camenen and Larson model	[-]
D_*	Particle parameter	[-]
D_{50}	Median grain size; grain size for which 50% is finer	[m]
D_{90}	Grain size for which 90% is finer	[m]
Q	Discharge	[m^3/s]
T	Transport stage parameter	[-]
Z'	Modified suspension parameter	[-]
a_b	Bed load layer thickness	[m]
a_{ref}	Height of the reference concentration	[m]
a_s	Suspended load layer thickness	[m]
c_a	Concentration at reference height $z = a_{ref}$	[-]
c_b	Concentration of the bed load layer	[-]
c_R	Reference concentration at level $z = 0$	[-]
c_s	Concentration of the suspended load layer	[-]
g	Gravitational acceleration	[m/s^2]
h	Water level	[m]
h_s	Height of suspended load layer	[m]
q_{tot}	Total sediment transport per unit width	[m^2/s]
q_b	Bed load transport	[m^2/s]
q_s	Suspended load transport	[m^2/s]
$\bar{u}$	Depth averaged flow velocity	[m/s]
u'_*	Grain shear velocity	[m/s]
u_*	Bed-shear velocity	[m/s]
$u_{*,cr}$	Critical bed-shear velocity	[m/s]
u_p	Particle velocity: velocity of a moving bed load sediment particle	[m/s]
w_s	Particle fall velocity	[m/s]
z_b	Bed level	[m]
Δ	Relative density of sediment	[-]
Φ_b	Bed load transport parameter	[-]
δ	Active layer thickness	[m]
δ_b	Height of bed load layer	[m]
ε_b	Porosity of the riverbed	[-]
ε_v	Vertical sediment diffusivity	[m^2/s]
θ'	Grain Shields stress	[-]
θ_c	Critical Shields parameter	[-]
κ	Von Karman constant	[-]
μ	Ripple factor	[-]
σ	Schmidt number	[-]
ν	Kinematic viscosity of water	[m^2/s]
ψ	Flow parameter	[-]

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