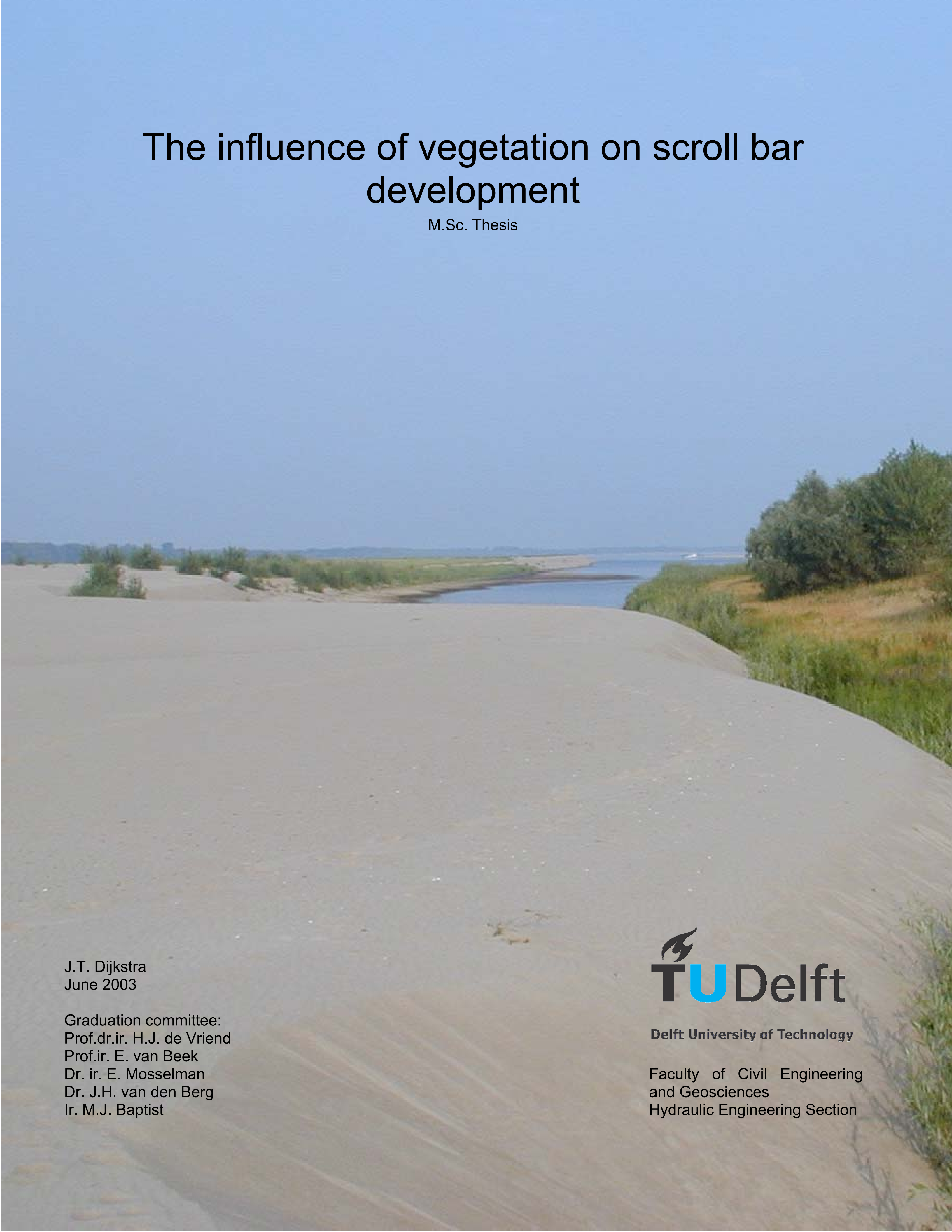

The influence of vegetation on scroll bar development

M.Sc. Thesis

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Preface

This M.Sc. thesis describes the work done in the final phase of my Civil Engineering Studies at Delft University of Technology. In this phase I dealt with modelling the influence of vegetation on scroll bar development in the Volga River using the Delft3D-package from WL | Delft hydraulics. I also took part in a joint fieldwork of RIZA and Moscow State University at the Volga River, both to study developments of this natural river and to obtain model input data. Apart from being useful as a tool to study the behaviour of a river, modelling is also a very valuable experience, and mostly -despite some difficulties- enjoyable. The same applies to the fieldwork undertaken in the Allier and Volga Rivers, which was enjoyable at all times.

Therefore I would like to thank my graduation committee, prof. dr. ir. H.J. de Vriend, prof. ir. E. van Beek, dr.ir. Erik Mosselman, dr. Janrik van den Berg and ir. Martin Baptist for their comments, advice and support. Dr.ir. Kees Sloff has not been part of the committee, but nevertheless offered a great deal of help with many modelling difficulties, for which I am very grateful.
Also I thank Margriet Schoor of RIZA, Antoine Wilbers, Jurgen de Kramer, Anouk Cormont and Sietske van der Sluis of Utrecht University, Dmitri Babich, Miha Samohin and Seva Moreido of Moscow State University, Tanya Baluk of the Institute of Water problems from the Russian Academy of Sciences, and of course my fellow students Lara van den Bosch and Sander Kapinga, for the information and help they provided and for the fun we had during the fieldworks.

The influence of vegetation on scroll bar development.

Summary

Within the framework of the 'Room for the River' policy to reduce flood risks and restore nature in the Netherlands, the Cyclic Floodplain Rejuvenation (CFR) strategy is studied. This strategy aims at a regular human removal of vegetation and sediment from the floodplain in order to maintain a safe conveyance capacity. The limits for this policy have to be derived from calculations that take into account the influence of floodplain vegetation on morphology and vice versa; a field of science about which little is known so far. Therefore research is done for instance in natural reference rivers abroad, in laboratory flumes and now by modelling the influence of vegetation and outer bank erosion on scroll bar development in a bend of a natural river.

The model has been made for the Zakrutsky bend in the Lower Volga River, Russia. This bend has been studied by RIZA (the Dutch Institute for Inland Water Management and Wastewater Treatment), the University of Utrecht and Moscow State University using satellite images, historical maps and several fieldworks. Together these sources provide enough information about hydrology, bed topography and vegetation to make a numerical model that shows the development of a scroll bar over a period of 16 years.

Furthermore, the fieldwork provided insight into rejuvenation rates and the development of vegetation under different morphological circumstances. After decades of outer bank erosion, the bare point bar starts to become vegetated because the wider profile reduced flow velocities on the point bar. Probably this vegetation development led to an increase in point bar accretion because it further reduced the flow velocities. The development of the scroll bar started at the same time. In about the first ten years of scroll bar growth and point bar vegetation development, erosion of the outer bank occured faster than before: 25 m/yr vs. 15 m/yr at the point of maximum erosion.

The development of vegetation is strongly determined by morphology. Gradual accretion will raise the terrain level, thus creating suitable conditions for dryer species and more protection against severe flow, leading to more mature vegetation types. Rejuvenation can occur, however, when larger accretions however bury vegetation, thus creating fresh deposits on which new pioneers can develop, or simply when vegetation is removed by erosion at locations with severe flow conditions.

In the model, the influence of point bar vegetation is modelled by applying a Nikuradse roughness value *k* that is calculated on the basis of characteristics like vegetation height, density and stem diameter for a number of vegetation zones. To follow the development of vegetation, these values are calculated for every five years. Applying a roughness value means that mainly the rerouting effect of vegetation on flow is studied; possible sediment catchment by vegetation due to reduced flow velocities cannot be modelled reliably.

After calibration and a sensitivity study, which showed the model is susceptible for the upstream discharge distribution and the water level at the downstream boundary, six scenarios have been made. These discriminate between the effect of outer bank erosion only, the direct effect of vegetation causing higher flow velocities in the main channel and the more indirect effect of vegetation that increases outer bank erosion.

In all cases a scroll bar formed; therefore this is probably a result of the bed topography of the point bar, which shows a kink at the origin of the scroll bar. Also the ratio between suspension transport and bed load transport turned out to play a role in scroll bar development, but this is not studied in detail. The simulations show that both vegetation and outer bank erosion have an effect upon scroll bar development, but do not determine the origination of a scroll bar.

The effect of outer bank erosion is that the scroll bar can grow wider and farther into the main channel, and that it is elongated less quickly. The effect of vegetation is less unambiguous: the most direct effect is that its roughness concentrates the flow more in the main channel rather than on the point bar, thus creating a thinner and more elongated scroll bar. The more indirect effect is that the stronger flow in the main channel causes more outer bank erosion, which on its turn creates more room for the development of the scroll bar. In case of the natural vegetation development, the effect caused by additional outer bank erosion is dominant. In case of dense vegetation however, the direct effect of vegetation is stronger. Removing point bar vegetation as part of the CFR-strategy generally causes more accretion on the point bar and less erosion in the

main channel. The magnitude of thes effects depend on the amount of vegetation present before removal.

The insight into the mutual influences between vegetation and morphology may be applied in, for example, the river Meuse or the side channels of the Waal River: riparian vegetation may reroute flow from the winter bed to the channel, thus increasing channel dynamics, which can favour ecology because more rejuventation occurs or because the channel bed is washed clean.

A numerical model like Delft3D is a useful research tool to model complex morphological processes in natural rivers in a quantitative manner, but it does not directly show the reasons for changes and one should be well aware of its shortcomings and uncertainties. For the Dutch rivers, with their high demands for safety and shipping, these uncertainties are still far too large. Therefore, the room for nature in these rivers will remain very limited. More research on the effect of vegetation on flow and sediment transport may lead to better models that can calculate more precise limits.

1 Introduction and problem approach

1.1 Problem background

1.1.1 Cyclic Floodplain Rejuvenation

After ages of raising the dikes to reduce flood risks in the Netherlands, a new strategy has been adopted: creating more ‘Room for the River’. Besides improving safety by increasing the flood conveyance capacity of the river using measures like the excavation of side channels and floodplain widening and -lowering, this strategy will also provide an opportunity for ecological benefits (Duel et al., 2001). However, sedimentation and vegetation growth in time will reduce the extra conveyance capacity, thus causing a safety risk in the longer run.
Therefore this strategy is extended to the so-called ‘Cyclic Floodplain Rejuvenation’ (CFR). This management strategy aims at a regular removal of vegetation (softwoods, weeds) and floodplain lowering as a compensation for channel migration and floodplain sedimentation, in order to restore the safe conveyance capacity. This is very similar to processes occurring in natural rivers: if the vegetation becomes too dense or the floodplain too small, the river itself will create the room it needs. By depositing fresh soil or clearing older vegetation, rejuvenation also creates an opportunity for a new start of an ecological succession cycle. Such a restart is ecologically interesting because different stages of succession contribute to biodiversity.
In order to optimize the CFR strategy for both safety and ecology, and without causing economic damage by interference with shipping, insight is needed in the relation between hydrodynamics, morphodynamics and vegetation (Figure 1-1).

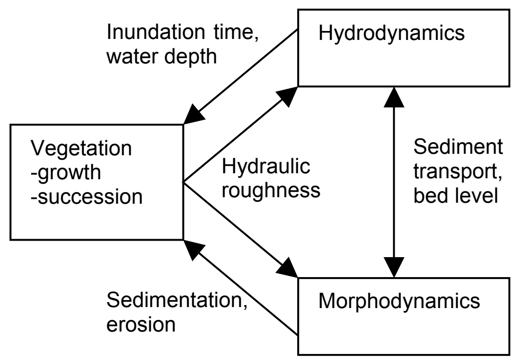


Figure 1-1 The interaction between vegetation, hydrodynamics and morphodynamics.

Therefore research is undertaken in different ways. Laboratory experiments are used to find out more about the relation between vegetation and sediment transport (e.g. Baptist, 2003), historical river data are used to reconstruct the dynamic potential of the normalised rivers in case they are allowed to move more freely (e.g. Schoor et al., 1999). Also foreign natural rivers are studied as a reference for how vegetation and morphology might develop (e.g. De Kramer et al., 2000), since presently little is known about the behaviour of large natural rivers, as the majority of the large rivers in Europe has been normalised to a large extent.
Hitherto, most studies of these reference rivers mainly comprise fieldworks, hydrological analysis and aerial or satellite image analysis. Hydro- and morphodynamic modelling have been applied in a very limited manner only, but are a useful support to these studies. The knowledge obtained in these ways can be used to model the behaviour of a more dynamic and free river in order to obtain safe limits for the CFR policy (Baptist et al., subm.).

1.1.2 Waal and Volga Rivers

The main Dutch river of interest is the Waal River, a meandering branch of the Rhine River that is intensively used for shipping and therefore strictly normalised. The two natural rivers that are studied as a reference are the Allier River in Central France and the Lower Volga River in Russia (Figure 1-2). In both rivers the natural rejuvenation process is hardly affected by human interference.
The natural part of the Allier River is a rather small and steep meandering river that has a gravel bed. Therefore it is used as a reference for the river Meuse at the Belgian border, but it is less suitable for most other rivers in the Netherlands since these are sandy and have a low gradient.

The Lower Volga River on the contrary is much larger than the Dutch rivers. On some stretches it meanders, on others it is a braided river and it has a small gradient and sediment size. These characteristics make it suitable as a reference for Dutch rivers like the Waal River.

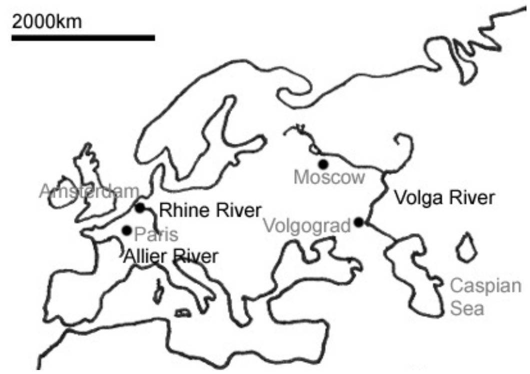


Figure 1-2 The situation of the rivers Volga, Waal (Rhine) and Allier.

Both climate and vegetation of the floodplains of these rivers differ somewhat from the Dutch situation, but these differences in general do not prohibit a comparison. The discharge of the Allier River (about 140 m^3/s averagely) is dominated by heavy rains in spring and fall, the summer is dryer. The Volga River discharge is determined by the regime of a large dam: when snow melts in April and May the discharge is high (up to 30.000 m^3/s), during the rest of the year it is constantly low (around 5500 m^3/s). During winter the river is largely covered with ice for about three months. The Dutch Waal River is fed more continuously by both glaciers and rainfall, and has an average discharge of about 1500 m^3/s.

Though the exact species might differ, the main types of vegetation are present in all three rivers: softwood forests with poplars and willows, some hardwood species in later succession stages, grasses and weeds. The main difference between the three rivers is the way they are managed, which does have a considerable influence on biotic and abiotic processes.

1.1.3 Volga River research overview

The Lower Volga River has been studied on different scales for several years. Whereas the Allier River is studied by the Physical Geography department of Utrecht University (UU) and the Civil Engineering Hydraulics section of Delft University of Technology, the Volga River is mainly studied by RIZA (Dutch Institute for Inland Water Management and Wastewater Treatment) and Utrecht University, in co-operation with Moscow State University (MSU) and several local organisations as part of the project Morphodynamics Lower Volga and Waal.

On the Volga River three fieldworks have taken place in the past years, as well as several desk studies. The first fieldwork in 1999 covered almost the entire reach of the Lower Volga River from Volgograd to Astrakhan at the Caspian Sea to get an overall impression of the river. Also maps and satellite images and other data were analysed in order to know more about general morphological aspects like stream power, width/depth ratios and Shields parameters. The second expedition concentrated on more local morphology and vegetation succession in three smaller areas about 100 kilometres downstream of Volgograd. By then, also bend migration rates had been derived from images of several years. The last fieldwork, in the summer of 2002, concentrated on just one bend: the Zakrutksy area. This was also visited one year earlier, which made it possible to measure changes in more detail than can be done by image analysis.

During the most recent fieldwork also the Akhtuba River, a side branch of the Lower Volga River, was studied. This is a much smaller and less dynamic river, and therefore more similar to the Dutch rivers. Here mainly the traces of vegetation succession in a number of cross-sections were studied. Too little data are available to make a model of this river.

From April 2002 until 2005 MSU and UU co-operate in a NWO-project that aims at studying the response of large European rivers systems to climate change and human activities. This project comprises further field studies at several sites along the entire Volga River, as well as modelling water balances and morphological changes.

For more information about both the Lower Volga River and the research done there, one is referred to the final report of the RIZA-project (Dijkstra and Schoor, 2002).

1.2 Study objectives and approach

1.2.1 Study objective: modelling scroll bar formation

The limitations for a CFR policy need to be quantified, which means models are necessary to calculate changes and their effects. Despite the efforts made to develop computational models like Delft3D that are able to deal with the influences between morphology and hydrodynamics on one hand and vegetation on the other, so far no realistic models exist. Traditionally, the emphasis of river models has been on the prediction of channel depths for navigation rather than developments on the point bar.

Most information about biogeomorphological processes is still largely qualitative, although some quantitative relations have been derived. The largest advances have been made in describing the hydraulic roughness of vegetation, whereas the effect of vegetation on morphology and that of morphology on vegetation development still need a lot of research. Meanwhile, in order to perform more reliable predictions for more natural rivers, additional knowledge is needed about how a model of a more natural river stretch can be made with existing techniques, what problems have to be solved and how such a model predicts changes.

The information obtained in the Morphodynamics Lower Volga and Waal project provides enough data for such a model on the scale of one river bend: the Zakrutsky bend. Moreover, this bend has an interesting feature, about the development of which little is known: a scroll bar. A scroll bar is the most recent result of meander migration. It is a ridge partly attached to the point bar at the inner bend of the river; the point bar is built out in a discontinuous manner. Traces of older scroll bars can be seen as ridges and swales on more mature parts of the point bar. Because of their dynamic nature and level gradients, scroll bars are interesting from both a morphological and an ecological perspective (De Kramer et al., 2000).

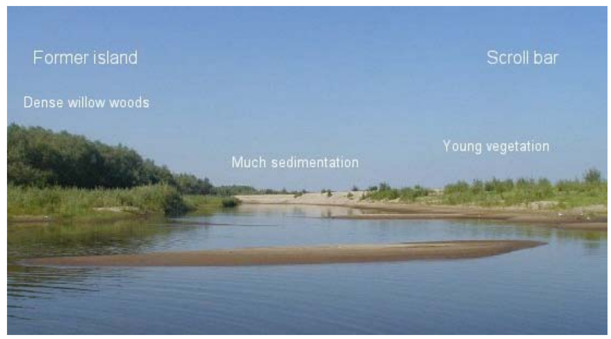


Figure 1-3 Different vegetation types on and around the scroll bar.

Therefore this study concentrates on the formation of scroll bars, and the influence of vegetation on their formation, as quantitative as possible. The Zakrutsky bend is used as an example for modelling. Based on the considerations mentioned above, the main objective of this study is to determine what factors influence scroll bar development. Besides, this study provides more knowledge about the possibilities and limitations of Delft3D software for morphological modelling, and explores some modelling possibilities for the influence of vegetation on sediment transport.

1.2.2 Hypotheses

In order to determine what factors influence scroll bar development, the following hypotheses are formulated:

- The hydraulic resistance caused by point bar vegetation diverts the main flow towards the outer bend, which causes outer bank erosion. This results in a profile that is too wide, hence a scroll bar will develop.
- The hydraulic resistance caused by point bar vegetation decreases flow velocities, also immediately downstream of the vegetation. In this area with quiet flow, accretion will occur and a scroll bar develops.
- Point bar vegetation catches sediment because flow velocities in vegetation are lower than in an open channel. Therefore the flow just downstream of a vegetated area contains little sediment, and accretion will not occur, thus creating a shallow area between the old point bar and new accretions.

Since studying all three hypotheses thoroughly is too much for this thesis study, and sediment catchment by vegetation cannot be modelled yet, only the first hypothesis and the effect of point bar vegetation in general are studied. Section 1.3 offers a more elaborate explanation of these hypotheses of scroll bar formation.

1.2.3 Method

In order to test the hypotheses a numerical model of a river bend is made using Delft3D software. This model is based on a real river bend in which a scroll bar has formed over several years: 'hind casting'. A two-week fieldwork session provided information about the state of this bend. The model is kept as simple as possible both to keep the results generally applicable and because data about the area are limited. Nevertheless, the model has to reflect the actual situation with enough accuracy to give representative results.
The research consists of the following phases:

- Preparation: determination of objectives, model area, modelling approach and necessary data;
- Fieldwork: obtaining data about bed topography and vegetation;
- Elaboration of fieldwork and other data: documentation of measurements, describing biogeomorphological changes and their causes;
- Model set-up and calibration: determination of boundary conditions, bed topography and numerical parameters. Due to the limited data, verification on an independent dataset is not possible;
- Simulation and interpretation: making runs with different characteristics representing the hypotheses, interpretation of results regarding scroll bar formation;
- Discussion and conclusions.

These phases are discussed more elaborately in the following chapters.

1.2.4 Assumptions and limitations

- The model is conceptual; results are rather qualitative than quantitative, though quantitative comparisons are made whenever possible.
- A numerical model is used because the situation is too complex for an analytical analysis. A two-dimensional depth-averaged model has sufficient capabilities to represent the processes influencing scroll bar formation. A fully three-dimensional model would be too complex and computationally expensive.
- The model only aims to represent local changes; changes exceeding the model boundaries are not taken into account.
- Since the influence of vegetation on sediment transport cannot be modelled accurately yet, the influence of vegetation is represented using methods that depend on the specific effect of vegetation (e.g. increased accretion, flow diversion) to be studied.
- The data obtained during the RIZA-project are considered reliable and not submitted to further accuracy checks without special cause.
- Since data determining boundary conditions are limited and estimations have to be made, the sensitivity of the results for the boundary conditions has to be checked.
- The Zakrutksy bend is chosen for reasons of data availability and logistics.

Considerations specifically regarding modelling are discussed in Chapter 4.

1.3 Scroll bar development

In meandering rivers like the Volga River, the often scarcely vegetated area at the inner bend is called a point bar. Point bars develop as a result of sediment transport that is directed towards the inner bend by secondary flow (see also Annex 1). A scroll bar is the most recent extension of the point bar; the downstream end of the scroll bar is detached from the point bar (Figure 1-4). With respect to the hypotheses in Section 1.2.2, the formation of a scroll bar can be considered to be a result of a time lag between outer bank erosion and inner bend accretion: The quick and large erosion occurring during a flood creates a wider main channel. At lower discharges this

profile is too wide, which does cause inner bend accretion, but no further erosion of the outer bank. This way the point bar is built out discontinuously (Nanson and Hickin, 1983).
The channel at the point bar side is gradually filled with river deposits until it is completely attached to the point bar. The traces of this process can be seen in the field as (a series of) ridges and swales parallel to the stream direction.

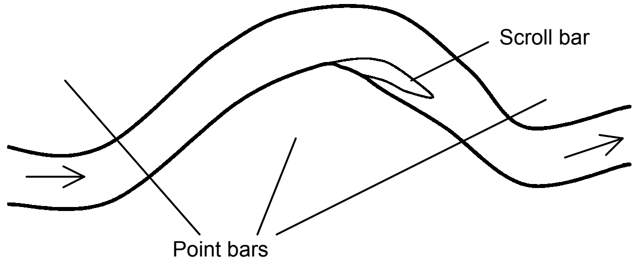


Figure 1-4 Position of point- and scroll bars.

Point bar vegetation can influence local flow velocities and morphology directly or indirectly. Indirectly, the increased resistance caused by vegetation can change the water level gradient and discharge distribution, which on their turn change local flow conditions. Since many other factors play a role on this scale, the research is limited to the more local and direct effects of vegetation on scroll bar development.
Directly, also several mechanisms might be determining. For example, the roughness of the vegetation might divert the flow towards the outer bend. This may accelerate outer bank erosion, causing over width of the profile and thereby scroll bar formation (Figure 1-5).

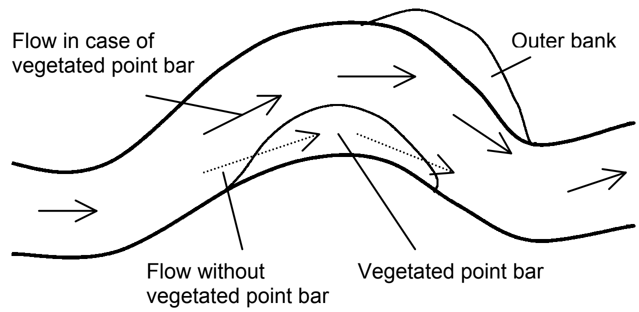


Figure 1-5 Flow diversion by vegetation.

The increased roughness may also cause a different flow pattern just downstream of the vegetation, which will affect morphology too: if flow velocities are lower, more sedimentation can take place (Figure 1-6). Vegetation can also influence the sediment transport directly by acting as a kind of sediment trap because of the low flow velocities. This means the water just downstream of the vegetation contains little sediment, hence no deposition will occur there. However, accretion may occur just beside this area, where the sediment load is unaffected by vegetation, and so a semi-detached bar can be formed (Figure 1-7).

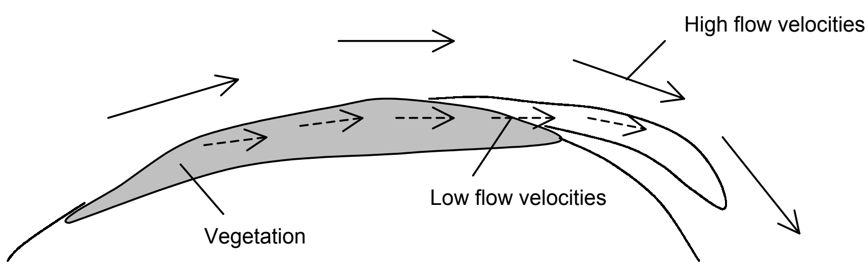


Figure 1-6 Flow velocities decreased by vegetation.

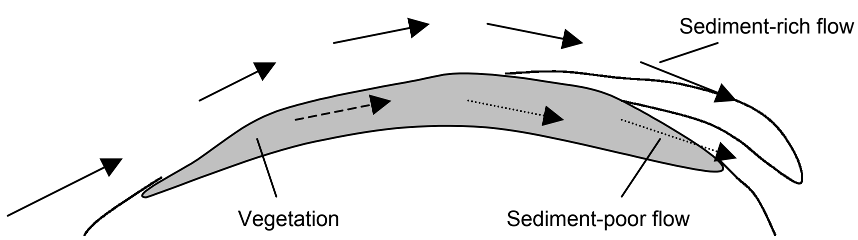


Figure 1-7 Sediment catchment by vegetation.

More information about the flow and bed level in river bends, bend migration and sediment transport can be found in Annex 1.

1.4 Contents of the report

Chapter 2 gives a description of the fieldwork undertaken at the Volga River, together with an analysis of other data sources. It ends with some descriptions of observed morphological changes in the Zakrutsky area. Chapter 3 explains how effects of vegetation have been modelled. The building of the model is discussed in Chapter 4 by describing the requirements for the model, the choices and assumptions made, together with a sensitivity study and brief calibration results. It concludes with a description of the reference scenario. The calibration results are discussed in more detail in Chapter 5 together with the results of the research simulations because these also provided interesting information about scroll bar development. It is found that vegetation and outer bank erosion mainly affect the shape of the scroll bar and not its origination. Other important factors are the upstream discharge distribution and the downstream water level. Chapter 6 contains conclusions about the findings of the model and the fieldwork, whereas Chapter 7 discusses the appliccability of these conclusions and provides recommendations for further research. The annexes contain background information about the flow and bed level in river bends, formulas for the calculation of hydraulic roughness of vegetation, a description of the technique used to apply different roughnesses according to the discharge and prints of the models input files.

2 The Volga River: Fieldwork and analysis of historical data

This chapter starts with an overview of the main hydrological, geological, ecological and economical properties of the Lower Volga River and its floodplain. This is followed by a sketch of the situation of the Zakrutsky bend; the area where the fieldwork took place. The succeeding sections deal with the methods applied in the fiels and the analysis of both fieldwork and historical data. The fifth section summarizes the main biogeomorphological changes observed in the Zakrutsky area. The uncertainties in these results are discussed in the final section.
All this information can be found in a more extensive form in the report by Dijkstra and Schoor (2002), which also contains information about fieldwork at the Akhtuba River.

2.1 The Lower Volga River

The Volga River is a large river flowing through the Russian Plain, which has its origin several hundreds of kilometres north of Moscow. The northern part of its drainage basin consists of taiga and woods, the southern part of steppe and (semi-)desert. The Volga River usually is divided in three parts: the Upper Volga River from the source to the Rybinsk dam, the Middle Volga River from the Rybinsk dam down to the confluence with the Kama River, and the Lower Volga River that ranges from this confluence until the Caspian Sea. The part of interest for the research is the southern part of the Lower Volga River, downstream of Volgograd where the river is almost entirely natural with meandering and braided stretches. The Lower Volga River upstream of Volgograd is merely a cascade of reservoirs.

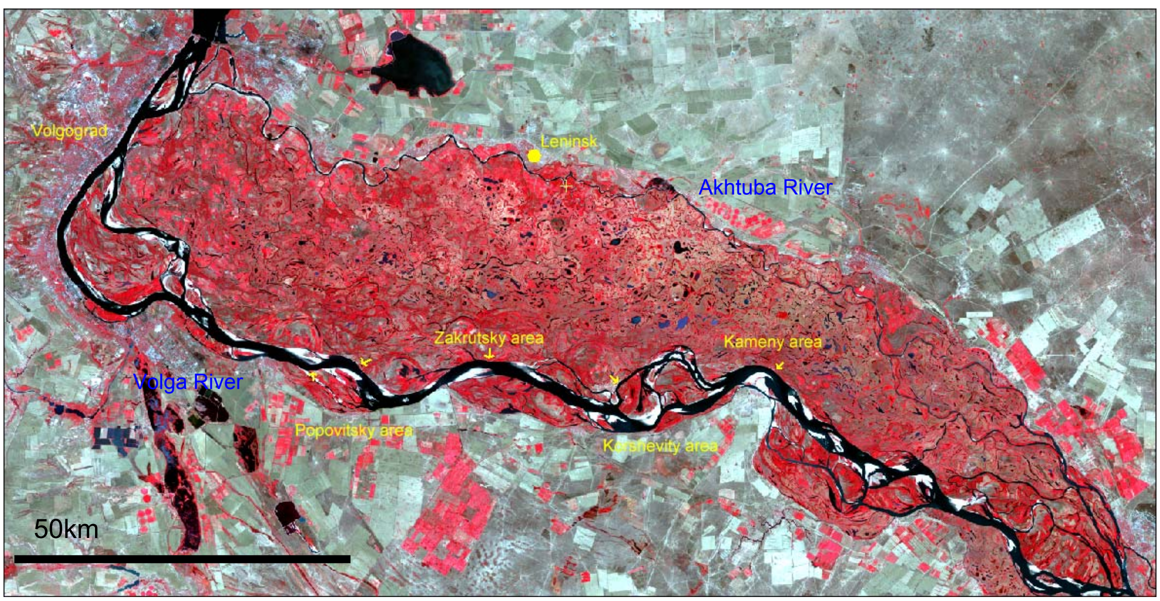


Figure 2-1 The Volga floodplain, Volgograd and the research areas.

Figure 2-1 gives an idea of the position of the Lower Volga basin, the Lower Volga River and his main side-branch the Akhtuba River, the Volga-Akhtuba floodplain and important cities in the area. The length of the rivers between Volgograd and Astrakhan is about 450 km. Downstream of Astrakhan the Volga River flows out in a delta in the Caspian Sea. Together, the Akhtuba and Volga Rivers create a 15 to 30 km wide wet zone in the otherwise dry steppe area: The Volga-Akhtuba floodplain, which can be regarded as a kind of oasis in the steppe and semi-arid zones around it. Over 300 species of flora are present in this area, a number of them rare and endangered. The ecological map made by RIZA (1999) gives an idea of what kind of ecotypes

are present. Lists of species present in the area can be found in De Kramer (2001) and Schoor & Middelkoop (2001; list is in Dutch).
At some places the right bank of the river erodes the cliffs of the steppe situated 20 meters higher, at most places it erodes its own sediment deposits or older low-lying sediments. At most places the top layer of soil, which is several tens of meters thick, consists of Caspian Sea deposits (clay, loam and fine sand). Therefore the sediment transported by the river is very fine (200-450 μm).
The climate in the area is continental: warm in summer (July-average in Volgograd: 24,2 °C), cold in winter (January-average in Volgograd: -9,6 °C) and dry (368 mm/yr). The warm period lasts from mid June until half September; transitions occur quickly. In winter the river is covered with ice for about three months, in summer the water temperature is 24-29 °C (Mordukhai-Boltovski, 1979).
In 1959 a very large dam was completed just north of Volgograd to support irrigation, shipping and hydropower generation. Since the construction of this dam the maximum discharge decreased from over 50.000 m^3/s to 34.000 m^3/s; the average peak is around 27.000 m^3/s. Also the duration of the spring flood in April / May decreased from 8 weeks to 5-7 weeks, but the discharge during summer is higher; see Van de Ven (2000) and figure 2-2. Just downstream of the dam this discharge is distributed over the Akhtuba River and the Lower Volga River. Since the Akhtuba is very small in proportion to the Volga River, the discharge of the latter can be regarded as almost equal to the discharge at the dam.

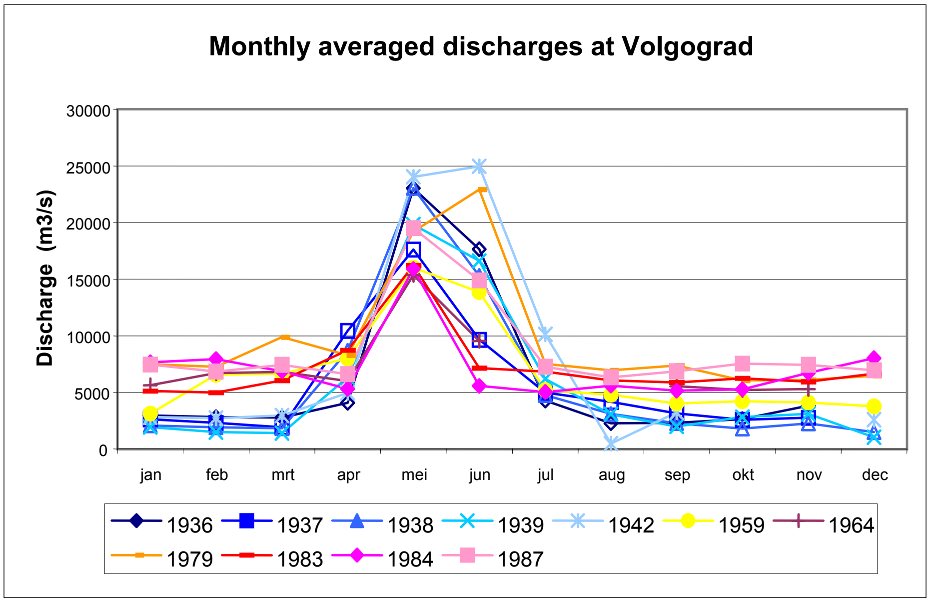


Figure 2-2 Discharges of several years.

The Lower Volga River still is quite natural because of the land use in the area: a large part of the floodplain and surrounding area is a Nature Park, with very limited land use. Industrial and residential areas are situated near Volgograd; therefore bank protection in the Nature Park is not necessary. The Nature Park area is not completely natural however, but also used for limited farming and recreational activities, especially fishing. Because of these activities several villages and roads exist within the Park. The human pressure on the area probably will increase further after completion of a bridge that facilitates an easy connection between Volgograd and the Nature Park on the other bank.
The Volga River is an important shipping route, but the amount of ships passing is rather low. Dredging is executed only rarely since the river in its natural state is deep enough for most shipping, and dredging is expensive. Besides its transport function, the Volga River is also a very important source of water for irrigation of the surrounding steppe area.
Besides influencing morphology, the dam and discharge regime also cause ecological problems. The flooded area and the flood duration are smaller, which has a negative effect on the reproduction of economically very important sturgeons. Many fishermen are complaining.

The water quality of the Lower Volga River is quite good. Pollution by industry or domestic wastewater is relatively low, also because of the large amount of water with respect to the limited amount of people living in the area. Remarkable however is the number of plastic bottles and old fishing equipment that can be found everywhere.

2.2 The Zakrutsky bend

The Zakrutsky area is situated about 90 km downstream from Volgograd, exactly south of Leninsk. It lies in a meandering stretch of the Volga River. Here the river width is around 1000-1200 metres at low discharge, at floods it reaches over 1600 metres. The depth of the shipping channel at low stage is around 10 metres, varying between 6 and 18 metres.

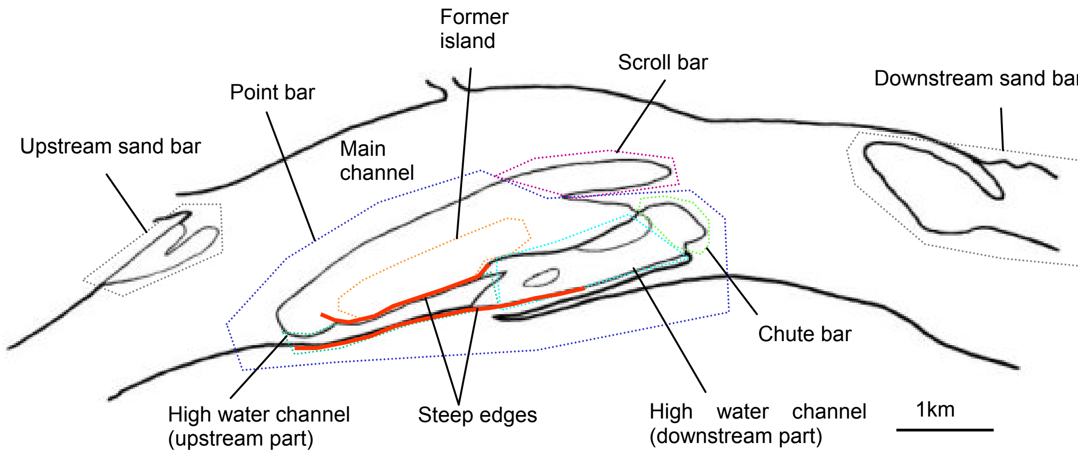


Figure 2-3 Morphological entities in the Zakrutsky bend.

The bend at Zakrutsky shows a lot of morphological activity with a high water channel, an accreting scroll bar, and average outer bank erosion of 19 m/yr. The point bar was originally formed as an island decades ago, but since the 1960's it has been attached to the main land, see Figure 2-3. Sedimentation of the inner bend goes on continuously, resulting in e.g. higher terrain levels (and therefore dryer vegetation types) and the formation of the scroll bar. In more recent years also some erosion of the upstream side of the point bar can be seen. The scroll bar narrowed the main channel significantly.
The height of the terrain is found to be a key factor for which species are present: On low and moist areas dense willow (*Salix alba*) woods can be found, as well as moist herbage and grasses. On higher and therefore dryer areas sedimentation and germination occur more spread out, which creates a more open landscape consisting of trees (mainly *Populus nigra*) of different ages along with dry grasses and herbs. Rejuventation of vegetation occurs continuously with the formation of new land (e.g. the scroll bar), by covering older vegetation with fresh sediment or by erosion.

2.3 2002 Fieldwork data

The data necessary for modelling and for the RIZA-research were determined during the preparation phase (see Section 4.1; model requirements). Eventually the following was measured in the four days available at the Zakrutsky area:

Boundary conditions:
- Estimating the height of flood marks.

Bed topography (Figure 2-4):
- Mapping contour lines of large morphological entities like the scroll bar, high water channel and waterline with the use of GPS-handhelds

- Levelling three profiles, one of them at the same location as the year before.
- Sounding the river bed for a stretch of about 13 km.
- Measuring outer bank height with a laser distance meter and a compass, storing locations with a GPS.

Vegetation:

- Auging/sawing and measuring the stem perimeter of trees to determine their age. The locations of these trees are stored using a GPS.
- Administrating what species grow where in combination with morphological entities, taking pictures and making sketches.
- Mapping vegetation density: counting the numer of trees in a certain area, measuring their stem perimeter and height, estimating coverage and height of smaller vegetation and locating this with a GPS.

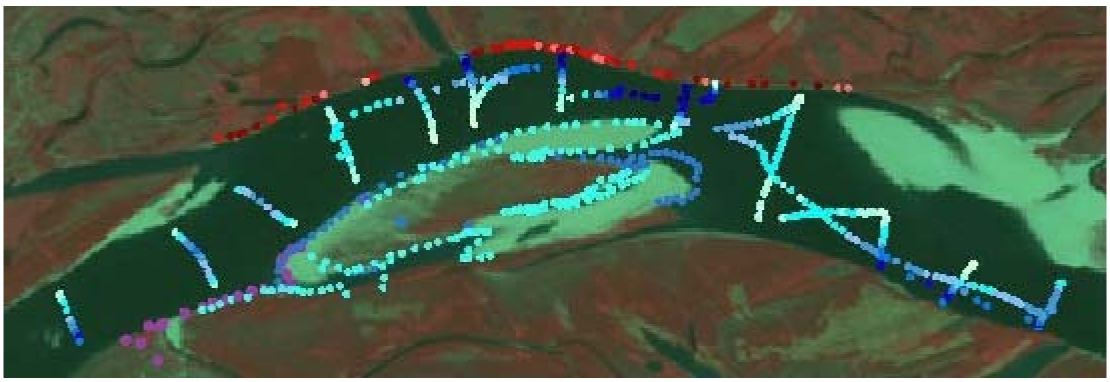


Figure 2-4 Depths, heights and contours in the Zakrutksy bend measured in 2002.

Additional/calibration:

- Measuring of flow velocity profiles in the river from the boat using Ott-mills.
- Checking whether the grain size throughout the area is more or less the same using a set of standard samples (a sand ruler).

2.4 Other data sources

The information obtained during the 2002 fieldwork is not sufficient for a representative model: it lacks for example historical information of vegetation and morphology, and hydrology data.

The fieldwork of 2001 by RIZA (see De Kramer, 2001 and Cormont and Van der Sluis, 2002) provided a lot of information about flood traces, terrain heights, spatial distribution of vegetation types and -ages, and grain sizes. The grain size (D_{50}) in the channel is 375 μm, on the point bar it is around 270 μm. Figure 2-5 displays the vegetation map made that year, combined with vegetation density measurements of 2002. Cormont and Van der Sluis also derived a –not very accurate- relation between the height or circumference of a tree and its age for poplars and willows, using data of both 2001 and 2002. Using this relation, the development of vegetation can

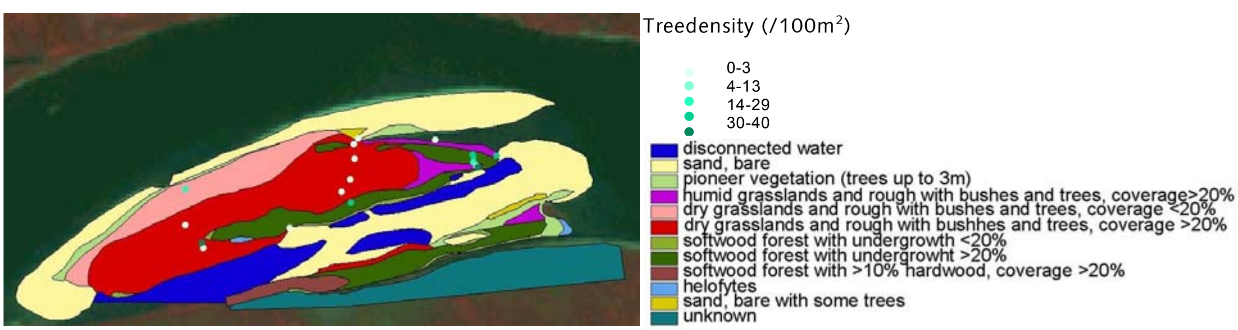
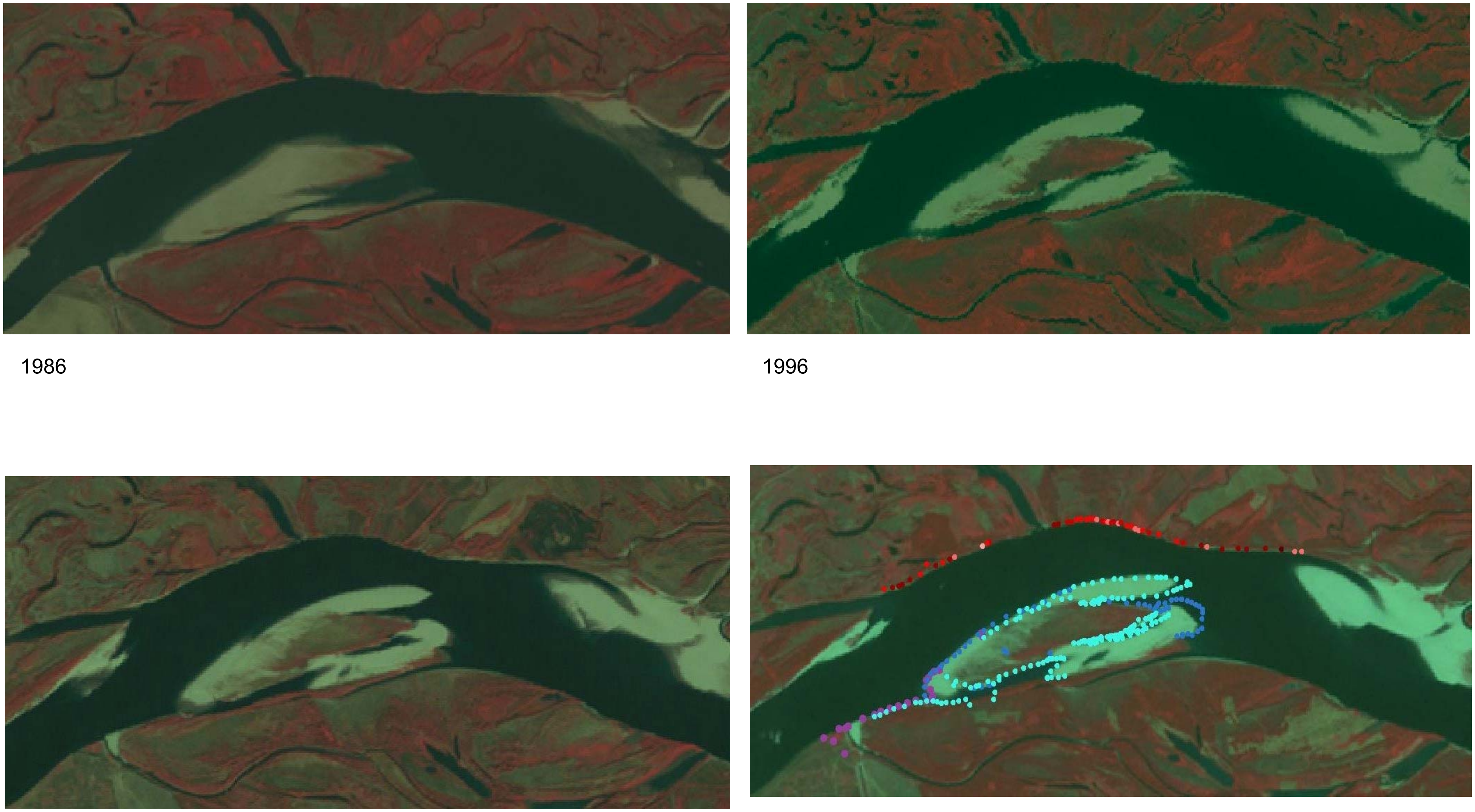


Figure 2-5 The vegetation map by Cormont and Van der Sluis (2002).



1986

1996

1999

2000 with contours from 2002

Figure 2-6 The changing situation around Zakrutsky 1986-2002.

be reconstructed, which on its turn can be used to reconstruct morphological developments.
Besides the fieldwork measurements the Landsat-images of the years 1986, 1996, 1999 and 2000, and the flood images of 1985 and 2001 are also very important sources of information. However, they have two important shortcomings: their pixel size is 30 by 30 meters –too large to see details like a sharp waterline or relatively small groups of trees, they do not provide information about the situation before 1986, and they have not been georeferenced accurately, which for the Zakrutsky area results in a systematic error of about 200 meters. This error is corrected by cutting the areas of interest out of the complete image, and giving these new coordinates based on a visual fit of morphologically stable marks that were measured with a GPS. These corrected images can still have an estimated error of less than one pixel (ca. 15 meters) with respect to their actual location. These images make it possible to see and roughly quantify morphological changes.

Older spatial and bathymetry information is only available in the form of navigational maps. Because these are made for shipping they mainly display the navigational channel; they do not provide very accurate dimensions of other entities like banks, shallow water or landscape forms. The depths they provide are with respect to an unknown chart datum. This chart datum is estimated by comparing the depths displayed by the map with the depths measured in 2002. The thus found difference of 2 m determines the chart datum; the underlying assumption is that the average depth has not changed during the years.

The hydrological information available is limited to the data obtained by Van de Ven at Moscow State University and some discharge data obtained by Babich (pers. comm., MSU-RIZA 2002). The latter show the discharge at the Volgograd dam in 1975 (dry), 1979 (wet) and 1991 (average), plus the floods of 1985 and 2001. The information of Van de Ven contains water levels of various hydrological stations over the years 1975, 1979 and 1997. Here the stations at Volgograd, Svetliy Yar (about 35 km upstream of Zakrutsky) and Kameniy Yar (about 35 km downstream) are of importance.

2.5 Elaboration and interpretation

The navigational maps, satellite images and tree augings have been used to reconstruct the morphological and vegetational development of the area. Here the parts of the report concerning migration/erosion rates, scroll bar formation, and the influence of vegetation on point bar development are summarized. Figure 2-6 shows the series of satellite images.

2.5.1 Downstream migration and erosion rates

The Zakrutsky bend has a radius over width ratio of about 4, which means it is a rather flat and therefore slowly migrating bend. The high and vegetated outer bank eroded 77 hectare in 16 years (from 1986 until 2002), while the upstream part of the point bar eroded about 14 hectare. The scroll bar and chute bar accreted 52 and 29 hectares respectively, and the middle of the point bar accreted some 4 hectare. With 91 hectare of erosion and 85 hectare of accretion the migration seems quite balanced, but this is only two-dimensional.
The rates mentioned above are measured in an area of 1282 hectare (that is used during flood), which means that 7.7% of this area is eroded in 16 years. This means a yearly rejuvenation rate of 0.48% or 5.7 hectare (at a local maximum of 19 m/yr). Compared with the average of 40 m/yr or 5.9 hectare/yr that Van de Ven (2000) calculated this is a little lower, but similar to bends with the same r/w ratio.

2.5.2 Scroll bar formation

The channel has become wider since 1964 as a result of outer bank erosion. The 1986 picture shows a very wide channel, with a strange bend at the point bar side. At the leeside of this kink the scroll bar has its origin. Its formation between 1986 and 1996 narrows the profile very much, and outer bank erosion occurs faster than before its formation: 25 m/yr instead of 15 m/yr. However, it should be realised that the increased outer bank erosion can also be caused by the

slowly decreasing curvature of the bend. The river bed is also eroded after scroll bar formation: the 1974 navigation map shows a maximum depth of 13 meters close to the outer bank, the 2001 soundings show this is 19 meters.
The scroll bars shape and location also make itself shift towards the inner bend: the flow direction is not really parallel to it, but also partly across. This makes the main channel side erosive (because of the powerful flow) and the inner side is filled up because there is a sudden drop in flow velocity. In the middle part the flow is more parallel to the scroll bar, which results in a rather constant velocity and therefore little sedimentation. On the downstream part the outer bank shape directs the flow more across the scroll bar, which causes it to shift towards the inside. The middle part allows vegetation to develop on its leeside: it is sheltered, but not immediately filled with sand. At the upstream end sand slowly covers older vegetation, while at the downstream end the yearly accretion happens too fast for vegetation to develop.

2.5.3 Influence of vegetation on point bar development

Before the outer bank strongly eroded, a relatively high discharge flowed across the almost bare point bar; conditions were probably too severe for vegetation to develop. Only sheltered and high areas allow vegetation development. Between 1940 and 1980 the outer bank is eroded, and the main flow becomes more and more concentrated on the left bank. Flow velocities across the point bar become lower, accretion takes place and some vegetation can survive a flood period. Now the partly vegetated point bar lowers flow velocities, which causes more accretion on the point bar. This accretion further raises the point bar, providing more protection to the vegetation.
According to the limited information it can take decades for this process to get going, but after a few successful years (approximately around 1985) of accretion and vegetation growth it can gain momentum because the developments amplify each other. After a few years (from about 1995) the process slows down because a large area of the point bar is covered with vegetation. The majority of trees on the point bar are aged between 6 and 16 years, which corresponds to the period from 1985 to 1995. Older trees are only found on protected areas: the edge at the south side of the high water channel and in between other vegetation at the east side of the point bar.

2.6 Discussion

Besides inaccuracies in measurements and maps, also the method used in the field and the assumptions made during analysis have their influence on the results mentioned above. Inaccuracies in results relevant for modelling are dealt with in the modelling chapter (Chapter 4).

Measurement errors

- The accuracy of the waterline contours not only depends on the known GPS-error (15m), but also on unknown water levels. In general however the trends in erosion and sedimentation are clear, it particularly affects the accuracy of the erosion/sedimentation rates.
- One of the navigation maps shows such an illogical movement of the downstream side of the point bar that this is neglected. This indicates the maps are not very accurate in depicting entities outside the navigation channel, like banks, shoals and trees. Also the chart datum is not exactly known.
- Although the satellite images are corrected and seem to be on the right coordinates now, there still is some error in the positioning. The first reason for this has to do with the resolution: it is not possible to pinpoint them on the meter, but with interpretation of the pixels themselves an accuracy of about 15 meters is reached. The second reason is the lack of coordinates of reference points like crossings etcetera.
- Also the resolution of the satellite images is rather low: one pixel is 30x30 meters. This not only means that morphological changes are represented roughly, but also that not all vegetation present on the ground can be seen on the images.
- Tree ages can not be determined exactly by auging them: the heights at which the samples are taken differ because trees are sanded in or because one sample-taker is taller than the other. Also mistakes can be made in counting the yearrings. Therefore an error of a few years can easily be made.

Assumptions

- Since the Volga River is regularly covered with ice, this will have its influence on the area. For example, ice can disturb ‘normal’ vegetation development, or even remove vegetation, and the water motion is affected as well. According to local sources however, ice does not affect vegetation very much in this area because the water level in winter is below all vegetation, and little other information is available about ice coverage. Therefore ice-effects are not taken into account.

Methods

- Due to the fact that auging concentrated on old trees, only a few young trees on morphologically young areas are dated. Also some of the oldest trees in the area may have been overlooked, meaning the emergence of vegetation in the area is dated later than in reality.
- A comparison between the profiles measured on the same location in two years is not possible because the location of the measured points turned out to vary up to tens of meters (due to positioning inaccuracies in GPS and levelling instruments), and the differences in level are small.

3 Modelling effects of vegetation

The interaction between vegetation and morphodynamics is to a large extent unknown. Modelling the effect of vegetation on hydraulic roughness is possible, but the effect of vegetation on sediment transport can not be described accurately yet, despite the efforts put into studying these effects. One of the main reasons for this lack of knowledge is the natural variability of vegetation: it is highly variable in space and time and adapts to the circumstances, e.g. it bends and moves when overflown. Therefore it is difficult to describe the vertical velocity profile and turbulence structure in a vegetation layer. Together these flow characteristics determine the bed load and suspension transport.

Though there are many uncertainties, it is generally expected that vegetation protects the bed against erosion and adds to accretion because flow velocities, and therefore the sediment transport capacity, are lower. Besides the large-scale effect of lower velocities in a vegetated area, on a smaller scale grasses and herbs may facilitate 'hiding' oppportunities in the shelter of their halms. Larger vegetation like trees can show the same effect, but may also locally increase the flow velocity, thus creating a scour hole.

The first part of this chapter aims at describing the relevant methods available for modelling the hydraulic roughness of vegetation. The second section deals with the state of the vegetation at Zakrutksy over the years, and how this is modelled hydraulically. The third section describes what methods are applied to model the influence of vegetation on sediment transport. Finally the accuracy and applicabity of these methods are discussed.

3.1 Hydraulic roughness of vegetation

Early methods for predicting the hydraulic roughness of vegetation are mostly based on field measurements in streams and irrigation channels. E.g. Chow (1959) gives a list with photographs of vegetated channels with a Manning's n-value based on measurements of gradients, cross-sections and discharges. Such a list can be used to estimate the roughness of similar channels. It may be clear that this is not a generally applicable quantified relation between vegetation characteristics and hydraulic roughness based on physical properties.

Therefore other methods have been developed that calculate a representative Chézy coefficient depending on the water depth and vegetation characteristics like height, stem diameter and density. Important are the distinctions in modelling submerged or unsubmerged vegetation and flexible or inflexible vegetation. Flexible vegetation is more difficult to model since it deforms due to the flow forces (Fathi-Maghadam and Kouwen, 1997). In some cases however, like winter circumstances, these deformations are relatively small and vegetation can be considered inflexible. Modelling submerged vegetation is also more complex because the momentum exchange between the free flowing upper water layer and the lower vegetated layers has to be described well (Wu et al., 1999). Incorporating two vegetation layers –e.g. trees and undergrowth-adds to this complexity.

The representative Chézy coefficient can be derived if the vertical flow velocity profile in vegetation is known. This profile depends on the equilibrium between the gravitational driving force and the drag forces exerted by vegetation and bottom. Thus the water motion can be described by differential equations, which can be solved analytically. The outcome of such an approach is verified by flume experiments. An example of such an approach is the analytical model for submerged vegetation by Klopstra et al. (2002).

This model is also used by Van Velzen et al. (2002a,b) to develop a handbook for vegetation roughness in floodplains. In this handbook, the hydraulic roughness of several vegetation types (e.g. pioneers, softwood forest, reeds) as a function of the water depth is given for situations with and without grazing. The calculations are made based on representative parameters that are measured in the field: the average vegetation height, the number of stems per square meter, the representative stem diameter and a drag coefficient. The complete formulas can be found in annex 2.

3.2 The vegetation at Zakrutsky

In order to make a representative model of the Zakrutsky bend, the hydraulic roughness of the point bar vegetation has to be included. Since vegetation develops over the years, the representation in the model has to be adjusted regularly as well. Therefore the hydraulic roughness values (Nikuradse k-values) are calculated for the years 1986, 1991 and 1996. The years 1986 and 1996 are chosen because satellite images of these years show where vegetation is present. For the year 1991 no image is available; this has to be interpolated using the other images. Not updating the situation in 1991 would mean a too large gap in vegetation development.

The state of the vegetation in a specific year is determined using satellite images, the vegetation map of Cormont and Van der Sluis (2002; Figure 2-5), vegetation measurements of the 2001 and 2002 fieldworks and the RIZA handbook (Van Velzen et al., 2002a,b). The satellite images roughly show where vegetation is present in the year of interest. The vegetation map provides information about vegetation types and coverage in 2001, similar types (e.g. pioneers) will have been present earlier as well.

During both fieldworks the age of many trees was determined by counting their yearrings. This means they also provide information about where trees were present in a certain year. Futhermore, by measuring their circumference too, not only their diameter in a year of interest can be calculated, but also a relation between their age and diameter was derived (Cormont and Van der Sluis, 2002). Using this relation, one can also calculate the age and germination year of vegetation of which only the circumference has been measured. Once the age of trees on a location is known, also their diameter and height in earlier years can be reconstructed through a similar relation. The density of trees in several vegetation types was determined during the 2002 fieldwork. The handbook by Van Velzen et al. (2002) provides additional information about height, density and stem diameter for willows with relation to their age.

Characteristics of undergrowth and other vegetation types mainly consisting of smaller species like grasses and herbs are more difficult to reconstruct since they can not be dated in the field. However, since these characteristics can be considered to be rather comparable with those of the current vegetation, an estimation can be made of the parameters in earlier years. This estimation is based on the vegetation map, field measurements of vegetation height and density and information provided by the handbook.

Together, calculations and estimations of parameters for tall vegetation and undergrowth result in representative values for a number of vegetation zones for each year, which are presented in Table 3.1 below. The situation of the different vegetation zones for the year 1986, 1991 and 1996 is presented in Figure 3-1.

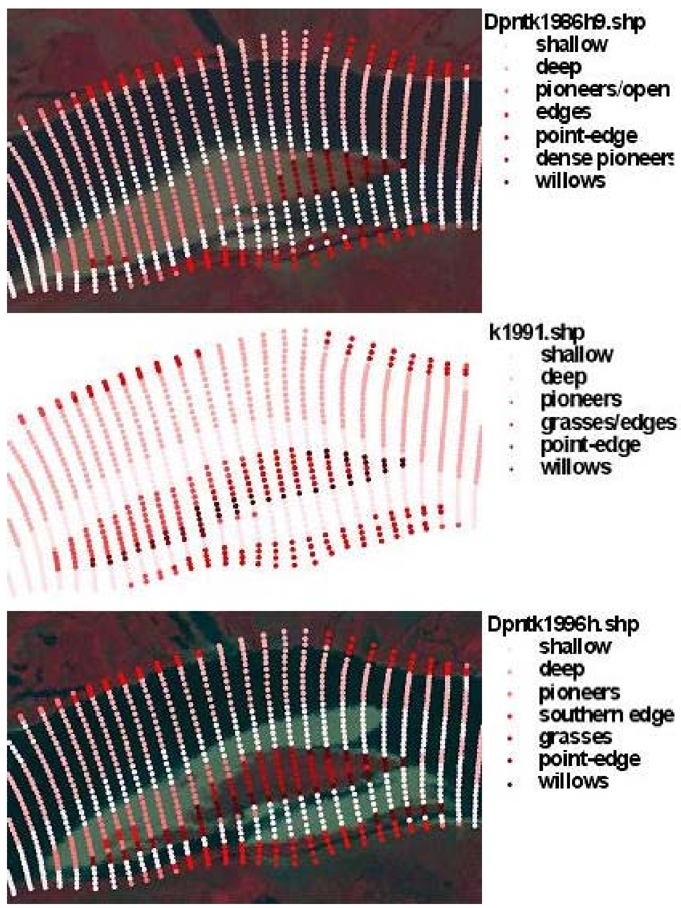


Figure 3-1 The vegetation zones at Zakrustky for the years 1986, 1991 (no satellite image available) and 1996.

Table 3.1 Representative roughness coefficients for vegetation zones at Zakrutsky.

Year	Vegetation zone	k representative (m)	Water depth (m)	Tall vegetation				Undergrowth			
				k	D	A	m	k	D	A	m
1986	Willows	18	4.2	2.5	0.04	0.13	3.3	0.2	0.003	0.3	100
	Grasses	0.32	2.5	1.5	0.016	0.0008	0.05	0.3	0.003	0.15	50
	Dense pioneers	4.2	4.0	0.3	0.003	0.021	140	0.2	0.003	0.023	100
	Southern edge	0.32	1.9	10	0.2	0.0022	0.011	0.4	0.003	0.3	100
	West point	2.4	1.2	1.2	0.02	0.02	1	0.4	0.003	0.3	100
1991	Willows	20	4.0	5.0	0.083	0.13	1.5	0.2	0.003	0.3	100
	Grasses	0.31	2.0	3.5	0.055	0.0028	0.05	0.3	0.003	0.42	140
	Southern edge	0.37	1.9	12	0.026	0.013	0.25	0.4	0.003	0.016	100
	Point-edge	0.95	1.2	1.9	0.25	0.0025	0.5	0.45	0.004	0.3	4
1996	Willows	15	3.5	4.1	0.068	0.10	1.5	0.45	0.003	0.24	80
	Grasses	0.70	1.5	5.2	0.095	0.0019	0.02	0.4	0.003	0.42	140
	Southern edge	0.47	1.9	14	0.32	0.0032	0.01	0.4	0.003	0.3	100
	Point-edge	1.1	1	4.8	0.085	0.017	0.2	0.45	0.004	0.016	4
	Southern willows	24	3	3	0.04	0.13	3.3	0.2	0.003	0.3	100

Explanation of the table:

- The names for the vegetation zones are made based on their location and/or vegetation present. photos
- The representative k-value is based on the mean water depth at high stage (called 'water depth' in the table) and vegetation characteristics. This means it is only valid for one water depth. The computations are made with stationary discharges, so water levels will be more or less constant in time. The bed level however does vary in time. Therefore the water depth is calculated from the water levels of a test simulation and the estimated real bed levels. The variation of bed level within one vegetation zone is not accounted for.
- The vegetation is divided into 'tall vegetation' like trees and 'undergrowth' like grasses and weeds.
- The parameters of the vegetation are: k=vegetation height (m), D= diameter (m), A= wetted area (m^2) and m= number of stems (m^{-2}).
- For all calculations the following values are used: drag factor C_d=1.5 (like in Van Velzen, 2002a), Von Kármán constant κ=0.4, and water level gradient i_s=4.5x10^{-5}.

3.3 Vegetation influence on sediment transport

The resistance of vegetation can cause a reduction of the bed shear stress up to 90% in comparison to unvegetated beds, which means a reduced bed load transport. The stems of vegetation cause turbulence of the flow because of their resistance, but they also limit the size of the turbulence eddies; therefore the effect on suspension transport is more difficult and cannot be generalised.

The incorporation of the Van Rijn transport formula in Delft3D allows some room to vary parameters concerning sediment transport spatially, which means they may have different values in vegetated areas. These parameters are (see also Annex 1, in which the formula is written out):

- Nikuradse k-value
- D_{50} grain size
- D_{90} grain size

The first is already adjusted to model the effect on the flow, and the second really represents a quality of the sediment, whereas the D_{90} is only used to determine the grain related Chézy coefficient, according to (WL | Delft hydraulics, 2001):

$$C' = 18\log\left(\frac{12h}{3D_{90}}\right)$$

This C' is used to calculate the effective shear stress $\mu_c \tau_{bc}$ that should be reduced in the following way:

$$C = 18\log\left(\frac{12h}{\xi_c}\right)$$

$$\mu_c = \left(\frac{C}{C'}\right)^2$$

$$f_{cb} = \frac{8g}{C^2}$$

$$\tau_{bc} = 0.125\rho_w f_{cb} q^2$$

In which:

h	= water depth	(m)
ξ_c	= roughness height or bed load layer thickness	(m)
g	= gravitational accelleration	(m/s^2)
ρ_w	= water density	(kg/m^3)
q	= depth averaged flow velocity	(m/s)

This means that by choosing a very small D_{90} the bottom is artificially smoothened, leading to lower transports (both suspension and bed load). Values of h= 4 m and q= 0.3 m/s are found representative for the vegetation zone 'willows'. Normally the D_{90} is 0.57 mm and ξ_c= 0.2 m everywhere. This means an effective shear stress of 0.152 N/m^2 (C= 43 $m^{1/2}/s$, C'= 80 $m^{1/2}/s$, f_{cb}= 0.0428 and μ_c= 0.316). A reduction of 90% should be reached by lowering μ_c by 90% (f_{cb} remains the same), which means a ratio C/C' of 0.178 hence a value of 242 for C' (C also remains unchanged). The D_{90} then would be smaller than the minimum of Delft3D, which is $2x10^{-6}$m. If this mimimum is used, C' becomes 124 and the effective shear stress is reduced 52% to 0.072 N/m^2.
When applied to the model of the Zakrutsky bend however no differences where visible: the transport in vegetation was low originally as a result of low flow velocities. It is not possible to view the value of the effective shear stress $\mu_c \tau_{bc}$.

3.4 Discussion

The Nikuradse k-values used to model vegetation roughness seem rather high, though they are comparable to those used by Van Velzen et al. (2002a). Nevertheless, many estimations were made about the state of the vegetation in earlier years. Also, the measurements on vegetation on the Zakrutksy point bar took place in summer when probably more weeds are present than during the flood period in May. The same applies to the satellite images, which were also made in summer. Apart from this, the measurements themselves are not very reliable: relative few samples were taken and especially the density of smaller vegetation is estimated instead of counted. Many estimations are made based on data measured at the floodplains of Dutch rivers, hence the difference in climate may lead to deviations, although these are probably small. Together, this makes that the obtained representative roughness can be seen as a useful and fair indication of the order of magnitude, but that the exact values are questionable. In this case the inaccuracy is not problematic since the model is conceptual rather than exact.
More problematic is the effect of vegetation on sediment transport. A high vegetation roughness can only simulate the rerouting effect of vegetation on flow more or less realistically, and may cause incorrect (high) transports in the vegetation itself. These are not observed in the model –

generally transports in vegetation are low because of low flow velocities, only the borders of the vegetated areas close to faster flow sometimes show large transports- but without more knowledge about the magnitude of sediment transport in vegetation it is not possible to verify what are correct values. Most measurements in laboratory flumes have the drawback of not taking into account the rerouting effect that vegetation can have; the flow is forced through the vegetation instead. Only a few papers, e.g. Naot et al. (1996) and Bennet et al. (2002), study the altering of flow direction by vegetation specifically.

By applying the Van Rijn transport formula in Delft3D with a a very small D_{90} value (which signifies a very smooth bed) it should be possible to lower the sediment transport in vegetation. To what extent this is necessary however remains unanswered as long as it is not clear what value it should have. Merely the very low flow velocities in vegetated areas result in low bottom shear stresses (a reduction of about 60% with respect to unvegetated areas with similar depths) and therefore low transports.

Apart from the effect of vegetation on sediment transport, also the effects of flow and morphology on vegetation are not actually simulated in the model. This means it cannot simulate natural rejuvenation: vegetation cannot be removed by flow or erosion or be buried by sediment, and it does not develop on fresh depositions. In the current model this is not problematic because it is used as a hindcast and the state of the vegetation can be updated with the actual situation. In models that are to be used for predictions however, this is a matter of concern.

4 Model building

This chapter discusses the building of the Delft3D model. It starts with the goals of the model, the simulation approach and the data necessary for modelling. The second section describes considerations regarding modelling, like determining boundary conditions, bed topography and roughness. After this, the calibration of both hydraulic and morphodynamic modules is described in brief, followed by a sensitivity study; Section 5.1 of the following chapter describes the insight gained by calibration more elaborately. The chapter concludes with a description of the resulting reference model and a discussion.

4.1 Model requirements

4.1.1 Goals

The aim of the model is to semi-quantitatively determine the influences of river features on scroll bar development. These features are:

- vegetation on the point bar;
- outer bank erosion.

The possible influences of these features on scroll bar formation were mentioned in the hypotheses, and explained further in Section 1.3.

The discharge regime is also important since morphological changes are largely dependent on changing discharges, with a strong non-linear character. More sediment is transported and deposited on higher grounds during floods, and e.g. outer bank erosion often mainly happens in the falling stage of a flood due to the soaked soil. Nevertheless this is not part of the simulations for two reasons: the inluence of a flood on scroll bar development partly occurs by outer bank erosion, which is simulated explicitly. Secondly, the discharge to be applied in the model will be similar to the discharge regime in reality, under which a scroll bar has formed.

4.1.2 Simulation scale

Like mentioned in the problem description and limitations in Chapter 1, the numerical model has a conceptual character. A more complex model demands a lot of precise data and modelling effort, and it would not make the phenomena to be studied clearer. However, a model that is too much simplified is not representative anymore and no comparisons with reality can be made. Therefore the scale of the model has to be chosen such that known and relevant phenomena are included and others can be left out. The same applies for the temporal scale.

Time scale

The time simulated is sixteen years. This period is chosen for the following reasons:

- it is long enough for a scroll bar to develop;
- for a longer period not enough data are available;
- a shorter period would not make use of the data optimally.

Area of interest

Local processes that influence the morphology on the same scale as the scroll bar, and therefore have to be included in the area of interest are:

- vegetation growth;
- outer bank erosion;
- point bar accretion;
- high water channel erosion/sedimentation.

The model area is somewhat larger than the area of interest because the errors introduced at the boundaries should not interfere with the phenomena of interest.

Model area

For the lateral direction (model width) the boundaries are clear: the left and right bank. These are closed boundaries. In reality these have some lower parts and small side channels, which are not taken into account in the model because their influence is neglectable due to their size. Some space at the left bank is needed to allow for bank erosion.
The location of the boundaries up- and downstream of the area of interest require more consideration because the conditions applied at these open boundaries determine what enters and leaves the model area. Prescribing a discharge boundary upstream in combination with a waterlevel on the downstream boundary is the most stable and straightforward combination given the data and model area. To save computation time the model area should be as small as possible, but to avoid disturbancies at the boundaries entering the area of interest the model extent has to be somewhat larger.

Upstream boundary
Time and space at the upstream boundary are needed for the adjustment of the secondary (spiral) flow and sediment concentrations, in which the upstream bend also plays a part (known as the overshoot effect). E.g. point bar accretion and outer bank erosion are strongly determined by this secondary flow. Equations A-4 and A-5 in Annex 1 give expressions for the adaptation lengths of flow (λ_w) and morphology (λ_s) according to Struiksma et. al. (1985). Unfortunately, the bed topography adaptation length is too long (18 km; the flow adaptation length is 1.5 km) to include in the model: measurements have been made only relatively close to the area of interest.

Downstream boundary
The position of the downstream (waterlevel) boundary also requires attention, since it causes a backwater effect for a considerable distance upstream if not prescribed accurately.
The formula of Bélanger can be used to calculate the length scale of the adaptation process. For depths much larger than the critical depth and close to the equilibrium depth, this can be written as:

$$\frac{dh}{dx} = \frac{3(h - h_e)}{L}$$

with:

$$L = \frac{h_e^3 - h_g^3}{h_e^3 \cdot i_b}$$

For low values of the Froude number (which applies in most lowland rivers due to their gentle slope) this reduces to (De Vriend, 1999):

$$L \approx \frac{h_e}{i_b}$$

For the Volga river (h_e=14 m, i_b= $4.5 \cdot 10^{-5}$) this means L is 315 km at high discharge. This is far too large to incorporate it in the model. However, since the aim of the model is to study changes and not to predict water levels, a small error in the water levels in the study area is not problematic as long as it does not effect the water motion too much. Besides, in the natural situation the waterlevels are constantly changing. The effect on the flow is the largest close to the boundary, therefore this is chosen a few kilometers downstream from the area of interest.

4.1.3 2DH or 3D modelling

Delft3D-FLOW uses the non-linear shallow water equations, which are derived from the three-dimensional Navier-Stokes equations for incompressible free surface flow (WL | Delft hydraulics, 1999). One of the most important choices is to make a 2DH-model (depth averaged) or a three-dimensional model. In both 2DH and 3D modelling the hydrostatic pressure relation is applied instead of the vertical momentum equation, which means that the vertical accelerations are assumed to be small with respect to the gravitational acceleration, and therefore can be neglected.

A 2DH model uses the vertically averaged velocity profile instead of the real velocity distribution. A three-dimensional model uses a number of horizontal layers over the vertical, which allows vertical differences in the velocity profile and their related phenomena to be simulated. The secondary (spiral) flow in a river bend is such a phenomenon.
A 3D simulation therefore seems to be the best option, but requires much more computation time and has its disadvantages in sediment transport modelling: Generally, transport models use the bottom shear stress, which is only present at the bottom layer. However, the on-line sediment transport module of Delft3D is able to deal with this problem.
The Delft3D-FLOW (hydrodynamic) module also has an option to represent secondary flow in 2DH-models in a parametric way, by means of the spiral motion intensity. Such a 2DH hydrodynamic model can be coupled to the Delft3D-MOR (morphodynamic) module, which can also include the effect of spiral flow. Many river models have been made in this way, using a MOR-tree to describe the interaction between the flow, transport and bottom modules (e.g. Baptist, 2001 and Van den Brink, 2002).
Given the computational load a 2DH model is preferred.

4.2 Simulation procedures and necessary data

Semi-stationary reference model

The basis of all simulations is the reference scenario, which resembles the situation at Zakrutsky during the years. This means it has to be updated several times because vegetation grows and the bed topography changes. The latter should result from the simulation itself, but especially outer bank erosion may not be simulated correctly, and is therefore corrected manually if necessary.
In stead of making a year-round dynamic situation, one year is split into a stationary high water period and a stationary low water period. This is done mainly for computational benefits: a stationary model is much easier to make and requires less computation time. The problem of modelling continuously changing hydraulic roughness (being a function of the water depth and flow velocity) is avoided, and calculation is much faster because the spin-up times are reduced to twice a year.
This simplification can be applied because the real discharge is already very constant, with one flood peak, thanks to the dam at Volgograd (see figure 2-2 and 4-3). Nevertheless, attention has to be paid to selecting the representative discharges, see Section 4.3.4.

After testing and calibration of this model, the simulations to test the hypotheses are made. In order to rule out other effects as far as possible all runs will be made very similar, apart from the specific changes mentioned below.

Necessary data

To represent the real situation in the model the following data are needed:

- bed topography for the years 1986, 1991, 1996;
- a representative high and low discharge;
- water levels during high and low discharge;
- sediment grain size;
- spatial distribution of vegetation in the years 1986, 1991, 1996, 2002;
- vegetation characteristics concerning roughness: type, height, diameter, coverage.

And for calibration/verification:

- water level gradient during high and low discharge;
- bed topography of the year 2002.

Research simulations

The first hypothesis, stating that the flow diverted by the vegetation erodes the outer bank and widens the profile, thus creating room for a scroll bar, is tested as follows:

- The flow is diverted by a high vegetation roughness; this should cause bank erosion.
- In case no or too little outer bank erosion occurs in the model, the profile is widened artificially by changing the bathymetry file.

The second hypothesis, stating that lower flow velocities just downstream of the vegetation increase accretion, is tested by:

- Applying different vegetation roughnesses; monitoring to what extent these affect flow and transport directly downstream of it.

4.3 Flow and morphology input considerations

Considerations regarding vegetation(roughness) modelling are made in the specific vegetation chapter (Chapter 3).

4.3.1 Grid

Both high and low simulations and FLOW and MOR modules use the same grid created by RGF-GRID, since all the exhange information is stored with respect to this grid. The grid is curvilinear and staggered: it can follow bathymetry contours, and water levels and flow velocities are calculated in different points.

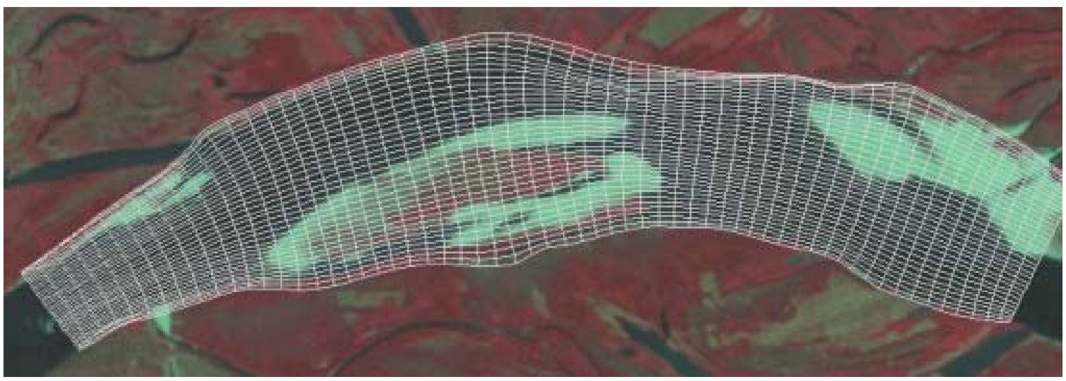


Figure 4-1 The computational grid on the 2000 image.

In defining a grid for this model, three features are important: the grid extent, the cell size and the shape. First of all, the model area has to be covered. The grid cells should be small enough to represent the smallest terrain characteristics of importance, i.e. the high water channel and the scroll bar. Since these both have a width of 200 to 400 m, a grid cell size of around 100 m seems appropriate. To save computation time the length of the cells in main stream direction can be larger, i.e. around 200 m. Smaller grid cells slow down computation, probably without giving better results. To follow the bathymetry as close as possible a curvilinear grid is used (Figure 4-1). The up- and downstream boundaries are perpendicular to the flow velocity vectors. After orthogonalisation, the grid cell length varies between 150 and 260 meters, and the grid cell width between 25 and 90 meters. It contains 61 x 37 cells. At the bend apex the grid is much wider than the river bed of 1986 to allow room for bank erosion.

4.3.2 Hydrodynamic timestep

The ADI (Alternating Direction Implicit) computational scheme used by Delft3D-FLOW is unconditionally stable. Nevertheless the use of large time steps can lead to an unrealistic water motion if in one timestep more water is transported through a cell than the cell itself contains. To avoid such instability, the Courant-Friedrich-Lewy condition has to be met. This reads:

$$CFL = 2c\Delta t\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}}$$

With Δx=200 m, Δy=80 m, $c=\sqrt{gh}$ =14 m/s (maximum depth is 20 m), CFL=0.38Δt. Since CFL should stay below 20 to obtain accurate results, the maximum timestep is 53 seconds. In practice however, timesteps of 60 and 120 seconds are possible for high and low water simulations respectively, probably because the water depth in most grid cells is much smaller than 20 meters.

4.3.3 Bed topography

The bed topography for the starting situation of 1986 is based on the satellite image of that year. However, this is only two dimensional, though shallow areas can be seen. Depth information is derived from the navigation map of 1981 and the depth measured during the fieldwork. Together these provide the chart datum, and the measured depths give an idea of what is realistic. Nevertheless a lot is estimated. Information about heights also comes from the navigation maps, in combination with the high water image of 1985 and measurements of the outer bank height, which has not changed.

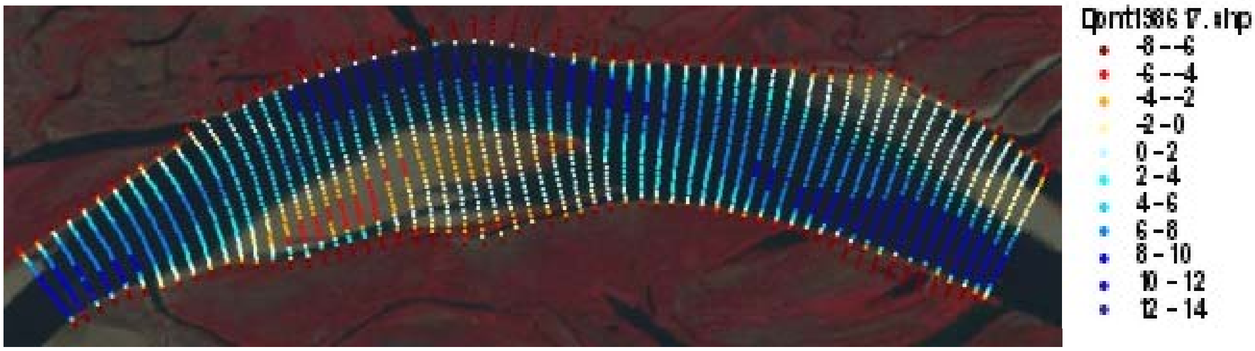


Figure 4-2 The bathymetry constructed for the year 1986.

When making the bed topography using Delft-QUICKIN, sudden bottom level changes are avoided if possible. The triangulation method attenuates most of these. The outer bank is steep, and the banks at the closed boundaries are made higher than the high water level to avoid computational difficulties regarding drying and flooding. The result can be seen in Figure 4-2.
Since Delft3D does not cope with outer bank erosion very well, the bed topography files for the years 1991 and 1996 are based on the bed level resulting from the preceding simulation period, but with an updated outer bank.

4.3.4 Boundaries

Upstream boundary condition

Both high and low discharge values are constructed using data of the years 1979 and 1997. The year 1997 has an average discharge (Babich, pers. comm.), which makes it suitable for modelling. The only known data about this year however are the water levels at several locations and the maximum discharge at the Volgograd dam. Therefore the year 1979 is used as a reference: Of this year both water levels and dam discharges are known, which makes it possible to get an indication of the stage-discharge relation for this location. The year 1979 itself is not suitable to use as a basis for hydrological boundary conditions itself because it is a rather wet year.
Such a stage-discharge relation has already been derived by Van de Ven (not published). This stage-discharge relation of Volgograd dam can be used to determine the discharges matching the water levels of the year 1997. The average discharge for of 1997 derived this way is 7892 m^3/s. Choosing a low discharge for the model of 5500 m^3/s for 47 weeks and a flood discharge of 27,000 m^3/s for five weeks, the average modelling discharge is 7567 m^3/s (Figure 4-3). This is slightly lower than at the dam to allow for inundation losses during floods and evaporation.
To divide the total discharge realistically over the gridcells at the inflow boundary, the discharge is proportional to $h^{3/2}$. This water depth is known because both the water level at the downstream boundary and the water level gradient are known.

Downstream boundary condition

At the downstream boundary a water level of 6 meters above reference level is applied for the flood simulation, and 0 meters for the low discharge: All bathymetry data were measured with respect to the water level during low discharge. The 6 meters are based on the height of flood traces found in the field and the height of inundated areas.

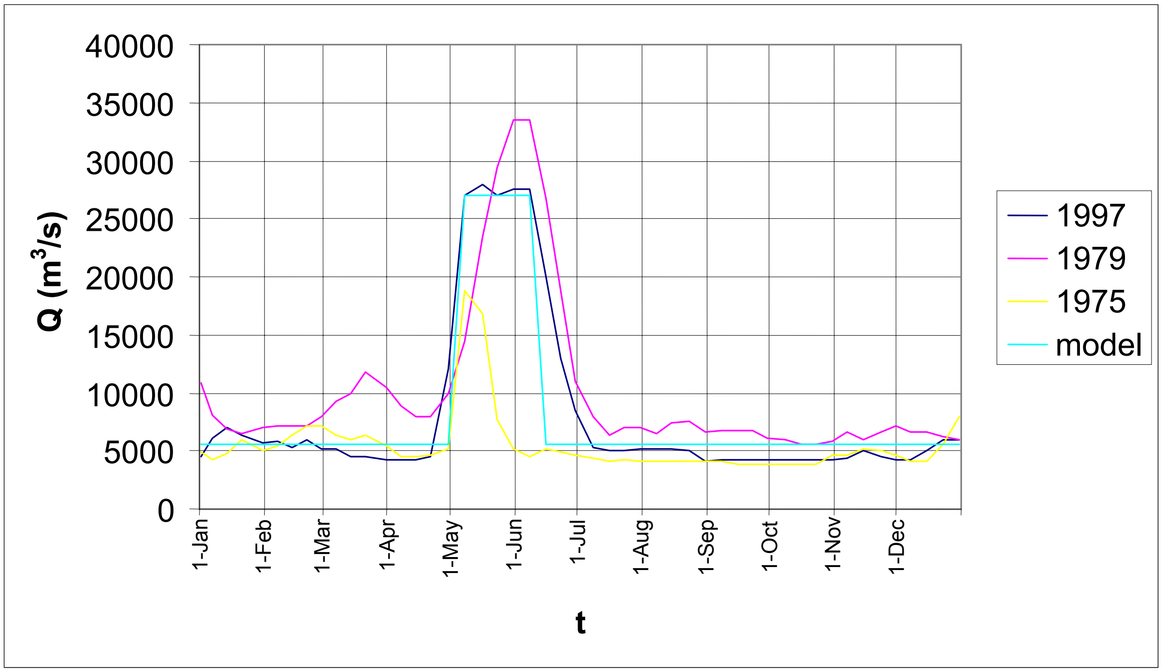


Figure 4-3 Hydrographs of 1975, 1979, 1997 and the modelling discharge.

Transport and bed boundary conditions

For both up- and downstream boundary the bed level is fixed. Since the model works in total transport mode it is not necessary to describe in- or outgoing sediment concentrations.

4.3.5 Bottom roughness

The bottom roughness of the main (unvegetated) channel is predicted using Van Rijn's (1984c) method, which accounts for bed form shapes as well. The dimensions of the calculated bed forms are a little smaller than measured. The thus obtained roughness height (k-value) is adjusted until the correct water level gradient is reached. For the low discharge situation -completely without flow through vegetation- this works reasonably well. For the high discharge situation however, the calculated roughness proved far too high: the water level gradient was twice what it should be, even without vegetation. A much lower k-value was necessary, which is entirely derived by trial-and-error (see also Section 4.4; flow calibration). For both low and high discharge, the roughness values vary spatially: a distinction is made between areas deeper than 4 meters with high flow velocities, and shallower areas with less flow. This distinction is made because the bed forms determining roughness differ between the areas. The boundary of 4 meters is rather arbitrary however.

The approach followed to determine the hydraulical roughness caused by vegetation is explained in Section 3.2. Runs using a uniform Chézy roughness factor show the roughness during floods is a little larger than during low discharge: 45 $m^{1/2}/s$ vs. 48 $m^{1/2}/s$ respectively. The Van Rijn prediction method is very sensitive to small changes in flow velocities.

4.3.6 Sediment transport formula

Considering the circumstances (grain size, flow velocities, absence of waves) two sediment transport formulas are applicable: the Van Rijn (1984) formula and the Engelund-Hansen formula.

Engelund-Hansen formula

The Engelund-Hansen formula (see Annex 1) is applicable under the following conditions:

0.19 mm < D_{50} < 0.93 mm
Since the sand in the Volga River has a D_{50} of 0.4 mm this condition is met. The sand on the pointbar has a D_{50} of 0.27 mm, also between the boundaries.

$w_s/u_*<1$
This is the ratio between fall velocity of a particle and the shear velocity. Being smaller than 1, this means suspended transport is the important transport mechanism, which applies for relatively fine material (low settling velocity). For values above 1 (coarser material) bed-load transport is more important and other formulas apply. According to Van Rijn (1984) the settling velocity for sediment of this size can be calculated using the following equation:

$$w_s = \frac{10\nu}{D}\left(\sqrt{1+\frac{0.01\Delta g D^3}{\nu^3}}-1\right)$$

Using a D_{50} of 0.4 mm, this gives a w_s of 0.06 m/s (kinematic viscosity ν= 10^{-6}, g= 9.81 m/s^2).
The definition of the shear velocity is:

$$u_* = \sqrt{ghi}$$

With an average water depth h of 10 m and an energy slope i equal to the river slope of $0.4 \cdot 10^{-4}$, this gives a value of 0.063 m/s. The fall velocity to shear velocity ratio corresponding to this situation is 0.94, which is within the range.

0.07 < θ < 6
Engelund and Hansen did their experiments for Shields parameter (θ) values between 0.07 and 6. The Shields parameter indicates the sediments mobility. Its definition reads:

$$\theta = \frac{u_*^2}{g\Delta D}$$

The θ-value corresponding to a D_{50} of 0.4 mm is 0.61, so all three conditions are met.
The Engelund-Hansen formula however is known to produce large errors for sediment transport through vegetation, due to the high power of the Chézy roughness coefficient.

Van Rijn formula
The Van Rijn (1984) formula (see Annex 1) has two advantages with respect to the Engelund-Hansen formula: The general hydraulic roughness is not applied to the bed material, but the bed form roughness determining transport is defined separately. This means a large vegetation roughness does not directly cause large transports. The other advantage is that it uses separate expressions to calculate bed load and suspended load, which can make it more accurate. De Vries (1993) however shows by comparing measured and predicted sediment transport values that the Van Rijn formula is not always better than the formula of Engelund and Hansen.
In the model the Van Rijn formula is used in 'Total mode'. That means the suspended load is added to the bed load, after which the transport of the total quantity is calculated rather than taking into account the different transport mechanisms that apply to sediment in suspension.

4.3.7 MOR-tree construction

The MOR-tree defines which processes (Figure 4-4) are simulated in the model and how they interact. The tree used for the first calibration simulations is relatively simple, since only high or low water is simulated in one run. For the research runs, the tree has to contain both floods and summer discharges with their specific bottom roughness, and they have to make use of the same bed-level file. Since this is not a standard feature of Delft3D, a special tree is constructed in combination with using MATLAB to update the communication file in which the roughness values are stored. The tree composition is explained below, the use of MATLAB is described in Annex 3.

A MOR-tree consist of nodes and connections (controllers). The end-nodes at the bottom contain the physical processes, the higher nodes determine the interaction between the processes. The controllers determine the duration of the processes; the highest controller determines the total simulation time. The tree for the calibration runs is made as follows (Figure 4-5):

- A flow node (1), that runs until the flow has adjusted to the bathymetry, after which the sediment node is ran.
- A sediment node (2), calculating sediment transport and bed levels. This also runs once, updates bed levels and time, after which another step with the flow node is made. This alternation goes on until the end time is reached.

The tree used for the simulations (Figure 4-6) uses two flow nodes, of which the first (1) is used to obtain a stable flow solution after a change of discharge, so the second (2) can be shorter in order to speed up the flow calculations in steady state. Annex 4 contains the morf input file matching this tree.

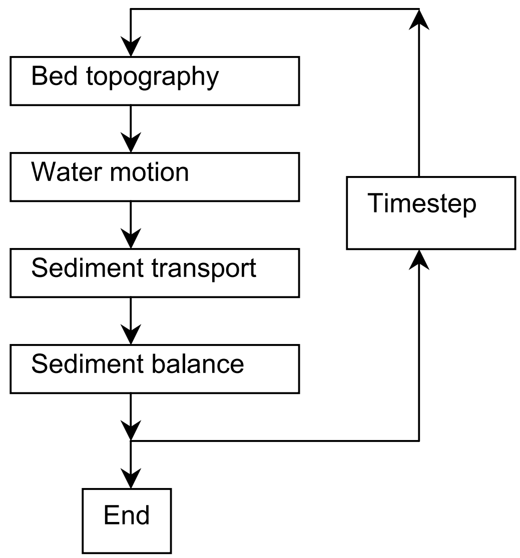


Figure 4-4 Simulating the interaction between hydrodynamics and morphology.

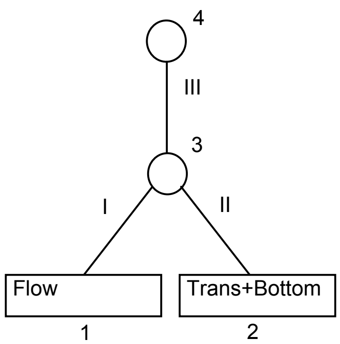


Figure 4-5 The simple MOR-tree for low or high discharge.

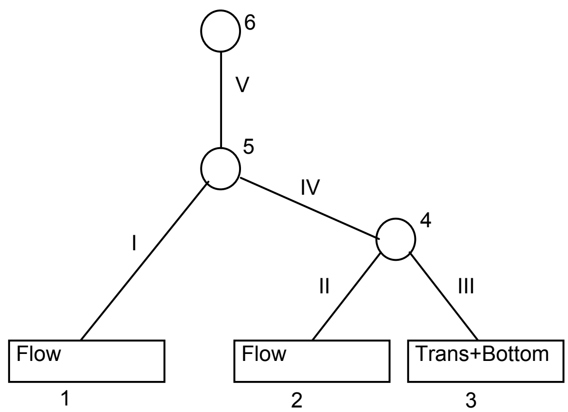


Figure 4-6 The simulation MOR-tree for varying discharge.

Node 1 runs a number of times for a simulation period of 60 minutes until a stationary solution is obtained (here the criterion is that the flow velocity difference between two runs is less than 1%), with a maximum of 20 times. After this, node 2 runs only 30 minutes, followed by the calculation of transport and bed topography. During this calculation Delft3D uses a continuity correction to calculate new flow velocities based on depths only; the flow is not diverted to other cells. Therefore this period can not be too long; one day (1440 minutes) is considered reasonable. After these 1440 minutes, the time is updated and the exact flow field is calculated again in node 2. It is possible to other stop criteria like bed level accuracy or relative flow velocities, which might speed up calculation time, but this is troublesome with the exchange of data between high and low discharge runs.

However, when some research scenarios results were compared to the calibration results it seemed that some morphological changes occurred remarkably slow: at about half the expected rate, which indicated a difference in time administration. Rerunning a calibration run with a MOR-tree used for the research scenarios confirmed this assumption. After checking the input files, the difference turned out to be a result of a different ratio between the execution times of the flow- and transport modules. For calibration a ratio of 60 minutes flow versus 1440 minutes transport was used, whereas this was 30 minutes versus 1440 minutes for the research simulations. This

change was made to accelerate calculation and it was not expected to affect morphological changes.
Since the results of the research scenarios at first seemed correct, the error was encountered very late, after most runs and interpretations had already been made. Comparing these results with those of a scenario similar to the reference scenario but using the time administration from the calibration runs shows the main difference is indeed the rate at which changes occur, and not the size or position of morphological entities. Therefore it was decided to retain the results and conclusions originally obtained, in combination with describing the results of the reference scenario at calibrated time administration. The latter has been done in Section 5.5.

4.4 FLOW calibration

Oscillations and other abnormalities

The first phase during calibration is checking whether the calculation remains stable and converges to a realistic solution. The simulation should neither show oscillations, very high flow velocities nor water on areas that remain dry in reality. Some errors were encountered, which meant adjustment of time step and bathymetry. Adjustment of boundary conditions or numerical parameters did not seem necessary.

Water level gradient

The downstream boundary of the model is situated 39.5 kilometres downstream from Svetliy Yar and 30 or 34 kilometres (the river has two channels here) upstream from Kameniy Yar. These are the two closest hydrological stations. Water level data for the year 1997 (on which the model discharge is based) are available from both stations. With these data the average gradient during the low and high discharge is calculated: 3.8×10^{-5} and 4.5×10^{-5} respectively. This gradient is used for calibration of the roughness.
Since the model area has a length of 13 kilometers, the difference in water levels between the up- and downstream water levels must be 50 cm for the low discharge and 59 cm for a flood. The k roughness values as calculated using the Van Rijn (1984c) roughness predictor were adjusted to 0.42 m and 0.05 m (low-high) for the deep parts and 0.25 and 0.035 m for the shallow parts. These values correspond to a Chézy roughness of 48 and 45 $m^{1/2}/s$. The roughness of the vegetated areas was not adjusted.

Accuracy

In order to check the general accuracy, a simulation is made with half the time step. The results are similar to the standard timestep. Another accuracy check would be halving the grid cell size, but since this is a very time-consuming operation it was not carried out.

4.5 MOR calibration

Calibration of the morphological part of the model is much more complicated than it is for the hydraulic model, partly because more processes are involved, and partly because errors in the flow model only become clear by the faults they cause in the morphological behaviour. The main medium of calibration is a check of the bed topography and especially the position of the scroll bar because this is the main field of interest and can be checked with the most accurate information. Most calibration runs are made for a period of about 100 weeks with only a high

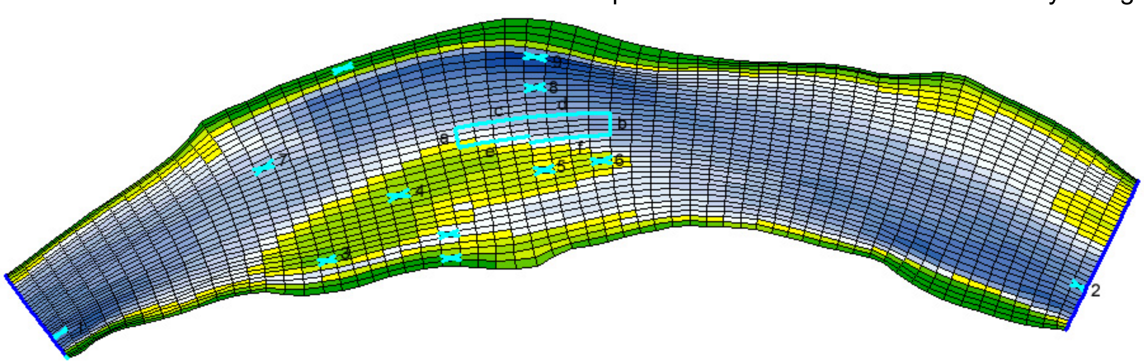


Figure 4-7 Model observation points (numbers) and cross-sections (letters).

discharge; this compares to 20 years with a yearly flood period of 5 weeks. The accuracy and repeatability of one run have been checked by making the same run once again with half the time step; this showed no differences.
The bed level, flow velocity and sediment transport are monitored with the aid of so-called observation points and cross-sections; the location of these is presented in Figure 4-7. The cross-sections however did not provide useful information since the position of the scroll bar in time is not entirely within the area.
Since many calibration runs also provided interesting information about morphological changes, they are described in Chapter 5 together with the results of the research simulations. Obviously those results are still used for calibration as well. The only parameters discussed here are the coefficients of the transport formula.

Alpha; coefficient for transport magnitude
One of the parameters most clearly influencing the morphological processes is the alpha coefficient in the transport formula. This parameter has no physical background and therefore has to be estimated. It mainly affects the sediment transport rate, thus the rate at which the morphology changes, and not the height or location of terrain characteristics. However, when using the Van Rijn formula a small error can be expected since bed- and suspended load are calculated separately, and Delft3D applies the alpha coefficient to suspended load only.
The right value for alpha is determined by comparing the height and position of the scroll bar and other entities in time with those on the satellite images. This way, a value of around 10 was found appropriate. Determining this factor more accurately is difficult because the rate of changes also depends on other factors.

Xi; hydraulic roughness
The Xi-factor in the same Van Rijn formula functions as a parameter for the hydraulic roughness. This means it represents a physical entity, nevertheless it is difficult to determine the right value. Studying its influence by means of a spreadsheet shows it only affects suspension transport, and that this is not very sensitive for the value of ξ around the value of 0.2 m. This value was chosen because it about equals the roughness height determined by flow calibrations.

The values of all other physical parameters have been derived either by measurements or by calculations and are considered correct. For the values of numerical parameters except the smoothing time the default values of Delft3D have been used. An overview of the parameters eventually used can be found in Section 4.7.2.

4.6 Sensitivity

The sensitivity of the results for the hydraulic boundary conditions is studied by varying these within reasonable limits. Both up- and downstream boundary conditions are not exactly known, and probably have a major effect on processes in the model area. This also applies to other parameters like the hydraulic roughness and the corresponding water level gradient. However, the hydraulic roughness of vegetation and its effect on morphology is subject of this studies, and the water level gradient is not an independent parameter. Besides the boundary conditions, also the sediment grain size is varied.

Water level
At the downstream boundary the water level is varied one meter with respect to the original water level of 6 meters while the discharge remains 27,000 m^3/s.

With a downstream water level of 5 m (Figure 4-8a) the decline in water level is 1,1 m, which is almost twice the original value. Also flow velocities and therefore sediment transports are higher.

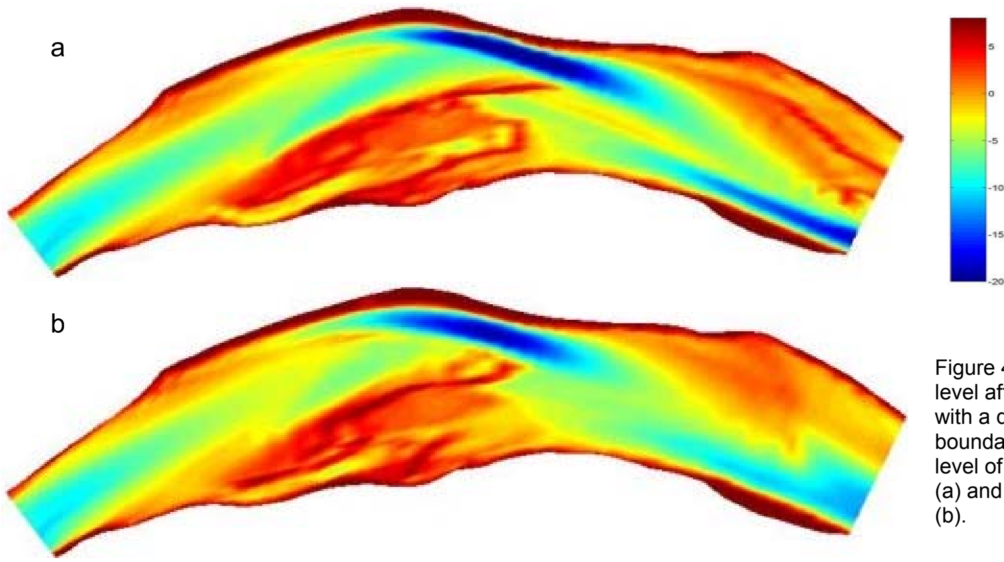


Figure 4-8 The bed level after 66 weeks with a downstream boundary water level of 5 meters (a) and 7 meters (b).

This shows itself in the rate at which changes occur: the morphological activity is certainly higher, not only as far as the scroll bar is concerned, but also the high water channel is more active. The scroll bar that forms initially consists of a few smaller parts, but these grow together to a thick scroll bar in a later stage. The main channel is deeper (the water depth is almost 30 m) and narrower, the flow is more concentrated in the channels.

For a downstream water level of 7 m (Figure 4-8b) the water level decline is 50 cm initially, which is less than the original value of about 60 cm. The flow velocity is slightly lower (1.9 m/s vs 2.1 m/s at point 7 in case of the lower water level), as is the sediment transport (around 20% less). The scroll bar consists of two separated parts. The main channel is less deep (just up to 20 m) and there is more flow on the banks. Large parts of the point bar grow higher than they would with lower water levels.

This study showed that the bed topography obtained with a water level of 5 m showed more resemblance to the actual situation than the original simulation. Additional simulation with a water level of 5.5 m seemed to give the best results, therefore the choice is made to use this as the downstream boundary for further simulations.

It can be concluded that the height of the downstream boundary is of major importance to the results, though the result is not very sensitive for small variations in the region around the chosen value of 5.5 m.

Discharge

The upstream boundary discharge at high stage is calculated at 27,000 m^3/s, so 24,000 m^3/s (Figure 4-9a) and 30,000 m^3/s (Figure 4-9b) seem reasonable alternatives regarding the data (Section 4.3.4). The discharge during low stage is not varied because the morphological activity during low discharge is small. In order to rule out effects caused by an incorrect downstream boundary, the water level there (originally 5.5 m) is ajusted to the discharge according to $Q \sim h^{3/2}$: the water levels are 5.1 and 6.0 meters respectively.

With the high discharge changes occur faster, and some changes occur in a different manner: the high water channel is more active, the scroll bar more elongated and narrow, the point bar becomes higher and the first part of the point bar accretes more towards the channel. The latter seems to be a result of a concentration of the flow at the left bank, since the bar that exists there at lower discharges is less distinct now. The gradient initially does not vary remarkably between the two simulations: it starts at about 75 cm, rising upto 90 cm for the low discharge and 1.2 m for the high discharge. However, since changes occur slower in the first case, and the rise has not

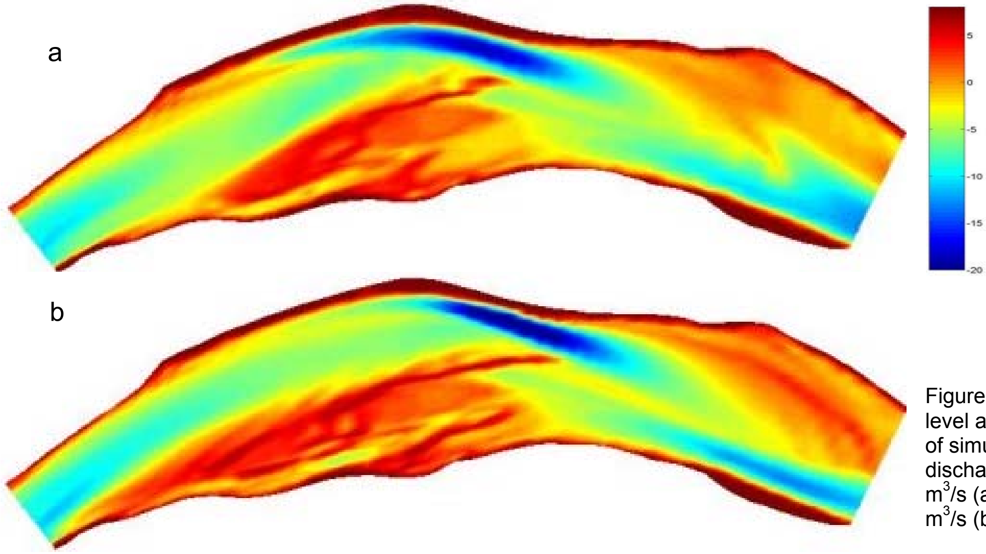


Figure 4-9 The bed level after 122 weeks of simulation for a discharge of 24,000 m^3/s (a) and 30,000 m^3/s (b).

ended at the end of the simulations, this is not necessarily significant. The values of sediment transports and bed shear stresses generally differ around 25%, depended on time and location. All things considered, these outcomes give the idea that these discharges are the boundaries between which the model functions without becoming unrealistic, and that the best fitting results are obtained with an intermediate discharge. It is also clear that an error upto 2000 or 3000 m^3/s in the magnitude of the discharge is not crucial to the results.

Grain size

The sensitivity with respect to the sediment grain size is studied by taking a D_{50} of 0.27 mm (instead of 0.40 mm). Since the transport formula also requires input of the particle fall velocity and the D_{90} these are adjusted accordingly, to 0.039 m/s and 0.45 mm respectively . The lower grain size value is based on the grain size of sand on the point bar, whereas the original value is that of the sediment in the channel. The sensitivity for larger particles is not studied since these are not found.

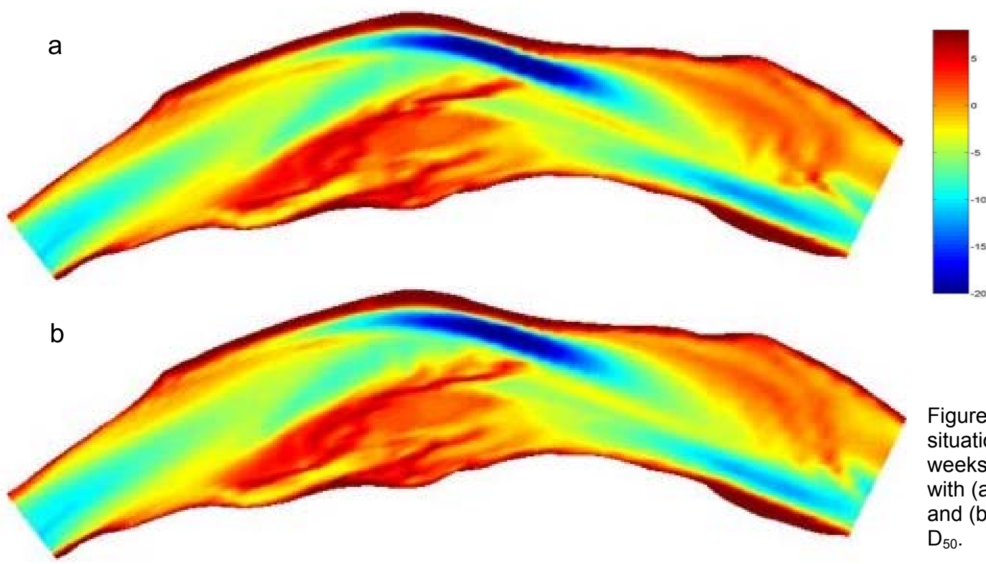


Figure 4-10 The situation after 53 weeks of simulation with (a) a small D_{50} and (b) the normal D_{50}.

The difference in bed topography between the different grain sizes at first is small if one takes into account that the changes in the simulation with a smaller grain size occur faster: the bed topography of 11 months simulation with large grains looks quite similar to that of 9 months with the smaller grain size. The development of the water level gradient and the bed level in several

points is also remarkably similar. An important difference however is the development of the scroll bar. At the beginning both simulations show a bar followed by smaller depositions (Figure 4-10), but after a while the bar with the finer sediment seems to have a ‘finer’ shape as well: it is a little slimmer and smoother than the bar in the standard D_{50} simulation. Whichever of these compares best to reality however is difficult to say.
Together, the results indicate a minor sensitivity for the sediment grain size, except for the scroll bar shape. One should realise however that only the direct influence of the sediment size on transport is studied and not the effect of smaller grains on bed forms, which can be very important since bed forms influence both flow and sediment transport.

4.7 The reference scenario

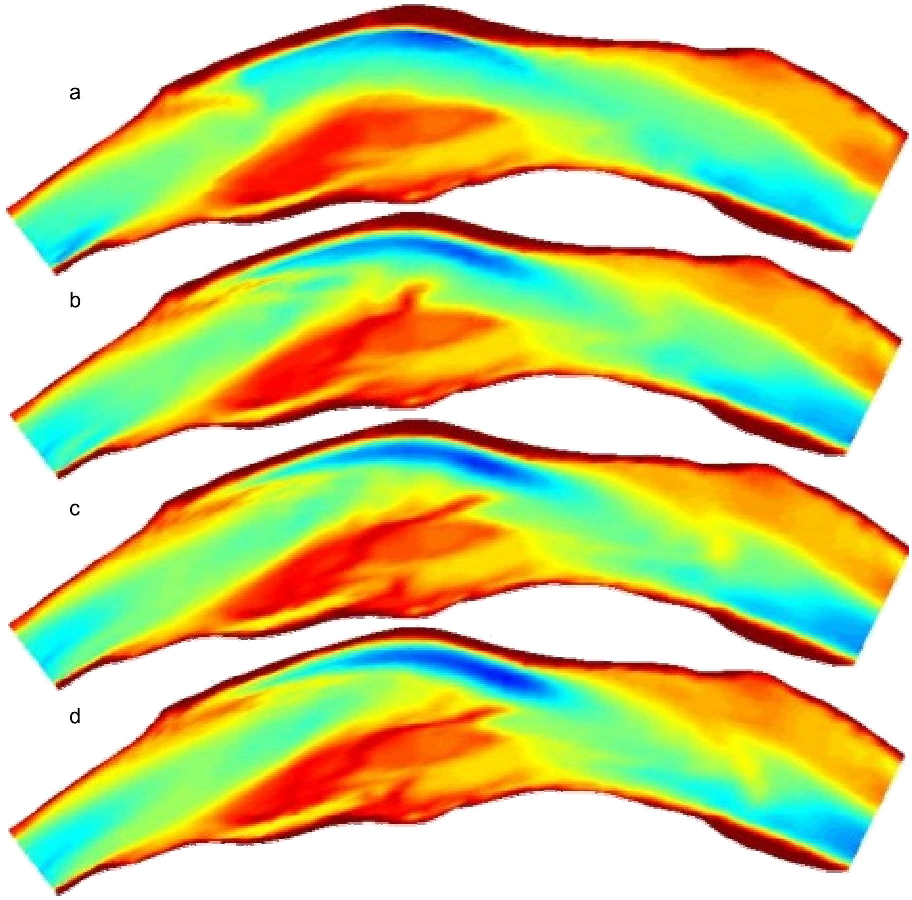
After all calibration adjustments the reference scenario is made. This has a varying discharge, and both vegetation and outer bank positions are updated in 1991 and 1996. It runs from 1986 until 2002. Here the developments in time are described and quantified if possible, and an overview of the input parameters is given.

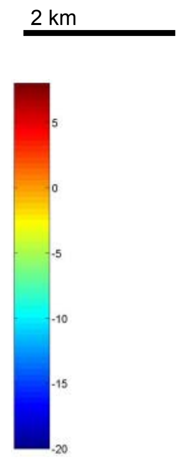
4.7.1 Development in time

Figure 4-11 shows the bed topography for the years 1991, 1996 and 2002, the flow pattern in 2002 and sediment transports during floods and low discharge. Graphs of the bed level in the points 3, 4, 5 (point bar) and 7 and 8 (main channel) can be found in Annex 5 together with those of the other scenarios. Annex 6 shows the depth averaged flow velocities and sediment transports at the observation points.

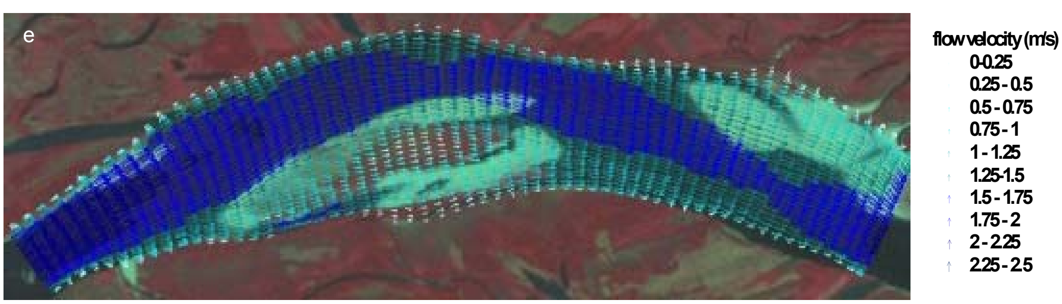
- The scroll bar remains small, slim and close to the point bar. Its tip does not pass the end of the point bar, and the channel between point bar and scroll bar tip remains several hundreds of meters wide. The eventual height is around 5 m, which is very well comparable to reality.
- The outer bank position is updated in the years 1991 and 1996 just before the flood. In 1991 it was updated about 20 m, and in 1996 30 m to catch up with the real erosion of 150 m in these ten years. Values are measured at the point of maximum erosion.
- The point bar seems to be almost continuously raised. Although at point 4 the point bar initially erodes some 50 cm, but later this point accretes from 3,4 m to 3,6 m. At point 3 the bed level is raised from 5,3 to 5,6 m, a little slower in the last years. At points 5 and 6 in the densely vegetated area the sediment transport is too low to cause more than one millimeter of accretion.
- The high water channel is not very active: The first –narrow- part becomes a little deeper and wider, and in the middle –where it widens- accretion occurs. At the downstream part practically no activity is observed.
- The maximum channel depth reached in the bend is 16 m, which is less than reality (19 m). Nevertheless this means a deepening of more than 2 m.
- The decline in water level between up and downstream boundary increases a little over the years: from 71 to 74 cm during low water and from 78 to 82 cm during floods. This indicates the model is in a dynamic equilibrium unlike the constant discharge runs, where the change is much larger.
- Flow velocities in the main channel (point 7) are around 1.9 m/s, in the densely vegetated area (point 6) they are 0.2 m/s, and in point 4 they change from 1 m/s to 0.6 m/s when the area becomes more vegetated.

In general, the developments of the bed topography seem to be smaller than in reality: the scroll bar remains small, the channel does not get much deeper and the point bar height is small too. The height reached at point 3 is close to reality (5.5-6 m), but the other points remain lower than reality: the actual height of point 4 is around 5-6 m, and points 5 and 6 have a height of 3-4 m. Also the activity in the high water channel is much less: the chute bar at the end of the channel that formed in the real bend does not develop at all, only the first and middle part of the channel are active.

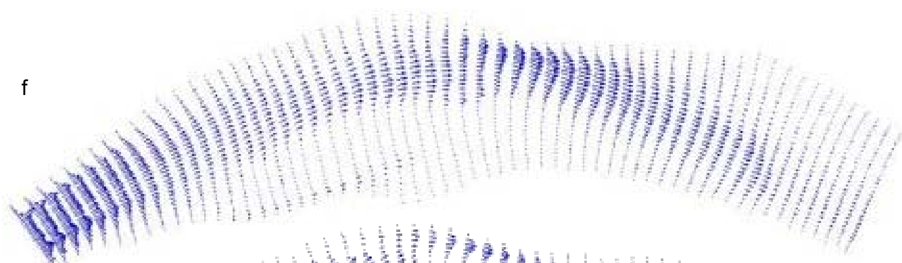




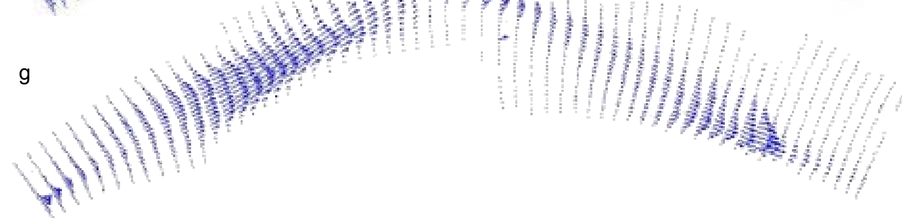
The bed levels in the years 1986 (a), 1991(b), 1996 (c) and 2002 (d).



(e) Depth averaged flow velocities and directions on the 2000 image.



(f) The sediment transport during flood in 2002.



(g) The sediment transport during low discharge in 2002 (scale differs from (f)).

Figure 4-11 The results of the reference scenario.

4.7.2 Numerical and physical parameters

In all cases the default values of the numerical parameters are used. These can be found in the prints of mdf- (flow), md-tran- (transport) and md-bott- (bed topography) files in Annex 4. The physical parameters are listed in Tables 4.1 and 4.2. The computation time with a grid of 61x37 cells amounted 65 minutes for 47 weeks at a low discharge and 8 minutes for 5 weeks for floods on an 1,8GHz/256 MB RAM PC.

Table 4.1 Parameters varied according to discharge.

Parameter	Low water	Flood
Discharge (m^3/s)	5,500	27,000
Duration (weeks)	47	5
Water level downstream (m)	0	5.5
Representative Chézy value ($m^{1/2}/s$)	48	45
Water level gradient (-)	$5.5x10^{-5}$	$6.3x10^{-5}$
Timestep (s)	120	60

Table 4.2 Constant parameter values.

Parameter	Value
Water temperature (°C)	15
Salinity (ppt)	0
Water density (kg/m^3)	1000
Kinematic viscosity (m^2/s)	$1x10^{-6}$
Alpha (-)	10
Xi (m)	0.2
Particle fall velocity (m/s)	0.061
D90 grain size (m)	0.00057
D50 grain size (m)	0.0004
Sediment density (kg/m^3)	2650
Sediment porosity (-)	0.4

4.8 Discussion

Building a model is very much a cyclic process: this not only becomes clear during the calibration phase by repeatedly testing small adjustments, but also during the earlier phase of construction, when one is often confronted with choices made during preparation. During prepararion however, it is difficult to assess all consequences of decisions. Therefore experience with modelling is very useful, and help of experienced modellers is much appreciated.

When reviewing the preparation with the knowledge obtained by modelling, mainly the data collection requires attention. The model shows to be very sensitive to the correct bed topography and downstream boundary waterlevel height, and it was difficult to rule out the disturbances in the first part of the model area. If this was known in advance, more attention could have been paid to gathering data like flood marks and the bed topography of the river upstream during the fieldwork. The lack of reliable bed topography data of earlier years also adds to the inaccuracies in the bed level, but this cannot be overcome with a better preparation.

During calibration it becomes clear that the choice of the grid strongly limits the choices that can be made, since all important information (like bed topography, bottom roughness and boundary conditions) is stored with respect to this grid. This is also the reason that the grid cell size is not halved to check the accuracy, though it seems a useful check, especially since the grid showed to have a direct effect on the results. The choice of the sediment transport formula seems to be right because no problems with large transports in vegetation are observed, although this might not have happened with an other transport formula neither.

Furthermore, the calibration itself of a two-dimensional morphological model is difficult. Firstly because the relationship between a parameter change and the resulting morphological change is non-linear and difficult to predict. Secondly, because it is difficult to verify changes exactly. The latter has two causes: the lack of verification data and the variations in both time and space. The velocites measured at one location during the last fieldwork are not useful for calibration purposes. For values much higher or lower than 1 the calibration coeffient alpha influences not only the rate of changes but also the shape of morphological entities because it only applies to suspension transport and not to bed load transport. Especially the shape of the scroll bar is susceptible to this effect.

Nevertheless, it is found that the reference model, after many adjustments, resembles reality sufficiently to be used for the simulations aimed at studying scroll bar formation. With a long period of further trial-and-error it might have improved further, but this is not the object of making the model. The sensitivity study shows the model is sensitive to the downstream boundary water level height, but quite insensible to the sediment grain size and applied discharge. The difference between the eventual water level gradient and the calculated one is rather large, which might be a matter of concern. Nevertheless, the developments shown by the model correspond with reality quite well, thus indicating the eventual value may be closer to reality than the one calculated initially.

5 Simulations and results

Since the many runs made for calibration also provide interesting results about factors influencing scroll bar formation and other morphological processes, some of these runs are discussed in this chapter too. After this, the simulations made specifically to test the hypotheses –the influence of outer bank erosion and of point bar vegetation, respectively- are discussed. Also some simulations to study the effect of Cyclic Floodplain Rejuvenation measures were made. These are described in Section 5.5. The chapter concludes with a general discussion of the simulations and results.

5.1 Calibration simulations

The starting-point for all calibration simulations is the scenario based on the calculations and assumptions made in the previous chapter. In general, the calibration simulations are made using only the high discharge and without adjusting the position of the outer bank manually. The steady discharge is used because the largest transports and therefore the most important changes occur during high stage, and it reduces the computation time to about 1/6 of a simulation with a varying discharge. The outer bank position is not adjusted during simulation because the calibration simulations had to show whether this is necessary or not: the channel width is already adjusted in the starting situation.

5.1.1 Discharge distribution

The distribution of the flow over the 37 cells of the upstream boundary affects the morphology in the first part of the model largely. If the discharge per grid cell is applied in proportion to the cell width and height, initially the velocities and spiral flow intensities at the right side are very high, which results in accretion of that side. After some time this accretion almost blocks the flow, resulting in a very unreal flow and bed topography. Distributing the flow more equally (i.e. more to the left) gives a more realistic pattern, though in most cases the entrance of the high water channel and the first part of the point bar tend to accrete (see e.g. Figure 4-11).

5.1.2 Bank full discharge

The bank full discharge is often regarded as the discharge determining morphology. Therefore it is interesting to see what happens if this discharge is used in the model. Cormont and Van der Sluis (2002) calculated a bank full discharge of around 13,000 m3/s. The downstream boundary water level is adjusted to this discharge according to $Q \sim h^{3/2}$, which gives a *h* of 3.7m. In the

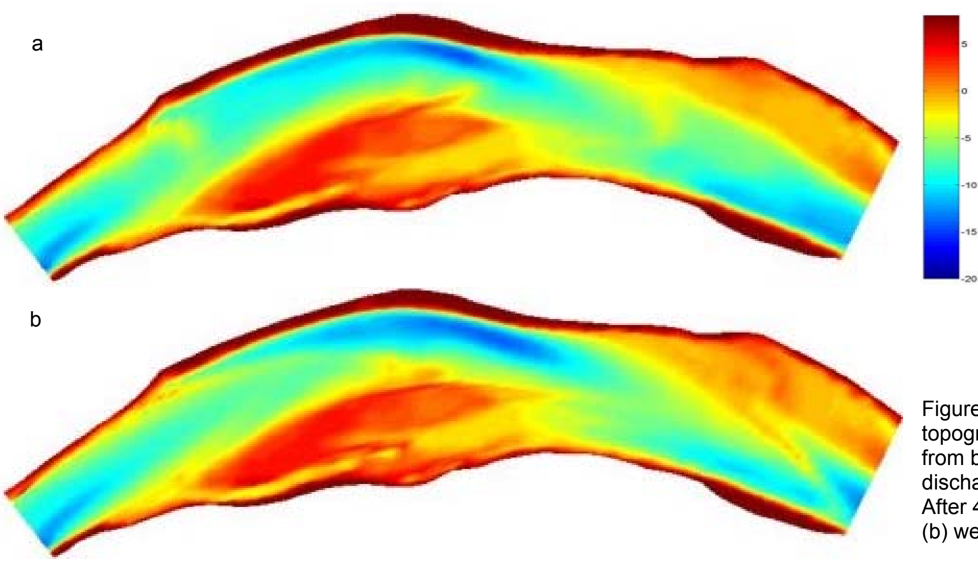


Figure 5-1 Bed topography resulting from bank full discharge simulation. After 47 (a) and 173 (b) weeks.

model this results in a very small and thin scroll bar that quickly becomes completely attached to the point bar, see Figure 5.1. Changes occur much slower if compared to a high discharge: about three years versus six months.

5.1.3 Varying discharge

All simulations with only a high discharge have one thing in common: the bars formed at the location of the scroll bar are rather small, and sometimes they seem to be more like a collection of small bars than one scroll bar. This might indicate that their formation is the result of processes on a different scale than the one studied. Another explanation might be that the grid is somewhat too coarse to represent these processes smoothly. Also the absence of low water periods, which can have a smoothing influence, may contribute to such irregular shapes.
Simulations made with varying discharges (Sections 4.7, 5.2 and 5.3) indeed show a smoother scroll bar, of about the right length but a little less wide. Remarkably, the downstream part of the high water channel does not silt up with a changing discharge, whereas this does happen with a continuous high discharge and corresponding boundary conditions (like in Figure 4-8a). This might be a result of the fact that the water level gradient increases in time in simulations with a high discharge, as an adaptation to a different equilibrium. This also means water levels at the point bar are higher, and the high water channel has a higher discharge. In simulations with a varying discharge the water level gradient increases only a few centimetres in 16 years.

5.1.4 Outer bank

Simulations have been made with the original bank position of 1986 (with a width of 875 m at the narrowest cross-section) and with the outer bank position of 2002 (which is 300 m wider at the point of maximum erosion) as the initial bed level. By keeping the rest of the bed topography the same, the main channel in the latter case is much wider. In both cases a kind of scroll bar develops in a similar way. In both cases first a small bar forms, which grows a little towards the outer bank. At the moment this bar becomes elongated parallel to the point bar, a second scroll bar follows the first in a similar manner. Eventually the two bars grow together. In the case of a wide bend the bars grow more in lateral direction, whereas in the case with the normal bend width the bars are moved in downstream direction at an earlier moment, see Figure 5-2a (wide) and Figure 4-10b (normal).

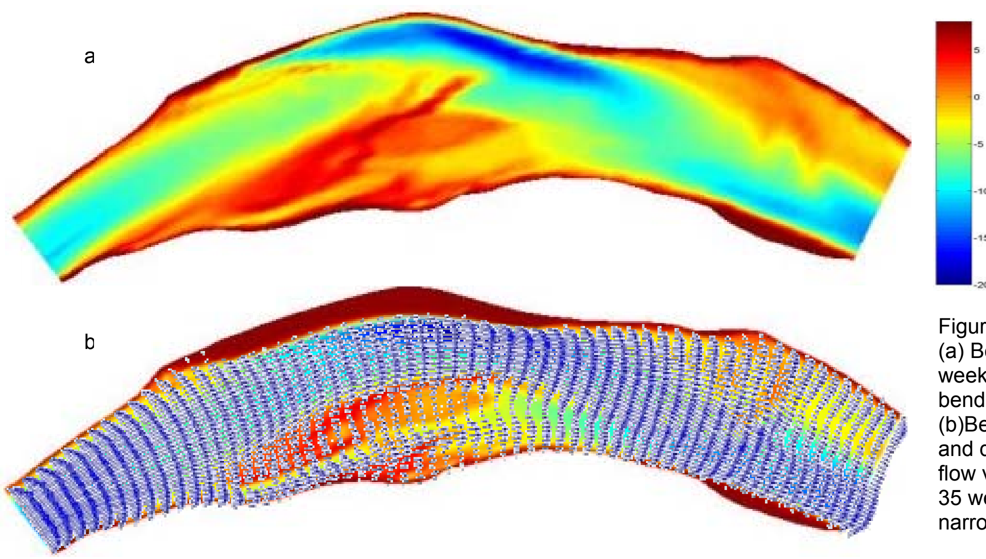


Figure 5-2
(a) Bed level afer 52 weeks for a wide bend.
(b)Bed topography and depth averaged flow velocities after 35 weeks for a narrow bend.

Also simulations have been made with a very narrow bend (the mimimum width is about 700 m) and with an outer bank fixed in the 1986 position. In both cases erosion of the main channel bed and deposition on the point bar are less than in the normal situation, and the scroll bar is smaller. In the simulation with the very narrow bend the scroll bar is also very narrow and stays close to the point bar. It clearly consists of one piece only and its tip passes the downstream end of the point bar quickly. One should notice that in reality no scroll bar has formed in such a narrow channel, but only after the channel has widened considerably. If the bend is fixed the scroll bar develops more towards the main channel and less quickly in downstream direction. Now the first part is followed by some smaller parts.

5.1.5 Bed topography

Obviously a correct bed topography is of major importance. Early simulations show large sediment transports in the first part of the model area, which after some time interfere with the morphology in the area of interest. After several years a more stable situation is achieved. This problem is solved by replacing the original bed topography of the first two to three kilometers by that of the stationary situation.
Also a very simple point bar and an artificially created scroll bar have been applied. The simple point bar was flat, its roughness did not vary spatially and its contours followed a smooth line through the contours of the point bar in 1986. This simple point bar was distorted quickly. The same applies for the artificial scroll bar, which was based on the position of the scroll bar in 2002 and had a height of 2 meters. In the simulation, with a wide outer bend, it is split into several smaller bars and washed away.

5.1.6 Grid

Many early simulations showed a very deep hole at the right side of the channel at the inflow boundary (Figure 5-3), and also a strong secondary flow although there is no bend in the model. This turned out to be a result of the non-orthogonality of the grid: in this area the orthogonality was around 0.07 whereas for the rest of the grid it is around 0.02, which is regarded as a good value. After orthogonalizing the grid again, the orthogonality nowhere exceeds 0.02. Comparing Figure 5-3 with for example Figure 5-2, in which the newer grid is used, clearly shows the effect

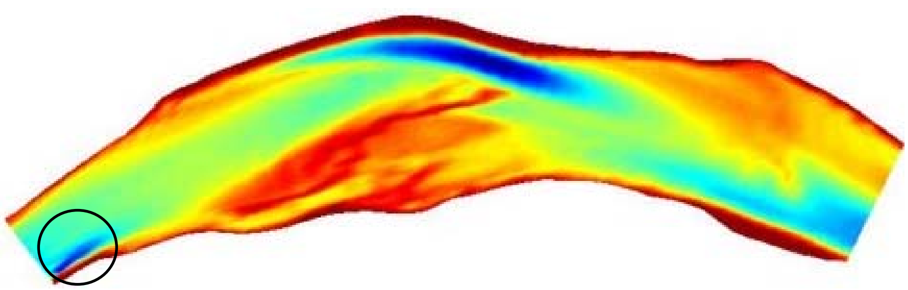


Figure 5-3 A scour hole (encircled) resulting from the non-orhtogonality of the grid.

of this change; discharge distribution and initial bed level are the same. With the improved grid the secondary flow intensity is about a quarter of its earlier value, and its direction is reversed. Instead of the deep channel scour, now accretion occurs on the right side. To what extent this occurs also depends on the distribution of flow over the upstream boundary (Section 5.1.1).

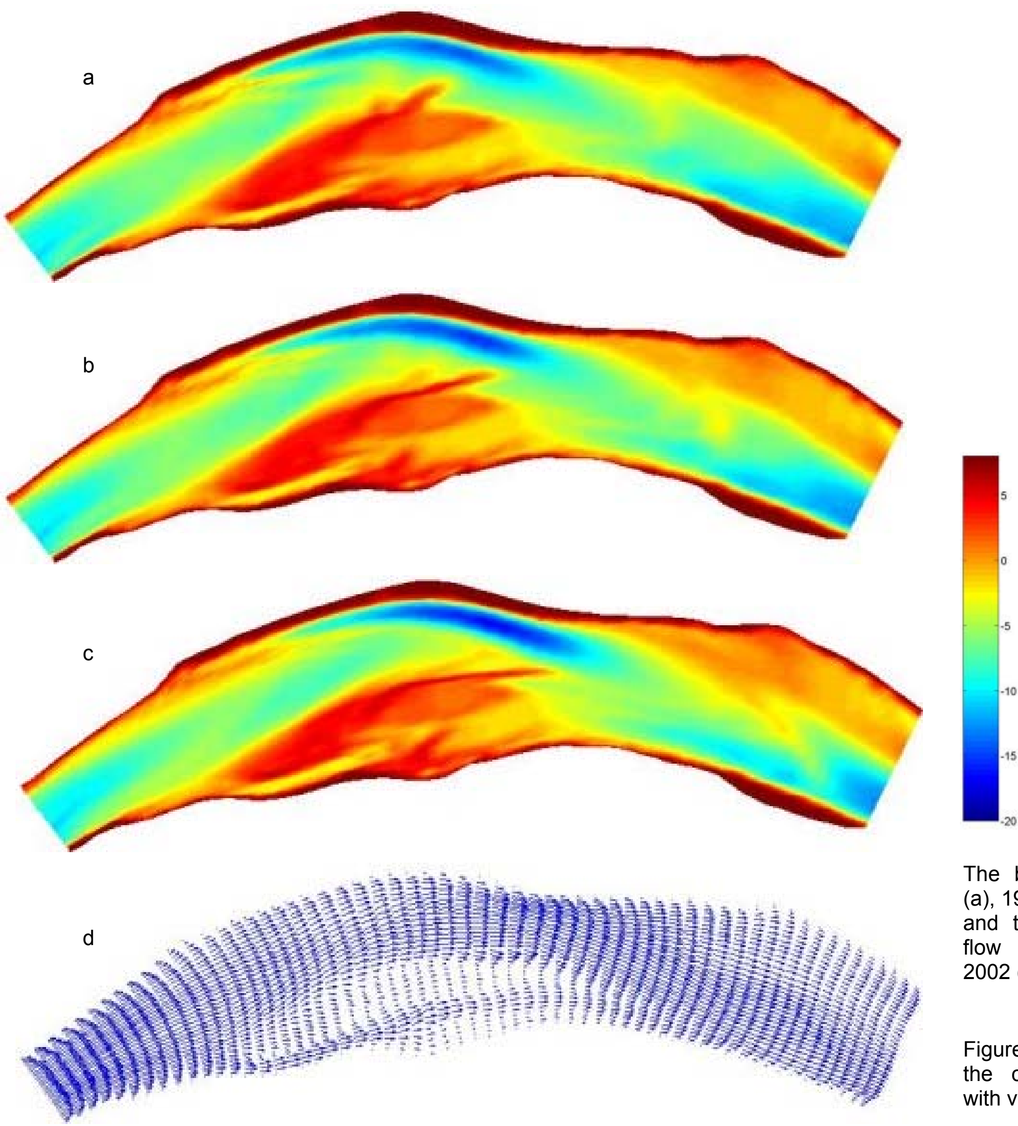
5.2 Influence of outer bank erosion

Already during calibration it became clear that the position of the outer bank strongly affects the development of a scroll bar. The origination itself of a scroll bar does not seem to depend on the outer bank position, unlike the further development. This means the reason for the origination of the scroll bar probably should be looked for somewhere else, like for example the upstream discharge distribution and sediment transport or the sudden kink of the point bar at the origin of the scroll bar.
In order to study the influence of the position of the outer bank on the development of the scroll bar in the model, the following scenarios are used:

- *The reference scenario*, in which outer bank position and vegetation are updated according to the actual situation every five years. The results are described in Section 4.7;

- *1986 vegetation*, in which the vegetation is updated in 1991 and 1996 as described in Section 3.2, but the outer bank position is not;
- *1986 continuous*, which runs continuously without any update of vegetation or outer bank position.

The outer bank position is updated by locally changing values in the depth points file, the vegetation is updated by replacing the roughness file. All three scenarios use the same initial bed level, boundary conditions and parameters as described in Section 4.7. The last two simulations are made to distinguish between the effect of vegetation and autonomous morphological developments. First the results of the scenarios are described, second these results are compared.



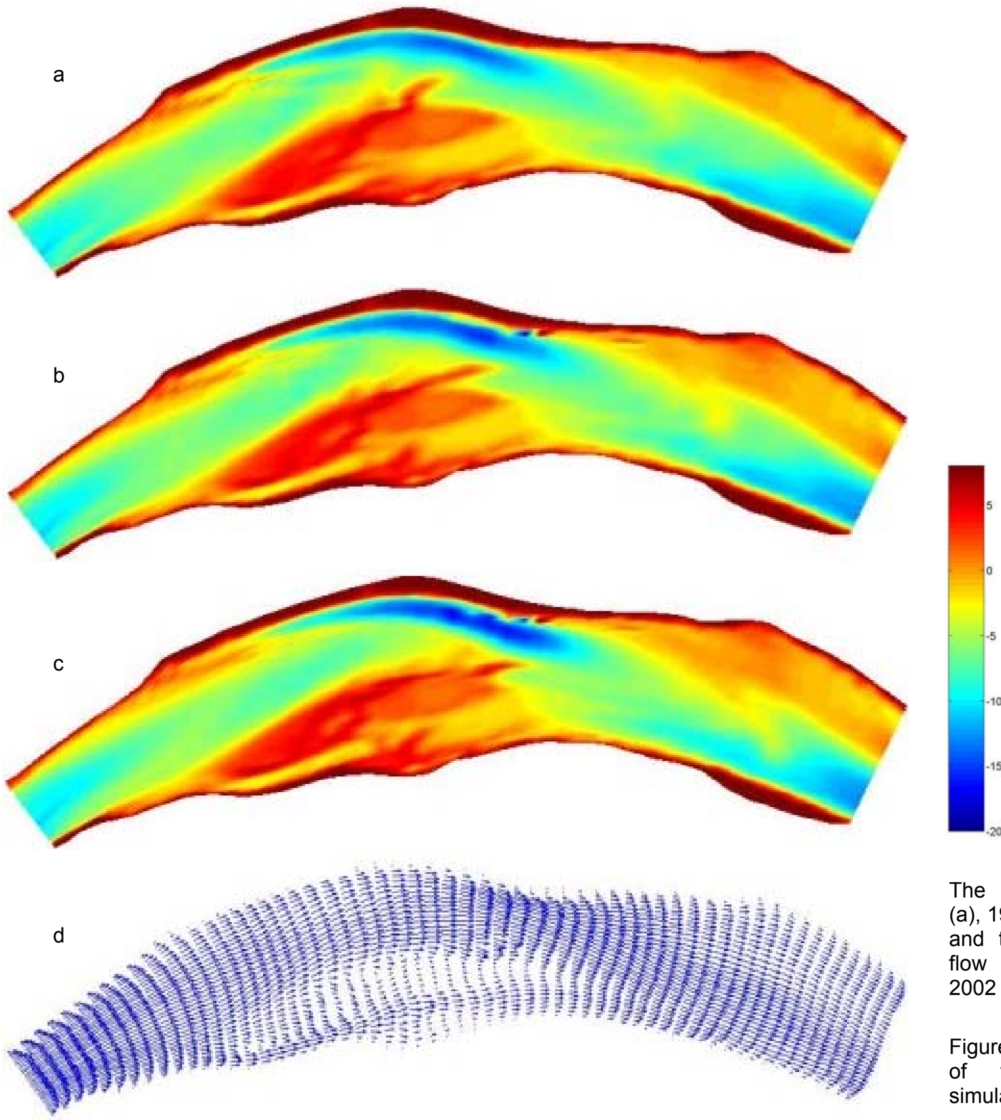
The bed levels of 1991 (a), 1996 (b) and 2002 (c), and the depth averaged flow velocity vectors of 2002 (d).

Figure 5-4 The results of the continuous simulation with vegetation update.

5.2.1 1986 vegetation

Figure 5-4 shows the bed level of the years 1991, 1996 and 2002 and the depth averaged flow velocities of 2002.

- The scroll bar is very long, thin and close to the point bar; more than in the reference situation.
- The outer bank mainly seems to erode in the first years of the simulation. Overall outer bank erosion is less than in the reference scenario.
- Point bar height: Point 3 is raised from 5.3 m continuously up to 5.7 m, the bed level at point 4 first is lower 50 cm to 3.4 m until 1991, after which it increases to 3.8 m in 2002. The changes at points 5 and 6 are very small.
- The high water channel is not very active: The first –narrow- part becomes a little deeper and wider, and in the middle –where it widens- accretion occurs. At the downstream part practically no activity is observed.
- The main channel does not become deeper than 16.5 m, which is reached at the end of the simulation. This is half a metre deeper than in the reference situation, but less deep than the 19 m in reality.
- The water level gradient, which can be regarded as an indication of the hydraulic roughness, initially amounts 78 cm during a flood, 81cm after the first update and 86 cm at the end. This incline is not entirely the result of more vegetation: also in a period in which the vegetation remains constant, the water level difference increases. During the low water periods the difference at first is 71 cm, later this becomes 77 cm. The increase in gradient is larger than in the reference situation, in which it amounted 3-4 cm.
- The flow velocities on the point bar are 0.2 m/s in point 3, 0.7 m/s at point 4 and 0.5 resp 0.2 m/s in the vegetated points 5 and 6. In the main channel, velocities are 1.9 and 2.0 m/s for points 7 and 8, respectively.



The bed levels of 1991 (a), 1996 (b) and 2002 (c), and the depth averaged flow velocity vectors of 2002 (d).

Figure 5-5 The results of the continuous simulation.

5.2.2 1986 continuous

Figure 5-5 shows the bed level of the years 1991, 1996 and 2002 and the depth averaged flow velocities of 2002.

- The scroll bar formed is long and thin, and followed by a shallow area. At the end of the simulation it becomes almost completely attached to the point bar. The eventual height is around 5 m, like in reality.
- The outer bank erodes very little.
- Point bar height: Point 3 becomes gradually higher; the eventual raise amounts 40 cm (2.5 cm/yr) up to 5.7 m; 10 cm more than the reference scenario. Point 4 is lowered some 50 cm to 3.4 m in the first five years jsut like the reference scenario, later it accretes up to 4.8 m (13 cm/yr), which is 1.2 m more than in the reference situation and much more like reality. The bed level in the vegetated points 5 and 6 does not change.
- The high water channel is not very active: The first –narrow- part becomes a little deeper and wider, and in the middle –where it widens- accretion occurs. At the downstream part practically no activity is observed.
- The maximum depth eventually reached in the main channel is 17 m; 2 m less than reality but a little more than in the reference scenario.

- The water level gradient during a flood amounts 78 cm at first, later this grows to 86 cm, During the low water periods it initially is 71 cm, which increases over the years up to 75 cm. This increase is somewhat larger than in the reference scenario.
- The flow velocities on the point bar are 0.4 m/s in point 3, 1 m/s at point 4 and 0.3 m/s in the vegetated points 5 and 6. In the main channel, velocities are 1.9 and 2.0 m/s for points 7 and 8 respectively.

5.2.3 Interpretation and comparison

The differences in the results from the scenario without updating outer bank erosion and that of the reference scenario show that the position of the outer bank does influence the development of the scroll bar. If the bend is wider, the scroll bar has more room to grow at some distance from the point bar. In a narrow bend, the flow directs the scroll bar more towards the point bar and in downstream direction.
The scenario without vegetation update shows the thinnest and longest scroll bar, in combination with the least outer bank erosion. Here probably the influence of vegetation on flow is too limited to divert the flow such that the outer bank erodes more rapidly, though the main channel does become deeper than without vegetation update. The fact that the outer bank now erodes less than if the vegetation grows rougher proves that the outer bank erosion is not just the result of the bend becoming sharper (see Annex 1.3).

5.3 Influence of vegetation

The calibration runs already showed some influence of point bar roughness on scroll bar development. In order to study this influence, which can be regarded as one of the effects of vegetation, the following scenarios are studied:

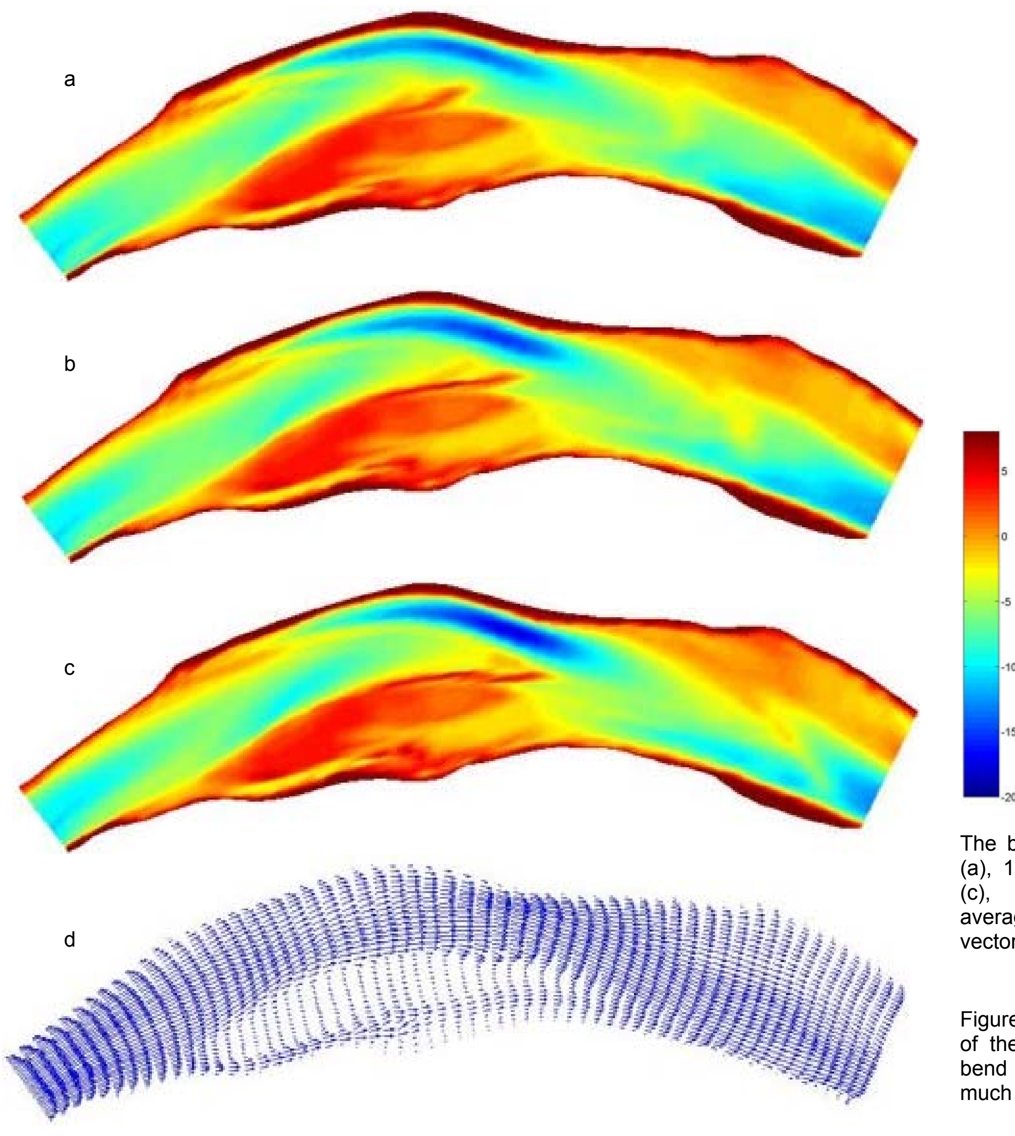
- *The reference scenario*, in which outer bank position and vegetation are updated in 1991 and 1996 to resemble the real situation every five years;
- *1986 vegetation*, in which the vegetation is updated according to reality in 1991 and 1996, but the outer bank position is not;
- *Bend update much vegetation*, in which the outer bank position is updated in 1991 and 1996, and the entire point bar continuously has a uniform roughness of k= 5 m, thus representing a densely vegetated point bar;
- *Bend update no vegetation*, in which the outer bank position is updated in 1991 an 1996, and the point bar continuously has a uniform roughness equal to the shallow areas (k= 0.035 m), thus representing a point bar of bare sand.

These scenarios can only show the effect of flow diversion on scroll bar development. The method used to model vegetation cannot simulate sediment catchment by vegetation.
The outer bank position is updated to avoid the influence of a too narrow profile on developments. Besides these scenarios also two similar scenarios have been made with much and no vegetation, but without updating the bend.

5.3.1 Bend update much vegetation

Figure 5-6 shows the bed level of the years 1991, 1996 and 2002 and the depth averaged flow velocities of 2002.

- The scroll bar that is formed is very thin and lies close along the point bar, though a small gulley between scroll bar and point bar remains. The tip of the scroll bar reaches well beyond the edge of the point bar. The height is around 5 m.
- The outer bank erodes considerably in the first ten years; in the last years erosion is minimal.
- Point bar height: Point 3, which is at the border of vegetation, slowly grows 2 cm lower. The bed level in points 4, 5 and 6, which lie in vegetated areas, does not change.
- The high water channel is not very active.
- The maximum depth finally reached in the main channel is 17 m.
- The water level gradient during a flood varies between 82 and 86 cm; during the low water periods it lies between 65 and 73 cm. In both cases it does not show a trend over a longer period.
- Flow velocities on the entire point bar are low (0.1-0.3 m/s), except for the high water channel. In the main channel the eventual flow velocities are 1.9 m/s at both points.



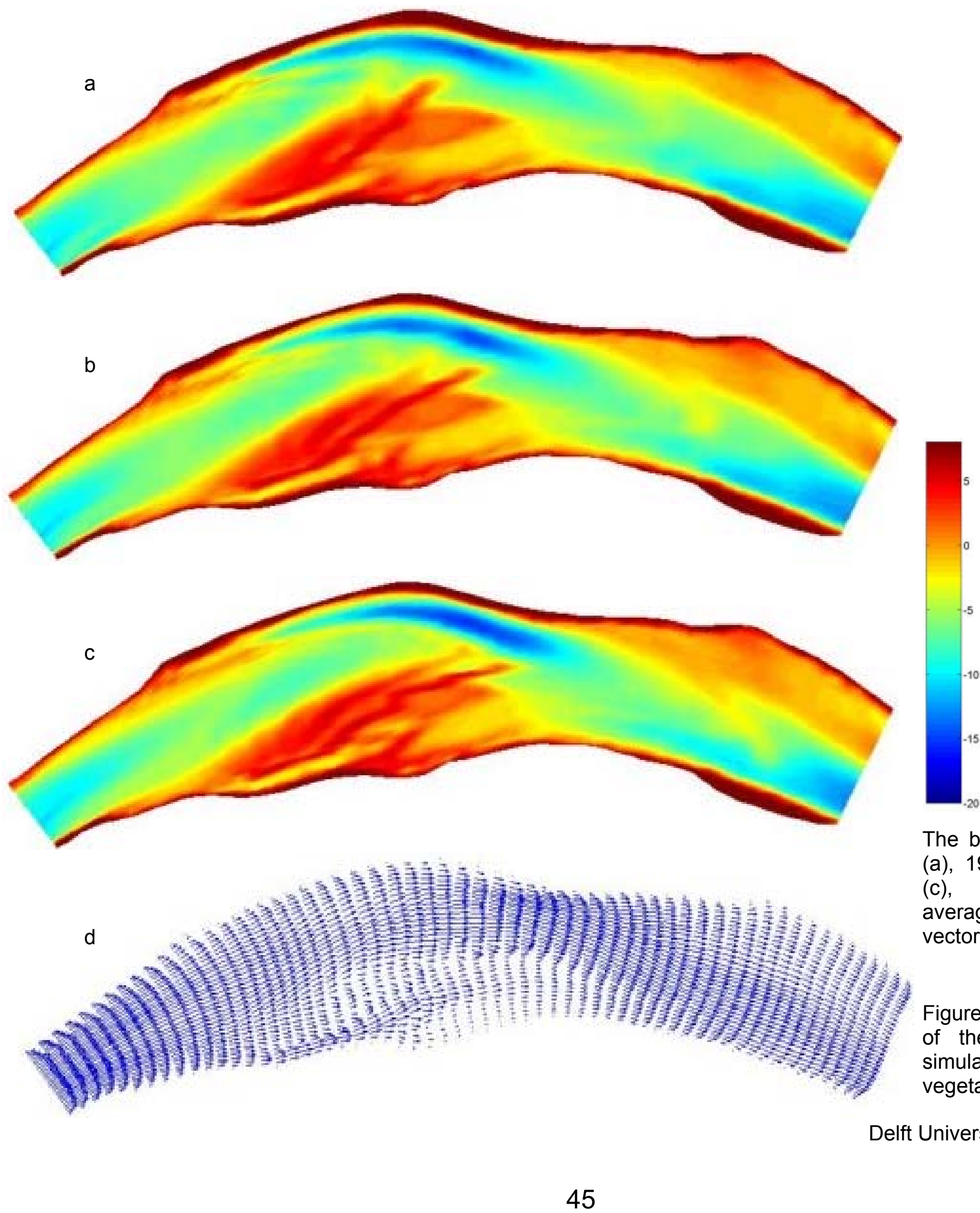
The bed levels of 1991 (a), 1996 (b) and 2002 (c), and the depth averaged flow velocity vectors of 2002 (d).

Figure 5-6 The results of the simulation with bend update and much vegetation.

5.3.2 Bend update no vegetation

Figure 5-7 shows the bed level of the years 1991, 1996 and 2002 and the depth averaged flow velocities of 2002.

- The scroll bar slides over the point bar: A high ridge, which continues in the scroll bar, is moving from left to right over the point bar. From 1997 on it is followed by a second scroll bar. Both of these are rather wide an reach far into the main channel.
- The erosion of the outer bank resulting from the model itself is small.
- Point bar height: At point 3 the bed level decreases more than half a metre, after an increase of 25 cm over the first six years. At point 4 a similar development is observed some two years later: first half a metre of accretion, than 25 cm of erosion. Now also points 5 and 6 show changes in bed level, though still small: an increase of 11 and 1 cm respectively.
- The high water channel seems to be less active than in other scenarios; more flow is diverted over the point bar.
- The maximum depth reached in the main channel is 15 m.
- During floods the difference in water level initially is 75 cm, which grows to 83 cm in 2002. For the low water periods this is 65 cm, growing to 77 cm. The increase is largest in the last few years.
- The flow velocities on the point bar are much higher than without vegetation: 0.6-0.9 m/s. Also the depth averaged velocity at the scroll bar is high. The flow velocites in the channel are somewhat lower: 1.8 m/s in point 7 and 1.9 m/s at point 8.



The bed levels of 1991 (a), 1996 (b) and 2002 (c), and the depth averaged flow velocity vectors of 2002 (d).

Figure 5-7 The results of the bend update simulation without vegetation.

The scenarios without manual adjustment of the outer bank give results very similar to those described above, see Figure 5-8 below.

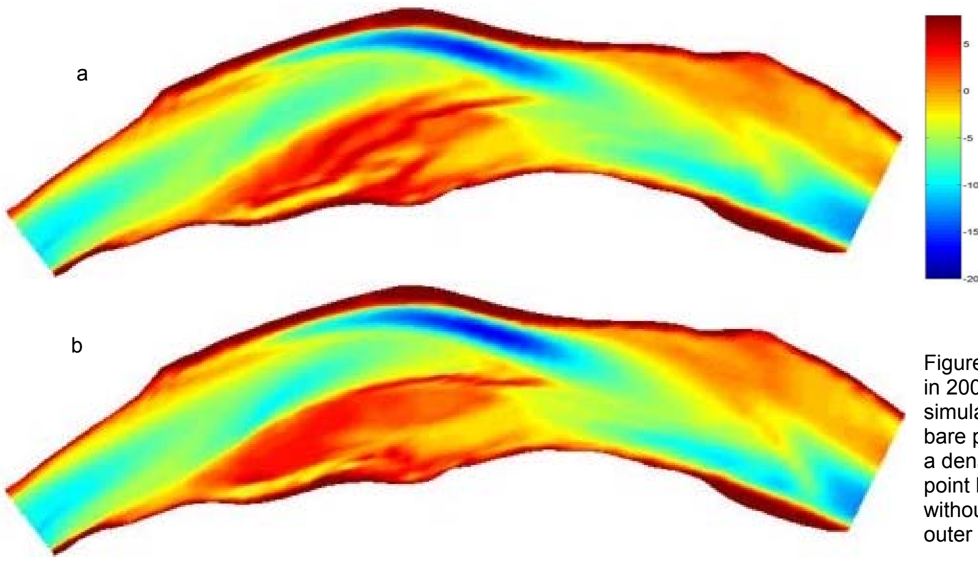


Figure 5-8 Bed levels in 2002 resulting from simulationswith a bare point bar (a) and a densely vegetated point bar (b), both without updating the outer bank positoin.

5.3.3 Interpretation and comparison

It is clear that the morphological developments are largely influenced by the effect of vegetation on the flow pattern. With a high vegetation density on the point bar, the flow is much more concentrated in the main channel and the high water channel. The flow velocities on the point bar are very low, as are sediment transport and bed level changes, which are practically zero. As a result of the concentration of flow in the main channel the scroll bar is shaped thin and long close to the point bar, and the outer bank is eroded more than in a situation with a less vegetated point bar.

If the vegetation density on the point bar is low, there is more flow over the point bar. This causes also more sediment transport and bed level changes on the point bar itself. The flow in the main channel is less strong, and therefore outer bank erosion and channel deepening are less. Also the scroll bar can be wider and it stretches farther into the channel without being washed against the point bar.

In comparison with the reference scenario it can be said that the influence of vegetation alone on the development of the scroll bar is large; with this large differences in vegetation density the effect of vegetation is more important than that of outer bank erosion.

5.4 Cyclic Floodplain Rejuvenation measures

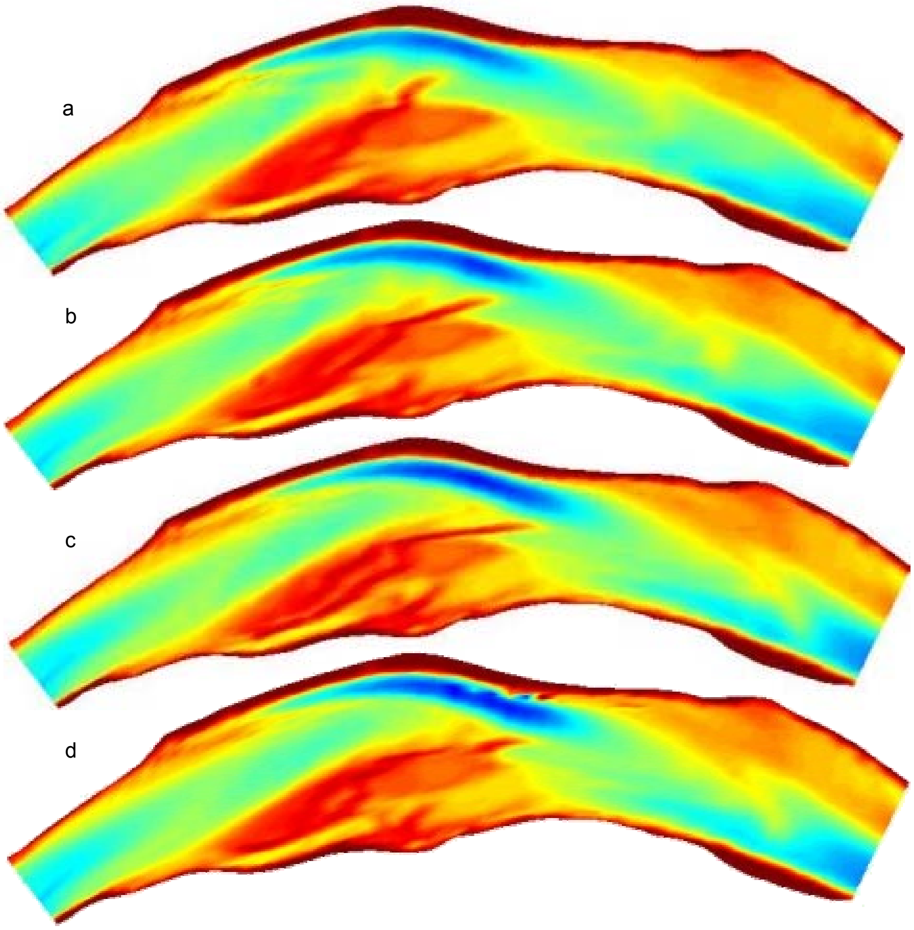
Now the preceding paragraphs have shown that point bar vegetation can have a considerable influence on morphology, it is also interesting to see what happens in case this vegetation is removed as a floodplain rejuvenation measure. Such a measure may be carried out because the vegetation causes a safety risk by causing higher water levels or by rerouting flow towards eroding banks. Rejuvenating the vegetation in order to diversify vegetation types for ecological reasons may be an other reason.

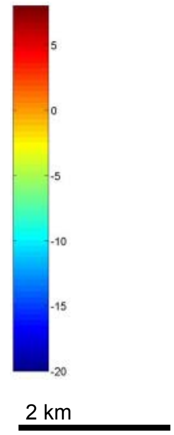
5.4.1 Vegetation removal scenarios

Two scenarios have been made in which the vegetation is removed after five years simulation with vegetation. These five years have been chosen to allow vegetation and morphology to develop before the intervention and to be able to compare developments in the remaining ten years. The difference between the two scenarios is that the one starts with a normal vegetation density, whereas the vegetation in the other is dense all over the point bar. These situations can be seen as a kind of extremities: relatively little and young vegetation versus much and older vegetation. The scenarios are:

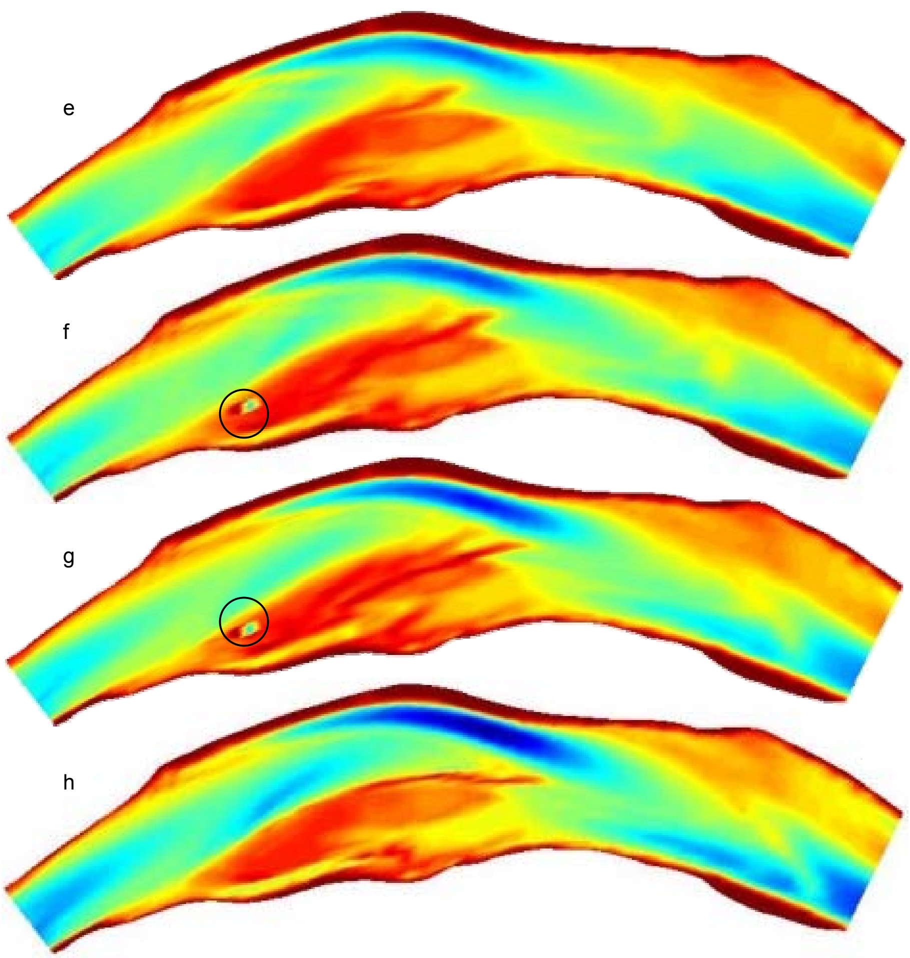
- *Normal vegetation removal*: In the first five years the vegetation is normal, i.e. equal to the reference scenario. In 1991 the vegetation is removed. The outer bank position is not updated, therefore it is compared best with the scenario ‘1986 continuous’.
- *Dense vegetation removal*: In the first five years the situation is equal to that in the scenario ‘Bend update much vegetation’. In 1991 the vegetation is removed, but the outer bank position is not updated.

In both scenarios the vegetation is completely replaced by the roughness of a bare sandy point bar (k= 0.035 m). No other factors have been varied





The bed levels of 1996 (b) and 2002 (c) after vegetation removal in 1991 (a). The vegetation before was normal. Figure (d) shows the situation in case the vegetation remains normal.



The bed levels of 1996 (f) and 2002 (g) after vegetation removal in 1991 (e). The vegetation before was very dense. Figure (h) displays the result if continued with dense vegetation.
The encircled areas show a bulge and a hole that result from a numerical instability. These affect the flow only locally.

Figure 5-9 Vegetation removal after 5 years.

The influence of vegetation on scroll bar development.

5.4.2 Interpretation and comparison

The results of both vegetation removal scenarios are presented in Figure 5-9. For both scenarios the results show a large difference compared to those of the original simulations they are based upon.

The eventual bed topography of the 'normal vegetation removal' scenario shows a ridge across the point bar similar to that of the scenario with a bare point bar, but the origin of the scroll bar keeps its original position instead of moving downstream. This may be the result of the vegetation of the first five years causing more accretion on the left side of the point bar, whereas accretion in the scenario without vegetation occurs more to the right, at the middle of the point bar.

The shape of the scroll bar is more pronounced than if the vegetation would remain constant, but the position of the tip is similar. The difference in bank erosion seems minimal, but is difficult to compare. The maximum depth in the main channel is 16 m, which is more than in the constantly unvegetated situation (15 m), but less than in the scenario with continuous vegetation (17 m). The water level difference is 85 cm for floods and 76 cm for low discharges finally. For the low discharge this is more than in the scenario with vegetation (74 cm), and 1 cm less than in the unvegetated situation, thus indicating that vegetation creates a smoother summer bed. For floods this is the other way around: 86 cm with vegetation and 83 cm without, showing the resistance caused by vegetation.

For the 'dense vegetation removal' scenario the eventual bed level and the shape of the scroll bar are very similar to that of the scenario without vegetation. Here the left side of the point bar does not have the opportunity to accrete in the first five years because it is too densely vegetated to allow much sediment transport.

The maximum depth reached in the main channel is slightly less than 15 m. This is almost equal to the scenario without vegetation, but much shallower than in the scenario with vegetation (17 m) and also shallower than in the scenario in which the normal vegetation is removed. Probably the outer bank erosion caused by the rerouting effect of the dense vegetation in the first five years has widened the river bed considerably. The relatively small water level differences of 75 cm during low discharge and 84 cm during flood indicate the same.

The point bar remaining unvegetated in the last ten years is probably not realistic, but nevertheless these scenarios show two general effects of point bar vegetation removal: the depth in the main channel is smaller, and more accretion occurs on the point bar itself. Both effects are stronger as the original vegetation has been denser. Outer bank erosion does not seem to decrease after vegetation has been removed.

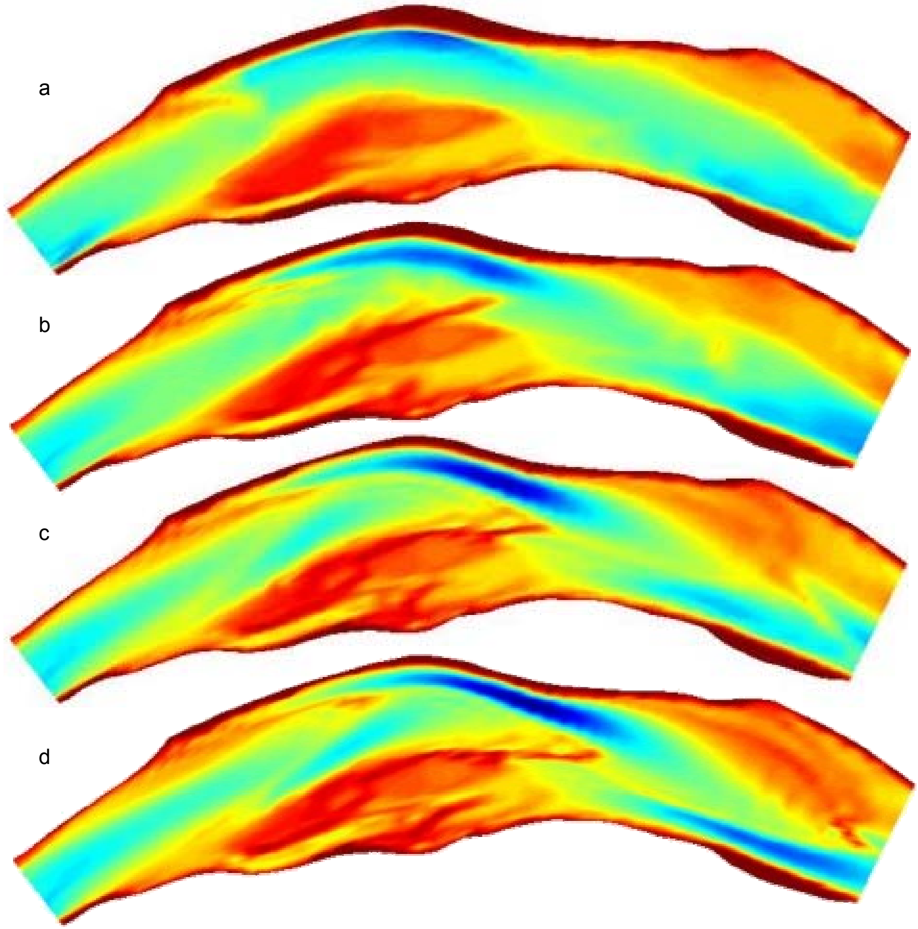
5.5 Consequences of changes in the MOR-tree

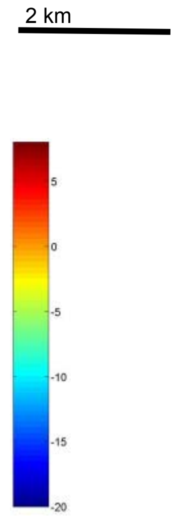
Like mentioned in Section 4.3.7 about the construction of the MOR-tree, the tree used for the scenarios differs from the calibration MOR-tree, with a different time-administration as a result. This section shows how the results would differ in case the same time-administration would have been used, with the reference scenario functioning as an example. It also discusses the influence of the calibration parameter alpha in the sediment transport formula, which has been varied when different time-stepping mechanisms were tried. This indicated that the development of the scroll bar also depends on the ratio between bed-load and suspension transport.

5.5.1 The reference scenario at the calibrated transport rate

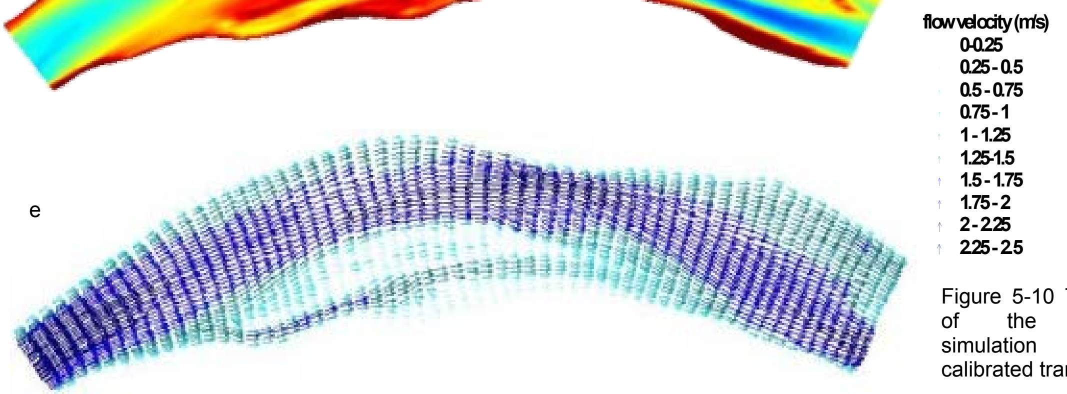
By applying the time-stepping mechanism form the calibration simulations, the morphological activity in this scenario is twice as high as in the reference scenario. However, this does not mean that exactly the same changes are visible after half the time because the update of vegetation and outer bank position take place at a relatively different moment: In the reference scenario updates are made in the same years (1991 and 1996; after 5 resp. 10 years), but at the time step used there it seems to be done after 2.5 years and 5 years, while the floods lasted 2.5 weeks and the low discharge 23.5 weeks. Therefore, in the scenario discussed here, more change will have occurred before an update.

Figure 5-10 shows the bed level of the years 1991, 1996 and 2002 and the depth averaged flow velocities of 2002. The results for the reference simulation are found in Figure 4-11.





The bed levels of 1986 (a), 1991 (b), 1996 (c) and 2002 (d).



(e) Depth averaged flow velocities of 2002.

Figure 5-10 The results of the reference simulation at the calibrated transport rate.

- The scroll bar remains slim and close to the point bar, though there is a wide shallow area next to it. Now its tip does pass the end of the point bar between 1991 and 1996, and is elongated much farther. In 2002 the scroll bar has become completely attached to the point bar, except for the tip that lies more than 1 km downstream of the point bar. This is farther than in reality.
- The outer bank position is updated in the years 1991 and 1996, but less than in the reference scenario.
- The point bar is continuously raised at most places, although point 4 in the first years erodes about 40-50 cm. Later this point accretes from 3.4 m to 4.8 m. At point 3 the bed level grows from 5.3 to 5.85 m, slower in the last years. At points 5 and 6 the accretion is not more than 1.5 cm, which is eroded again in the last five years.
- Still the high water channel is less active than in reality. The first part reaches a width comparable to reality, but the activity in the downstream part remains slower than it is in reality.
- The maximum channel depth reached in the bend is 22 m, which is 3 m more than than in reality (19 m). The maximum depth for the reference scenario amounted only 16 m, which is reached here in 1993.

Generally, bed topography developments seem to be larger than in reality, though the activity of the high water channel remains low. The scroll bar becomes very long and attached to the point bar and the main channel gets much deeper (22 m vs. 19 m in reality). The bed levels at points 3 and 4 are similar to the actual height of these points (5-6 m).
In comparison with the reference scenario it can be said that most developments simply take place twice as fast, but in some cases there are other differences. Especially for differences in the main channel these differences may be the result of the updates occuring at a relatively different time. Since some developments occur faster than in reality, choosing a somewhat smaller sediment transport calibration factor may give more realistic results: the actual situation lies in between the original reference scenario and this scenario.
The fact that the developments in the simulation now went too fast, means that the situation of 2002 actually may represent a possible situation in the next several years. This means the scroll bar will continue to grow longer and closer to the point bar. Also the upstream sand bar at the left side of the channel grows longer. However, care should be taken in making this kind of predictions, since other parts of the model area are not resembling reality that well. This especially applies to the high water channel, which development at the downstream end may have considerable influence on the behaviour of the scroll bar.

5.5.2 Different time-stepping mechanisms, influence of calibration parameter

Like mentioned in Section 4.3.7 about the construction of the MOR-tree, it was not expected that a different running-time of the FLOW-module would affect the rate at which changes occur. The way this is defined in Delft3D is rather unclear however. After consulting experts, a new MOR-tree was made in which the FLOW running-time does not influence results. Nevertheless, at first this tree caused a much faster morphological development. Therefore the sediment transport calibration factor alpha was set to 0.025 in order to get a similar development rate.
When viewing the results of this simulation, the development of the scroll bar turned out to be different from the earlier simulations. Figure 5-11 presents the results obtained with a varying discharge and no update of outer bank position or vegetation; similar to the scenario '1986 continuous' in Figure 5-5, though the rate of development differs. Now the scroll bar is wider, lower, shorter and it stays close to the point bar. The main channel becomes less deep, and the activity of the downstream part of the high water channel is still low: After 10 years the scroll bar has already reached a position where it does not get after 16 years in '1986 continuous', which means this development occurs faster and alpha may still be too large. At the same time, the bed level change in the high water channel in 1996 looks similar to that of '1986 continuous' in 1996, which implies alpha would have the right value.

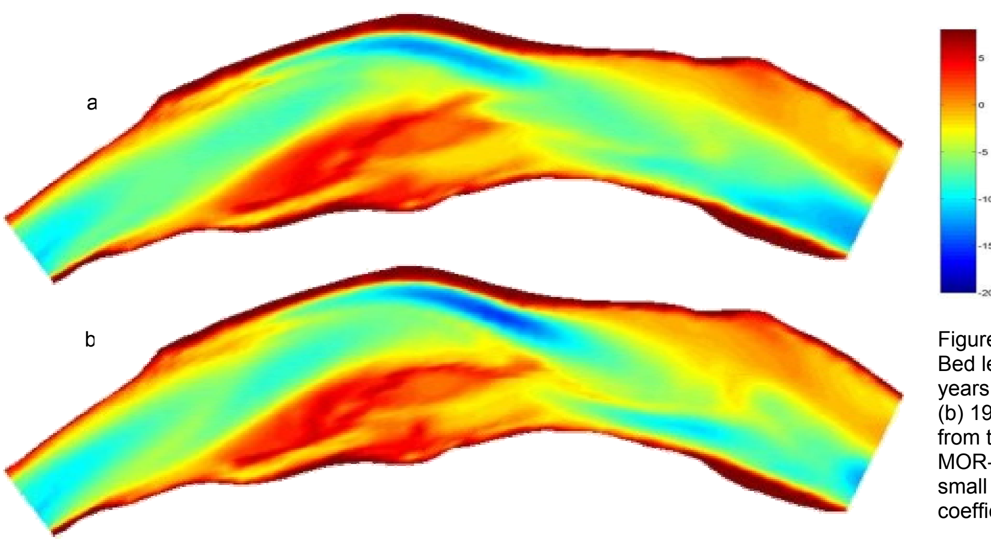


Figure 5-11
Bed levels for the years 1991(a) and (b) 1996 resulting from the improved MOR-tree with a very small alpha-coefficient.

Since alpha applies to suspension transport only, this is an indication that the development of the scroll bar and the high water channel depend on different processes. The scroll bar develops

faster than the high water channel when there is relatively little suspension transport (i.e. a small alpha). At a larger alpha (i.e. relatively more suspension transport) the rate of development is more alike. This can mean the scroll bar material is mainly transported as bed load. Nevertheless, the shape and lateral position of the scroll bar depend on suspension transport, because for a small value of alpha (0.025) these differ largely from the similar scenario ‘1986 continuous’ that has a large alpha (10).
Because applying such a small calibration coefficient is considered incorrect, further improvements of the MOR-tree have been made, of which Figure 5-12 presents the resulting bed topography. Annex 4 shows the difference between this final MOR-tree and the tree used for the research scenarios.

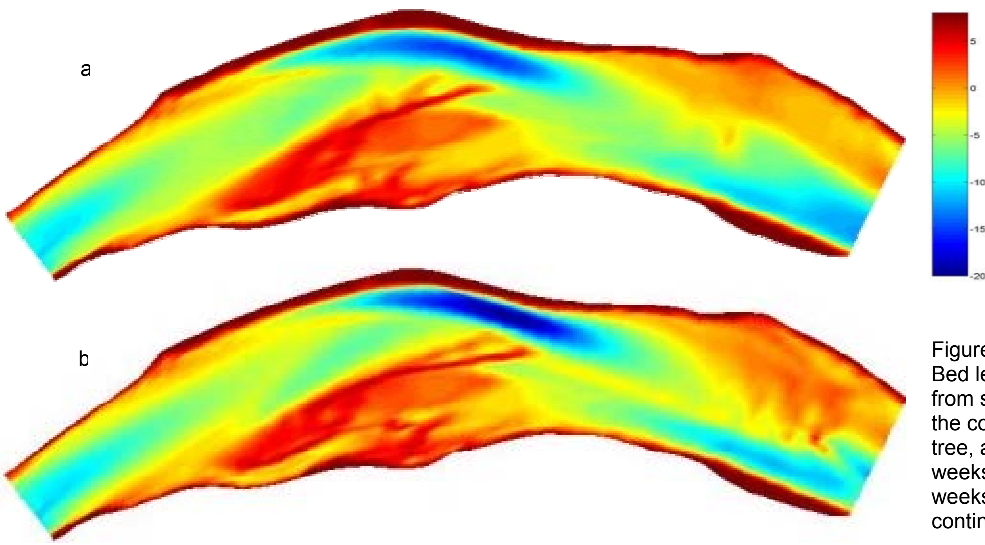


Figure 5-12
Bed levels resulting from simulation with the correct MOR-tree, afer 52 weeks(a) and 100 weeks (b) with a continuous flood.

5.6 Discussion

The simulations show that both vegetation and outer bank erosion have an effect upon scroll bar development, but do not determine the origination of a scroll bar. The effect of outer bank erosion is that the scroll bar can grow wider and farther into the main channel, and that it is elongated less quickly. The effect of vegetation is less unambiguous: the most direct effect is that its roughness concentrates the flow more in the main channel rather than on the point bar, thus creating a thinner and more elongated scroll bar. The more indirect effect, showing itself if the vegetation is not too dense, is that the stronger flow in the main channel causes more outer bank erosion, which on its turn creates more room for the development of the scroll bar. In case of dense vegetation however, the direct effect is stronger.
Removing point bar vegetation as part of the CFR-strategy generally causes more accretion on the point bar and a shallower main channel. This effect is stronger as more vegetation was present before removal.
Considering the interactions in the model between vegetation, outer bank erosion and other morphological changes some aspects require attention: The simulations only show the effect of flow diversion by vegetation to some extent reliably, and not the catchment of sediment. Another aspect that cannot be simulated is the rejuvenation of point bar vegetation by erosion or by covering with sediment, which can be important in reducing hydraulic roughness. For this hindcast model this is of minor importance, since only the vegetation present over the years is used, but for models that are made to predict changes it certainly is relevant. A main shortcoming of this model is the simulation of outer bank erosion: the bank erodes much slower than in reality. Also the activity of the high water channel is less than in reality, but this probably is mainly the result of attention during calibration being on other entities.

Apart from the modelling of these processes, other uncertainties are water level gradient that is higher than derived from data and the accuracy in measuring and calculating the roughness caused by vegetation, which may have resulted in a too rough vegetation and therefore too low flow velocities, sediment transports and bed level changes on the point bar. Other inaccuracies may be caused by the grid cell size or the sediment transport calibration factor. Also updating the outer bank position and vegetation roughness only once in five years and the limited visualisation of results do not add to the accuracy of the model.
All in all, the model reasonably shows to what extent outer bank erosion and vegetation, among other factors, influence scroll bar development. Therefore it can be a useful research tool to study the behaviour of natural rivers, as an extension to e.g. satellite image analysis and fieldworks. Nevertheless one may find that the effort for making a not very discriminating model is large since the exact contribution of one factor to morphological changes remains difficult to find out due to the many indirect effects.

6 Conclusions

Within the framework of the 'Room for the River' policy to reduce flood risks and restore nature in the Netherlands, the Cyclic Floodplain Rejuvenation strategy has been studied. As a part of studying the behaviour of more natural rivers, a numerical model has been made of the Zakrutsky bend in the Lower Volga River, Russia. Data for this model have been obtained by fieldwork and historical data analysis. The aim of the model has been to study to what extent vegetation and outer bank erosion influence the development of a scroll bar in this bend.

6.1 Fieldwork

The fieldwork and its elaboration provided insight in morphological developments in the Zakrutsky area and their relation with vegetation:

Old maps and tree-ages indicate that the point bar remained almost bare for several decades, except for some higher and sheltered areas. In this period the outer bank eroded, which in time created less severe flow conditions on the point bar, thus allowing more vegetation to develop. Within twenty years from then, almost the entire point bar had become vegetated. Probably this vegetation development led to an increase in point bar accretion because it reduced the flow velocities.

The formation of the scroll bar also began after a long period of outer bank erosion, a few years after the point bar vegetation started to develop. In the first ten years of scroll bar growth and point bar vegetation development, erosion of the outer bank occured faster than before: 25 m/yr vs. 15 m/yr at the point of maximum erosion. A part of this increase in erosion rate may be due to the fact that the bend became sharper, which also increased migration rates.

The succession of vegetation is strongly determined by morphology. Pioneer vegetation may develop into dense willow woods or weeds in low and moist areas, into swamp in very low and wet areas and into dry softwood or grassland with weeds in higher areas. Gradual accretion will raise the terrain level, thus creating suitable conditions for more arid species and more protection against severe flow, leading to more mature vegetation types. Rejuvenation can occur, however, when larger accretions bury vegetation, thus creating fresh deposits on which new pioneers can develop, or simply when vegetation is removed by erosion at locations with severe flow conditions.

6.2 Modelling

The numerical model of the Zakrutsky area was made to study the following hypotheses to explain scroll bar formation:

- The hydraulic resistance caused by point bar vegetation diverts the flow towards the outer bank, thus causing outer bank erosion. Therefore the profile becomes much wider, allowing room for a scroll bar to develop.
- The hydraulic resistance caused by point bar vegetation decreases flow velocities, both in and directly downstream of the vegetation. At the border between this area of quiet flow and the sediment-rich main flow the main flow will be slowed down, so its transport capacity is reduced, hence accretion will occur.

With respect to these hypotheses the following can be said about the results from the model:

- The hydraulic resistance of point bar vegetation deflects the flow towards the outer bank, thus increasing outer bank erosion, so creating room for a scroll bar to develop; the wider the bend, the wider the scroll bar and the farther it reaches into the channel. In case of very dense vegetation, however, the outer bank position is not of interest since the intensity of flow is such that only a slim scroll bar develops, which rapidly grows close to the point bar.
- The flow velocities directly downstream of a vegetated point bar are only slightly lower than they are in case of a bare point bar. The presence of the point bar itself is also a cause of the low flow velocities downstream. Therefore the sediment transport is low in both situations, and this mechanism does not seem to be determining scroll bar development. Besides, the

flow direction is such that the scroll bar develops more aside the vegetation than downstream of it. The flow direction at the scroll bar itself is not completely parallel to the bar but crosses it.

This means that both vegetation and outer bank erosion have an effect upon scroll bar development. However, since a scroll bar forms in practically every run, the origination itself of a scroll bar seems not to be determined by outer bank erosion or vegetation.

Apart from increasing outer bank erosion, the flow deflection by vegetation also causes erosion of the main channel bed: the main channel becomes about one metre deeper with dense vegetation than with normal point bar vegetation. The hydraulic resistance of dense point bar vegetation also decreases flow velocities in vegetated areas, resulting in lower bed shear stresses and lower sediment transports. This means the point bar itself is morphologically less active.
In case the point bar is bare, more flow can pass over the point bar itself instead of being forced through the main channel. This means flow velocities on the point bar are higher, and so is the morphological activity. There is less erosion of the outer bank, and also the main channel becomes less deep than in the situation with normal point bar vegetation.

Removing point bar vegetation after several years, as part of the CFR-strategy, generally causes more accretion on the point bar and less erosion in the main channel. This effect is stronger when more vegetation was present before removal: The resistance of the initially dense vegetation allowed little activity on the point bar and concentrated the flow in the main channel, thus creating a spacious profile. On the other hand, when the point bar in the beginning is normally vegetated, there is more activity on the point bar and less enlargement of the main channel initially. After removal of the vegetation, the accretions on the point bar affect the flow pattern, and the main channel erodes more than in case of the initially dense vegetation. Outer bank erosion does not seem to decrease after vegetation removal, but this is not modelled reliably.

Varying the ratio between suspension transport and bed load transport indicates that this ratio plays an important role in scroll bar development. The rate at which the scroll bar develops and moves downstream seems to be mainly determined by the bed load transport, since at a low suspension transport rate developments of the scroll bar occur faster in comparison to other morphological changes. Nevertheless, scroll bar development occurs more slowly at lower rates of suspension transport. Also the shape of the scroll bar is affected by the ratio: in case of low suspension transport rates the scroll bar remains close to the point bar, whereas at higher rates its shape and position are more realistic.

7 Discussion and recommendations

7.1 Discussion

This study did not provide an answer to the question by what factors the formation of a scroll bar is determined. The position of the outer bank and the presence of vegetation certainly influence the shape of the scroll bar during its development, but the cause of its formation probably depends on the local bed topography in combination with the upstream flow distribution and sediment transport that form a series of depths and shoals along the river.
Nevertheless, the combination of fieldwork and modelling in this study provided interesting information about the mutual influences between morphology and vegetation development in a natural river. The fieldwork mainly showed how vegetation develops and how this is affected by morphology (Dijkstra and Schoor, 2002), whereas the modelling indicates what effect vegetation can have on flow and morphology.

These insights might be used in the Netherlands, where the Room for the River policy will allow more natural dynamics in the winter bed than before. This room is very limited however, since safety and shipping are much more important than nature restoration. A comparison of physical parameters shows that the Waal river has the potential of being as dynamic as the Volga River, but river management does not allow it to be so. For example, the formation of a scroll bar in the main channel will not be allowed because it decreases the width of the shipping lane. Neither will outer bank erosion or large areas of dense vegetation be allowed because they endanger safety.
Nevertheless, within the winter bed there are opportunities to attain more dynamics, for example in side channels, where to some extent sedimentation and erosion can be allowed. This increase in morphodynamics will also stimulate vegetation rejuvenation processes and therefore the ecological variety. However, because the size of these side channels is small, the dynamics will be limited as well. On the other hand, the results of the model indicate that vegetation can be used to reroute and concentrate flow, thus increasing dynamics at the location the flow is routed to. This effect is similar to that of the traditional groynes, and might also be used in for example the natural part of the river Meuse to increase dynamics or clean the gravel bed from smaller sediments, which is benificial to fish habitats. Since the model did not allow removal of vegetation by erosion, it cannot be said to what extent the resistance caused by vegetation will only reroute the flow or will also cause such a flow intensity that the vegetation itself is removed.
When this natural dynamism is not sufficient to rejuvenate floodplain vegetation, Cyclic Floodplain Rejuvenation can be applied to keep flood levels acceptable and to maintain vegetation succession and the biological diversity it implies. Because the areas of interest in the Netherlands are much smaller than the Zakrutsky bend, and the risks for economy and safety are much higher, the accuracy and reliability of predictions need to be much better. This asks for more insight in the phenomena and better means of modelling them. In the smaller Dutch rivers, the rerouting effect of vegetation on flow may be smaller because the flow is forced more through the vegetation. Also modelling mainly the rerouting effect of vegetation and not the trapping of sediment can have considerable influence on the results. An other phenomenon that requires attention is modelling the effect that flow and morphology have on vegetation rejuvenation.

A numerical model like Delft3D is a useful research tool to model complex morphological processes in natural rivers. Therefore it is a useful extension to reference studies based on fieldworks and image analysis, which gives quantative results. However, the model does not explicitly show to what extent processes like vegetation growth, accretion and erosion interact, and what exactly is the cause of a certain morphological change. One should be well aware of the shortcomings of such a model.

7.2 Recommendations

For further research on the interaction of vegetation and morphology in the Zakrutksy bend, as will be done by Utrecht University and Moscow State University as a part of their NWO-project, it might be interesting to use Delft3D in order to study the following:

- The effect of the upstream discharge distribution and sediment supply on the formation of the scroll bar and the effect of suspension and bed load transport on its development.
- Reactions to changes in river management or climate. Examples are a different discharge distribution over the year due to a different dam regime or the absence of dams, the removal of point bar vegetation to various degrees, or dredging works at the scroll bar or the high water channel that may be executed in order to decrease outer bank erosion.
- Processes on the point bar on a smaller scale, like differences in flow patterns and accretion between vegetation zones.

In order to obtain a more accurate model it seems useful to extend the model area in upstream direction by including the preceding bend. Using Delft3D in 'suspended mode' instead of 'total mode' seems useful as well since the difference between suspension transport and bed load affects the development of the scroll bar. Also a finer grid may be used, certainly in case the processes on the point bar will be studied in more detail. The benefits of these changes however might be limited with respect to the effort they require. Therefore one should first determine what exactly is the purpose of the model. Making a fully three-dimensional model can be useful to study the flow -especially through vegetation- in more detail in case the topography is known better, but it is not useful to study morphology. To increase the accuracy and reliability of the current model, better information about water levels, bed levels and the state of vegetation are useful.

To increase the understanding of biogeomorphological processes in both natural rivers and natural areas in normalised rivers, it is useful to obtain more knowledge about both sediment transport in vegetation and the rerouting of flow by vegetation on a smaller scale (i.e. metres to tens of metres instead of hundreds of metres). Such effects can be studied in laboratory flumes, provided these offer opportunities to reroute flow. In order to compare those results to realistic situations, field measurements of vegetation density, flow velocites and sediment transports in Dutch or foreign rivers are useful. Natural rivers also offer possibilities to study the effect that flow and morphology have on vegetation, which on a longer term also might be useful to incorporate in morphodynamic models, and which is momentarily useful to predict the development of natural river stretches.

In order to make Delft3D more widely applicable it might be extended with a feature that deals with a varying bottom roughness, a relation for sediment transport in vegetation, a good outer bank erosion mechanism and a calibration parameter for the bed load transport.

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Annex 1 Theory of river bends, two-dimensional morphology

This annex provides some theoretical information about hydraulic and morphological processes in bends of alluvial rivers. Its aim is not to provide an extensive overview, but merely to facilitate understanding of the processes relevant to scroll bar formation and river bend modelling that are discussed in the report. General mathematical descriptions of water and sediment movement can be found in many textbooks on hydraulics like for example Jansen et al. (1979).
The first section describes the water motion in a bend including secondary flow. The influence of this secondary flow on the bed topography of a river bend is discussed in section two. Since alluvial river bends tend to migrate as a result of the forementioned processes, meander migration is dealt with in the third paragraph. The final section discusses sediment transport mechanisms and presents two relevant transport formulas: those of Engelund & Hansen and Van Rijn.

A1.1 Secondary flow

The flow pattern in river bends is rather complex and extensively studied (e.g. Rozovskii, 1961, De Vriend, 1981): apart from the obvious flow parallel to the channel axis, also a secondary flow is present. Together these phenomena cause the fluid particles to follow a helical path. Although this spiral flow is very weak in comparison to the mean flow, it is of major importance for bend morphology. The origin of this spiral flow can be explained as follows, assuming an infinite bend with constant radius and axial-symmetrical flow:
The water particles in a river bend have to experience a centripetal acceleration in order to follow the bend. This centripetal accelaration depends on the flow velocity and the radius of the flow path: $\frac{u^2}{r}$. The centripetal force results from a water level gradient in lateral direction: $g\frac{\delta\zeta}{\delta r}$.
Together with the vertical friction term, the momentum equation in lateral direction reads (after Kalkwijk and De Vriend, 1980):

$$-\frac{u^2}{r} = -g\frac{\delta\zeta}{\delta r} + \frac{\delta}{\delta z}\left(\nu_t \frac{\delta v}{\delta z}\right) \qquad (.1)$$

In depth-averaged form, it is:

$$-\frac{\overline{u^2}}{r} = -g\frac{\delta\zeta}{\delta r} - \frac{\tau_{br}}{\rho h} \qquad (.2)$$

In which:

u	= streamwise flow velocity	(m/s)
r	= radius	(m)
g	= gravitational acceleration	(m/s^2)
ζ	= water level	(m)
ν_t	= turbulence viscosity	(m^2/s)
v	= transverse flow velocity	(m)
h	= water depth	(m)
ρ	= water density	(kg/m^3)
τ_{br}	= radial bottom shear stress	(N/m^2)

If these two equations are subtracted, this gives:

$$-\frac{u^2 - \overline{u^2}}{r} = \frac{\delta}{\delta z}\left(\nu_t \frac{\delta v}{\delta z}\right) + \frac{\tau_{br}}{\rho h} \qquad (.3)$$

Which can be seen as an equation for *v(z)*. Since *u* is not uniform over depth but increases from bottom to surface, the term $u^2 - \overline{u^2}$ varies. At the bottom it is smaller than zero, at the surface it is larger. Therfore the lateral velocity is pointed towards the outer bend at the surface, and inwards at the bottom, causing a circular flow pattern. The depth-averaged value of *v* is equal to zero. Combining the circular lateral flow with the main flow gives a spiral flow pattern (Figure A1-1). This perception is a little more straightforward than measurements show: often also smaller secondary flow cells are encountered close the inner and outer banks.

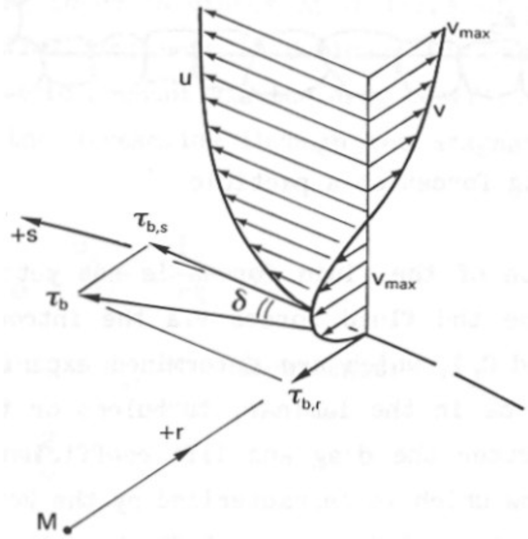


Figure A1-1 Main and secondary flow and bottom shear stress in a bend. From: Van Rijn (1994).

One of the consequences of the secondary flow is the redistribution of momentum (flow velocity) over the river cross-section. As a result of this, the velocity distribution in a river bend differs from the free vortex distribution: the maximum flow velocity gradually shifts from the inner bend towards the outer bend (Kalkwijk and De Vriend, 1980). Another consequence is the presence of a secondary bottom shear stress, which affects the bed level in a river bend.

A1.2 Bed deformation

A1.2.1 Axi-symmetric cross-section

If the secondary bottom shear stress is combined with the shear stress in longitudinal direction, the direction of the resulting bottom shear stress differs several degrees from the channel axis. The grains at bottom of the river bend will be transported in the direction of the shear stress rather than the direction of the average flow velocity. This means sediment is transported from the outer bend towards the inner bend, i.e. erosion of the outer bend and accretion of the inner bend, resulting in a bottom slope. This transport mechanism would create an ever steeper transverse bottom slope if it would not be counter-acted by the gravitational forces acting on the grains on the slope. These downward acting forces depend on the transport magnitude (the amount of grains moving) and the steepness of the profile. Eventually, an equilibrium cross-section is established.

Another factor of importance for bed topography and river width adjustment is the stability of the outer bank, i.e. its resistance against flow erosion and mass failure. Bank erosion processes are related to a wide range of fluvial and geotechnical processes, as well as different time scales. Dominant erosion processes and failure mechanisms differ strongly in space and time, hence it is impossible to develop one model for all rivers (ASCE Task Committee, 1998). Factors determined by upstream conditions that have to be taken into account are the rivers discharge and sediment load. Local circumstances are soil properties, profile geometry, bank stratigraphy, ground-water flow and vegetation.

A1.2.2 Overshoot effects

The description given above only applies to local conditions in an infinitely long bend with a constant radius. In a real river bend however, non-local effects due to the re-distribution of flow and sediment-motion affect the secondary flow pattern and the lateral bed slope significantly. This is called the 'overshoot phenomenon', which is described by Struiksma et al. (1985) with the equations below.

The length necessary for flow adaptations is:

$$\lambda_w = \frac{C^2}{2g} h_0 \quad (.4)$$

And the adaptation length of bed topography development:

$$\lambda_s = \frac{1}{\pi^2}\left(\frac{B}{h_0}\right)^2 f_s \theta h_0 \quad (.5)$$

With:

$$h_0 = \left(\frac{Q}{BC\sqrt{i_s}}\right)^{2/3} \quad (.6)$$

Where:

C	= Chézy roughness coefficient	($m^{1/2}/s$)
G	= gravitational acceleration	(m/s^2)
Q	= discharge	(m^3/s)
B	= river width	(m)
f_s	= grain shape factor	(-)
θ	= Shiels parameter	(-)
i_s	= water surface slope	(-)

These upstream disturbances causes steady bed deformations in a reach that might be initially straight. In one bend the one side of the channel is deepened and the other is accreted, in the following bend the same occurs but at the opposite bank. The length and bed topography of bends depends on how these oscillations of water and sediment motion are damped. Struiksma gives the following expressions for the wave length L_p and the damping length L_D of a point bar:

$$2\pi\frac{\lambda_w}{L_p} = \frac{1}{2}\sqrt{(n+1)IP^{-1} - IP^{-2} - \left(\frac{n-3}{2}\right)^2} \quad (.7)$$

$$\frac{\lambda_w}{L_d} = \frac{1}{2}\left(IP^{-1} - \frac{n-3}{2}\right) \quad (.8)$$

In which IP is the interaction parameter defined as λ_s / λ_w, and *n* is the exponent of the transport power-law (i.e. 5 in case Engelund-Hansen is used).

A1.3 Meander migration

Depending on geological and hydrological factors, vegetation and human interference, rivers can have several planforms. For lowland rivers the braiding and meandering patterns are most common. A braiding river has multiple channels, seperated by islands. A meandering river consists of only one channel that has a more or less sine-like shape. Most large lowland meandering rivers have large width-to-depth ratios and bends with a deep pool at the outer bank and a point bar at the inner bank.

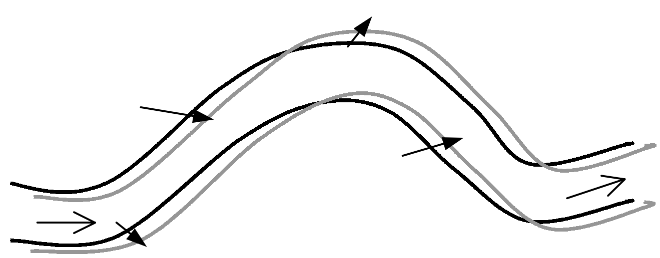


Figure A1-2 Meander migration. Black lines are former banks, grey lines are current banks. Solid arrows indicate migration direction, light arrows show flow direction.

In alluvial soils both types of rivers will migrate. In a meandering river, material is eroded at the outer bend and transported by the river to the subsequent inner bend at the same bank, where it is deposited (figure A1-2). If the lateral accretion is more or less in equilibrium with the erosion of the outer bank, the channel width is kept constant. The mechanisms responsible for this process of erosion and deposition have been described in the preceding paragraphs.

The migration process not only causes meander bends to change their location, but also to grow more curved in time. They start as a relatively flat bend, with a large radius of curvature (i.e. a high radius/width -value in order to make the radius dimensionless and generally comparable). As a consequence of migration their shape becomes more curved, which causes an increase in secondary flow and therefore an increase in migration rate *M* (Figure A1-3). After further increase in curvature (around r/w <3) the flow becomes more disturbed, thus less flow energy is available for bank erosion. Therefore very sharp bends migrate slower, and after a while a compound bend consisting of two smaller meanders develops, or the point bar is cut off by a chute channel (Nanson and Hickin, 1983). The exact manner and rate of meander migration depend on many factors like stream power, bank stability, channel width and bend radius.

The origin of meandering has long been a matter of dispute. It is considered to be a stability problem; small perturbations of the channel bed or of channel bends may grow to a meandering pattern. The first mechanism is often referred to as the 'bar theory', the second as the 'bend theory' The 'bar theory' states that migrating alternate bars in a straight channel with non-erodible banks eventually lead to the formation of meanders, the alternate bars being formed by bed instability. The 'bend theory' is introduced more recently by Ikeda, Parker and Sawai (1981). They developed a stability analysis of a sinuous channel with erodible banks, and concluded that both mechanisms operate at similar characteristic wavelenghts. Struiksma et al. (1985) assumed that upstream flow disturbances ('overshoot phenomenon') causing a steady bed deformation of the alternate bar type rather than migrating alternate bars are at the origin of river meandering since alternate bars migrate much faster than meander bends.

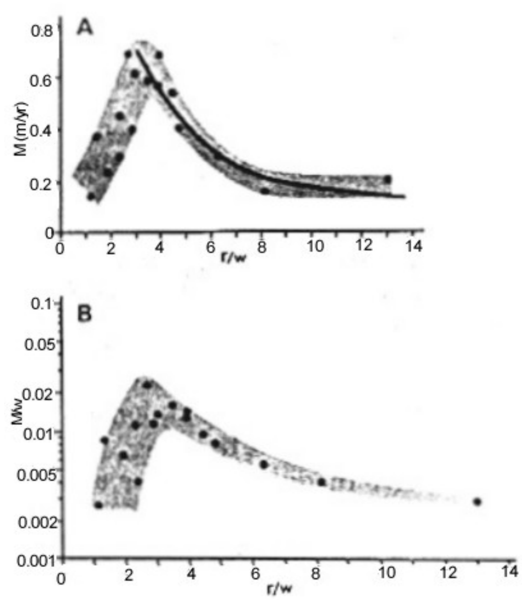


Figure A1-3 (A) Relation of migration rate (M) to curvature ratio (r/w) and (B) relation of relative migration rate (channel widths/year) to curvature. From: Hickin and Nanson, 1984.

Most probably both the overshoot phenomenon and migrating bars are at the origin of meander formation. Bank erodibility and the relative intensity of the two phenomena will probably determine which of these two mechanisms influences the bed topography the most (Crosato, 1990).

A1.4 Sediment transport

A1.4.1 Transport mechanisms

Sediment transport in alluvial rivers is an intensively studied branch of hydraulic science, and therefore many sediment transport theories exist to calculate the transport capacity of the flow. Which theory can be applied depends on sediment properties and flow characteristics, which together determine the bedform. A classification can be made as follows (Jansen et al., 1979, p90):

- Wash load means suspension transport of material finer than the bed material; it is washed through the river reach.
- Bed material transport takes place close to the bed, i.e. via the bed forms.
- Suspended load (transport) includes part of the wash load and part of the bed-material that is suspended in the fluid for some time.
- Bed load (transport) is defined as the transport of bed material by rolling and sliding.

For an alluvial channel the sediment transport generally equals the transport capacity of the flow, except if the flow shows abrupt changes (Jansen et al., 1979).

The interaction between flow, sediment transport and the river bed causes different bedforms and therefore different hydraulic roughnesses, depending on the flow velocity (see Figures A1-4 and A1-5). For this reason transport formulas and bottom roughness predictors are often developed together (e.g. Engelund and Hansen, 1967, Van Rijn, 1984a,b,c among many others). Nevertheless, the prediction of transport capacity, bed forms and corresponding roughness is very unsure.

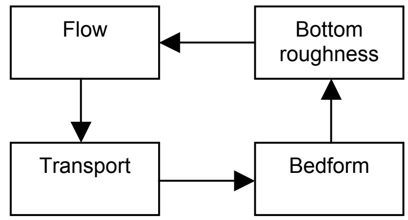


Figure A1-4 The interaction between flow, sediment and bottom.

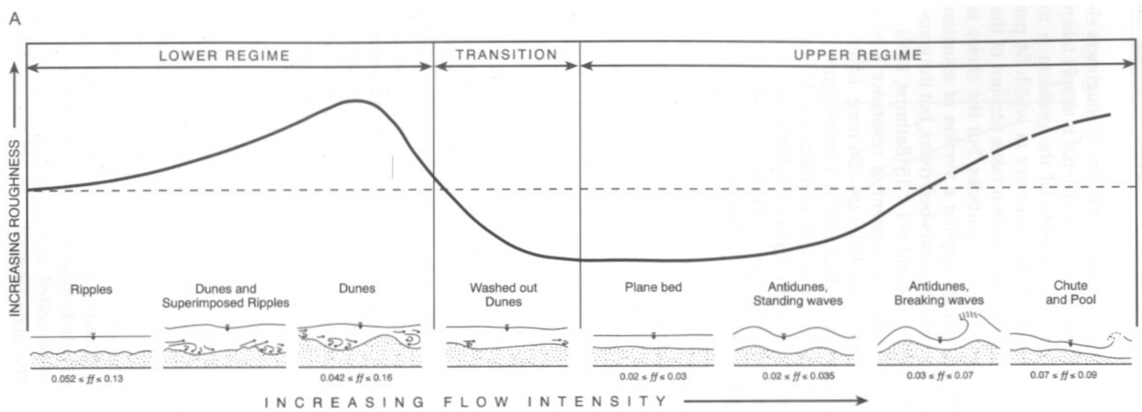


Figure A1-5 Bed form roughness as a function of flow velocity. From: Knighton, 1998.

The sections beow discuss two transport formula that are suitable to use in a lowland river with fine sediment like the Volga River.

A1.4.2 Engelund-Hansen formula

The Engelund-Hansen (1967) transport formula combines bottom and suspension transport in one formula. The local transport capacity in the Delft3D model is calculated as follows (WL Delft hydraulics, 2001):

$$s = mu^n \qquad (.9)$$

with:

$$m = \frac{0.05\alpha}{\sqrt{g}C^3\Delta^2 D_{50}} \qquad (.10)$$

where:

u	= flow velocity	(m/s)
n	= power	(-)
g	= gravitational accelleration	(m/s^2)
α	= calibration coefficient	(-)
C	= Chézy roughness coefficient	(m$^{1/2}$/s)
Δ	= relative density, $(\rho_s-\rho_w)/\rho_w$	(-)

D_{50} = characteristic grain size (m)

Generally the power law used for this formula is 5. This implies however a constant value of C, regardless the flow velocity, whereas in reality the value of C exponentially decreases as flow velocities become larger than about 0,8 m/s. Therefore for large rivers with fine sediment a power of 4 gives a better match with measurements.

A1.4.3 Van Rijn formula

The Van Rijn (1984) formula is more advanced than the Engelund-Hansen formula. It makes a distinction between suspended and bed load transport and calculates these using a specific bed form roughness rather than the overall Chézy roughness value, which describes the morphological behaviour more accurately. De Vries (1993) however shows by comparing measured and predicted values of s and C that the newer formula of Van Rijn is not always better than that of Engelund and Hansen.

The Van Rijn (1984) formula as incorporated in Delft3D is (WL Delft Hydraulics, 2001):

S=S_s+S_b (total transport= suspended load + bed load)

Where:

$$S_b = \begin{cases} 0.053(\Delta g D_{50}^3)^{1/2} D_*^{-0.3} T^{2.1} & for T < 3.0 \\ 0.1(\Delta g D_{50}^3)^{1/2} D_*^{-0.3} T^{1.5} & for T \geq 3.0 \end{cases}$$

With T a dimensionless bed shear parameter, written as:

$$T = \frac{\mu_c \tau_{bc} - \tau_{bcr}}{\tau_{bcr}}$$

The critical bed shear stress τ_{bcr} follows from Shields:

$$\tau_{bcr} = \rho_w \Delta g D_{50} \theta_{cr}$$

With θ_{cr} being a function of the dimensionless particle diameter D_*:

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

The term $\mu_c \tau_{bc}$ is the effective shear stress. This shear stress is calculated using:

$$\tau_{bc} = 0.125 \rho_w f_{cb} q^2$$

$$f_{cb} = \frac{0.24}{\left(\log(\frac{12h}{\xi_c})\right)^2}$$

$$\mu_c = \left(\frac{18\log(\frac{12h}{\xi_c})}{C'}\right)^2$$

where C' is the grain related Chézy coefficient:

$$C' = 18\log(\frac{12h}{3D_{90}})$$

And ξ_c is the user-specified reference level or roughness height, which can be interpreted as the bed load layer thickness.

For suspended transport the formulation reads:

$$S_s = f_{cs} q h C_a$$

In which C_a is the reference concentration, q the depth averaged velocity, h the water depth and f_{cs} a shape factor:

$$f_{cs} = \begin{cases} f_0(z_c) & if z_c \geq 1.2 \\ f_1(z_c) & if z_c \leq 1.2 \end{cases}$$

$$f_0 = \frac{(\xi_c / h)^{z_c} - (\xi_c / h)^{1.2}}{(1-\xi_c / h)^{z_c} - (1.2 - z_c)}$$

$$f_1 = \left(\frac{\xi_c / h}{1-\xi_c / h} \right)^{1.2} \log(\xi_c / h)$$

In which z_c is the suspension number:

$$z_c = \min(20.0, \frac{w_s}{\beta \kappa u_*} + \phi)$$

$$u_* = q\sqrt{\frac{f_{cb}}{8}}$$

$$\beta = \min(1.5, 1.0 + 2\left(\frac{w_s}{u_*}\right)^2)$$

$$\phi = 2.5\left(\frac{w_s}{u_*}\right)^{0.8} \left(\frac{C_a}{0.65}\right)^{0.4}$$

The reference concentration is written as:

$$C_a = 0.015\alpha_1 \frac{D_{50}}{\xi_c} \frac{T^{1.5}}{D_*^{0.3}}$$

The parameters used are:

w_s	= sediment settling velocity	(m/s)
α_1	= coefficient O(1)	(-)
ξ_c	= roughness height	(m)
D_{90}	= particle diameter	(m)

Annex 2 Hydraulic roughness of vegetation

A2.1 Unsubmerged vegetation

The following formula is used to calculate the representative Chézy factor C_r in case the water level exceeds the height of the undergrowth but not that of the taller vegetation ('unsubmerged vegetation'):

$$C_r = \frac{\sqrt{\frac{2g}{(A_{ru}+A_{rt})C_d}}k + \sqrt{\frac{2g}{A_{rt}C_d}}(h-k)}{h\sqrt{h}} \qquad (.11)$$

where:

A_{ru}	= representative wetted area of undergrowth	(m^2)
A_{rt}	= representative wetted area of tall vegetation	(m^2)
k	= height of undergrowth	(m)
C_d	= drag factor	(-)
h	= water depth	(m)

A_r is defined as:

$$A_r = \frac{\int_0^h A_v dz}{h}$$

A_v = wetted area of vegetation at height z ($m^2/m^2/m$)

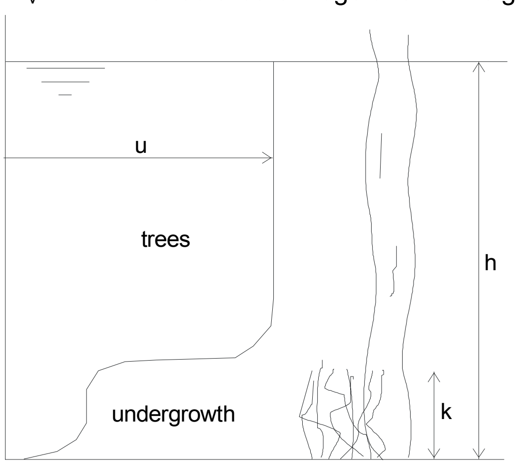


Figure A2-1 The vertical velocity profile in unsubmerged vegetation.

A2.2 Submerged vegetation

In case the water level exceeds the vegetation height ('submerged vegetation') the following formula is used:

$$C_r = \frac{kU_v + (h-k)U_0 + k_0(U_{d0} - u_{s0})}{h\sqrt{hi}} \qquad (.12)$$

with:

$$U_v = \frac{2}{k\sqrt{2A}}\left(\sqrt{C_2 e^{k\sqrt{2A}} + u_{s0}^2} - \sqrt{C_2 + u_{s0}^2}\right) + \frac{u_{s0}}{k\sqrt{2A}} \ln\left[\frac{\left(\sqrt{C_2 e^{k\sqrt{2A}} + u_{s0}^2} - u_{s0}\right)\left(\sqrt{C_2 + u_{s0}^2} + u_{s0}\right)}{\left(\sqrt{C_2 e^{k\sqrt{2A}} + u_{s0}^2} + u_{s0}\right)\left(\sqrt{C_2 + u_{s0}^2} - u_{s0}\right)}\right]$$

$$U_0 = \frac{u_*}{\kappa(h-k)}\left[\left(h-(k-a)\right)\ln\left(\frac{h-(k-a)}{z_0}\right) - a\ln\left(\frac{a}{z_0}\right) - (h-k)\right]$$

$$U_{d0} = \sqrt{\frac{2gi}{C_d m_0 D_0}}$$

$$u_{s0}^2 = -\frac{B}{A}$$

$$\alpha = 0.023k^{0.7}$$

$$A = \frac{C_d mD}{2\alpha}$$

$$B = -\frac{gi}{\alpha}$$

$$C_2 = \frac{-2B(h-k)}{\sqrt{2A}\left(e^{k\sqrt{2A}} - e^{-k\sqrt{2A}}\right)} + \frac{4Bge^{-k\sqrt{2A}}}{C_b^2 C_d mD\left(e^{k\sqrt{2A}} - e^{-k\sqrt{2A}}\right)}$$

$$E = \frac{\sqrt{2A}C_2 e^{k\sqrt{2A}}}{2\sqrt{C_2 e^{k\sqrt{2A}} + u_{s0}^2}}$$

$$F = \frac{\kappa\sqrt{C_2 e^{k\sqrt{2A}} + u_{s0}^2}}{u_*}$$

$$u_* = \sqrt{g(h-(k-a))i}$$

$$a = \frac{1 + \sqrt{1 + \frac{4E^2\kappa^2(h-k)}{gi}}}{\frac{2E^2\kappa^2}{gi}}$$

$$z_0 = ae^{-F}$$

in which:

h	= water depth	(m)
k	= average height of high vegetation	(m)
k_0	= average height of low vegetation	(m)
C_d	= drag factor	(-)
m	= number of stems per square meter high vegetation	(m^{-2})
m_0	= number of stems per square meter low vegetation	(m^{-2})
D	= stem diameter high vegetation	(m)

D_0	= stem diameter low vegetation	(m)
i	= water level gradient	(-)
g	= gravitational acceleration	(m/s^2)
κ	= Von Kármán constant; 0,4	(-)
C_b	= Chézy bottom roughness coefficient	(m$^{1/2}$/s)
C_r	= representative Chézy coefficient	(m$^{1/2}$/s)
a	= penetration depth	(m)
u_{s0}	= flow velocity in non-submerged vegetation	(m/s)
u_*	= virtual bed stress for surface layer	(m/s)

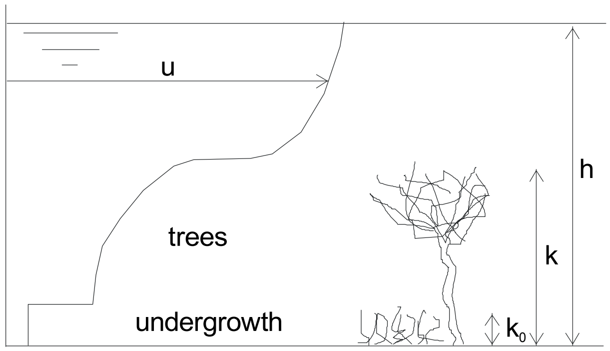


Figure A2-2 The vertical velocity profile in submerged vegetation.

For both submerged and unsubmerged vegetation, the representative bottom roughness height k_{rep} eventually is determined by:

$$k_{rep} = \frac{12h}{10^{\frac{C_r}{18}}} \quad (.13)$$

Annex 3 Changing bottom roughness values using MATLAB

Delft3D-MOR has no functionality to deal with time-varying hydraulic roughness. In one simulation only one roughness file for all occuring discharges can be specified. In case of a river with large differences between high and low discharges this is problematic, not only because the hydraulic roughness influences the water motion, but also because it affects the sediment transport. The effect of hydraulic roughness on both water motion and sediment transport can be included by making a series of simulations with different roughness files –e.g. one for flood and one for low discharge- in stead of one. This series is made using a batch file.
However, the simulation of a flood after a period of low discharges and vice versa requires the actual –updated- bed level. This bed level is stored in the communication file, and can be passed on from simulation to simulation; the following simulation is restarted from this file. Unfortunately, such a restart not only includes using the updated bed level, but also bottom roughness values and flow fields. This means that a flood simulation would still use the low-discharge roughness values. To avoid this, the correct flood-roughnesses have to be put in the communication file before the flood-simulation starts. This is done by using MATLAB-commands to read the correct data from an earlier created communication file, and pasting these values into the communication file resulting from the low discharge simulation.
Nevertheless this does not solve the problem yet, since also data about flow fields, water levels and active cells are passed on incorrectly. This causes critical errors in the flow-simulation. Therefore these data are replaced as well, with the values of the most recent corresponding simulation (e.g h26 uses flow data of h24, and l25 of l23). Furthermore it is necessary to pass on the transport history and –map files too in order to avoid errors in writing data, and to obtain a continuous output of results. Some scenarios need updating of the outer bank position after 5 years, which means these are restarted without passing on the communication file so their output cannot be continuous.

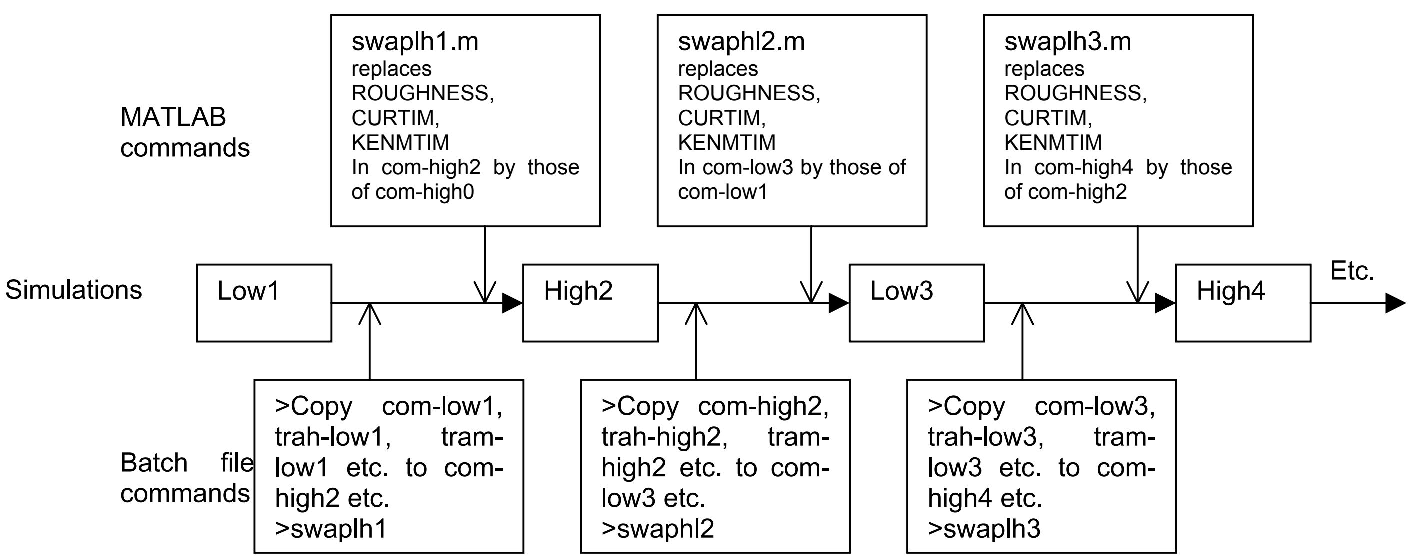


Figure A3-1 The sequence of simulations.

The commands in the batch-file to copy the necessary files and execute the MATLAB-instruction are:

```
copy com-l01.dat com-h02.dat
copy com-l01.def com-h02.def
copy trah-l01.def trah-h02.def
```

```
copy trah-l01.dat trah-h02.dat
copy tram-l01.def tram-h02.def
copy tram-l01.dat tram-h02.dat
copy botm-l01.dat botm-h02.dat
copy both-l01.dat both-h02.dat
copy botm-l01.def botm-h02.def
copy both-l01.def both-h02.def
r:\matlab\bin\win32\matlab.exe -r swaplh1
```

The MATLAB commands used to put the right values in the communication file are listed below. The example used is the file swaplh1.m, which contains the instructions for the first update from low to high discharge.

cd c:\matlab\delft3d-matlab-interface	Ensures that MATLAB uses the right directoty
cfh=vs_use ('C:\delft3d\jasper\fase3\com-h00')	Reads the high-discharge com-file
ruwunw=vs_get(cfh, 'ROUGHNESS', 'CFUROU')	Reads roughness in u-direction from high com-file
ruwvnw=vs_get(cfh, 'ROUGHNESS', 'CFVROU')	Reads roughness in v-direction
qunw=vs_let(cfh, 'CURTIM', {1:1:2}, 'QU')	Reads flow in u-direction
qvnw=vs_let(cfh, 'CURTIM', {1:1:2},'QV')	Reads flow in v-direction
wlzpnw=vs_let(cfh, 'CURTIM', {1:1:2},'S1')	Reads waterlevels
vunw=vs_let(cfh, 'CURTIM', {1:1:2},'U1')	Reads velocity in u-direction
vvnw=vs_let(cfh, 'CURTIM', {1:1:2},'V1')	Reads velocity in v-direction
sprnw=vs_let(cfh, 'CURTIM', {1:1:2},'RSP')	Reads spiral flow intensity
actupnw=vs_let(cfh, 'KENMTIM', {1:1:2},'KFU')	Reads active points in u-direction
actvpnw=vs_let(cfh, 'KENMTIM', {1:1:2},'KFV')	Reads active points in v-direction
cfl=vs_use ('C:\delft3d\jasper\fase3\com-h02')	Reads the low-discharge com-file
cfl=vs_put(cfl, 'ROUGHNESS', 'CFUROU', ruwunw)	Writes u-roughness to low com-file
cfl=vs_put(cfl, 'ROUGHNESS', 'CFVROU', ruwvnw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'QU', qunw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'QV', qvnw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'S1', wlzpnw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'U1', vunw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'V1', vvnw)	Idem
cfl=vs_put(cfl, 'CURTIM', 'RSP', sprnw)	Idem
cfl=vs_put(cfl, 'KENMTIM', 'KFU', actupnw)	Idem
cfl=vs_put(cfl, 'KENMTIM', 'KFV', actvpnw)	Idem
Exit	Exits MATLAB; re-activates batch-file

Annex 4 Delft3D input files

The input file of the FLOW-module; h12.mdf:

```
Ident = #DELFT3D.UI    .03.02 3.35.03#
Runid = #h12#
Commnt=
Runtxt= #hoog water voor swap, kort,   #
       #simstart na stop laag, breed  #
Filcco= #v10.grd      #
Fmtcco= #FR#
DxDy  = [.] [.]
Anglat= 0.000000
Grdang= 0.000000
Filgrd= #v10.enc      #
Fmtgrd= #FR#
MNgrd = [ ] [ ]
MNKmax= 62 38 1
Thick = 100.000
Fildep= #198617.dep  #
Fmtdep= #FR#
Commnt=
MNdry = [ ] [ ] [ ] [ ]
Fildry= #           #
Fmtdry= #FR#
MNtd  = [ ] [ ] [ ] [ ] #U#
Filtd = #           #
Fmttd = #FR#
Nambar= #                   #
MNbar = [ ] [ ] # #
MNwlos= [ ] [ ]
Commnt=
Itdate= #1986-01-01#
Tunit = #M#
Tstart= 2.75904e+006
Tstop = 2.80800e+006
Dt    = 1.00000
Tzone = 0
Commnt=
Sub1  = #   I#
Sub2  = #   #
Namc1 = #                   #
Namc2 = #                   #
Namc3 = #                   #
Namc4 = #                   #
Namc5 = #                   #
Wnsvwp= #N#
Filwnd= #           #
Fmtwnd= #FR#
Wndint= #Y#
Commnt=
Restid= #867#
Commnt=
Filbnd= #kh.bnd      #
Fmtbnd= #FR#
FilbcH= #           #
FmtbcH= #FR#
FilbcT= #bdl.bct     #
FmtbcT= #FR#
Filana= #           #
Filcor= #           #
FilbcC= #           #
FmtbcC= #FR#
Rettis= 0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
Rettib= 0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
       0.000000
Commnt=
```

```
Ag    = 9.81000
Rhow  = 1000.00
Alph0 = [.]
Tempw = 15.0000
Salw  = 0.000000
Rouwav= #    #
Wstres= 0.000630000 0.000000 0.00723000 100.000
Rhoa  = 1.00000
Betac = 0.500000
Equili= #N#
Tkemod= #            #
Ktemp = 0
Fclou = 0.000000
Sarea = 0.000000
Filtmp= #            #
Fmttmp= #FR#
Temint= #Y#
Tstmp = [.] [.]
Commnt=
Roumet= #W#
Filrgh= #k1986h9.rgh #
Fmtrgh= #FR#
Xlo   = 0.000000
Filedy= #            #
Vicouv= 1.00000
Dicouv= 10.0000
Vicoww= [.]
Dicoww= [.]
Irov  = 0
Z0v   = [.]
Cmu   = [.]
Cpran = [.]
Commnt=
Iter  =      2
Dryflp= #MAX #
Dryflc= 0.100000
Dco   = -999.000
Tlfsmo= 0.000000
Forfuv= #Y#
Forfww= #N#
Sigcor= #N#
Trasol= #Cyclic-method#
Commnt=
Filsrc= #            #
Fmtsrc= #FR#
Fildis= #            #
Fmtdis= #FR#
Commnt=                          no. observation points: 9
Filsta= #kh.obs      #
Fmtsta= #FR#
Tpar  = [.] [.]
XYpar = [.] [.]
Commnt=
Eps   = [.]
Commnt=
Commnt=                          no. cross sections: 2
Filcrs= #kh.crs      #
Fmtcrs= #FR#
Commnt=
PMhydr= #YYYYYY#
PMproc= #YYYYYYYYYY#
PMderv= #YYY#
PHhydr= #YYYYYY#
PHproc= #YYYYYYYYYY#
PHderv= #YYY#
PHflux= #YYYY#
SMhydr= #YYYYY#
SMproc= #YYYYYYYYYY#
SMderv= #YYYYY#
SHhydr= #YYYY#
SHproc= #YYYYYYYYYY#
SHderv= #YYYYY#
SHflux= #YYYY#
Commnt=                          attribute file fourier analyzed
Filfou= #            #
Online= #NO #
Prmap = [.]
Prhis = 8.96976e+006 0.000000 8.96976e+006
Flmap = 2.75904e+006 1440.00 2.80800e+006
Flhis = 2.75904e+006 1440.00 2.80800e+006
Flpp  = 2.75904e+006 1440.00 2.80800e+006
Flrst = 0.000000
Commnt=
Commnt=
```

The input of the MOR-module; morf.h12:

```
*--------------------------------------------------------------------------
* File Created at: Tuesday, 18 March 2003 17:38:24
* Created with   : Delft3D «ProTrEd» Béta Version 0.01M
* Created by     : jasper
*--------------------------------------------------------------------------
* Record 1  --> Filenames
* case - label - dummy - dummy
*--------------------------------------------------------------------------
    'h12'    ' '    ' '    ' '
*--------------------------------------------------------------------------
* Record 2  --> Restart option
* initial (0) restart (1)
*--------------------------------------------------------------------------
         1
*--------------------------------------------------------------------------
* Record 3  --> Reference Date and Time
* ref.date [yyyymmdd] - ref.time [hhmmss]
*--------------------------------------------------------------------------
         19860101            000000
*--------------------------------------------------------------------------
* Record 4  --> Starting Time and and Time Unit
* NOTE: Starting Time HAS to be expressed in Time Units
* Starting Time - Time Unit [s]
*--------------------------------------------------------------------------
  2757600   60.00000
*--------------------------------------------------------------------------
* Record 5  --> Creation of restart file for Transport module
* Do Not (0) or Create (1) restart file
*--------------------------------------------------------------------------
         0
*--------------------------------------------------------------------------
* Record 6  --> Number of Modules that is applied
* Range is from 1 to 4
*--------------------------------------------------------------------------
         3
*--------------------------------------------------------------------------
* Record 7  --> Identification of modules
* NOTE: has to repeated for Number of Modules
* Physical process numbers: 1)waves, 2)flow, 3) transport,
* 4) bed level change
* Physical Process Number - Version Number - File name
*--------------------------------------------------------------------------
         2                  1         'h12.mdf'
         3                  1         'md-tran.h12'
         4                  1         'md-bott.h12'
*--------------------------------------------------------------------------
* Record 8  --> Cycle Length expressed in Time Units
* NOTE:  Data in comm-file is always reduced to first cycle
*--------------------------------------------------------------------------
    99999999
*--------------------------------------------------------------------------
* Record 9  --> Tree structure
* Minimum Number of Branches (NOB) is 1
```

```
* Range Number of End Nodes (NOEN) is from 1 to NOB
* NOB  -  NOEN
*------------------------------------------------------------------------------
   5    3
*------------------------------------------------------------------------------
* Record 10 --> Tree structure combination
* NOTE: has to repeated for Number of Branches
* Child - Parent
*------------------------------------------------------------------------------
   5    6
   1    5
   4    5
   2    4
   3    4
*------------------------------------------------------------------------------
* Record 11 --> Specification of controls
* NOTE: has to repeated for Number of Branches
*------------------------------------------------------------------------------
* Record 11.1 --> Specification of Stop Criterion
* Controller - Stop Criterion - No.of Exec./Stop Time - Level
*------------------------------------------------------------------------------
    1        4        20              0.010   4      1      2      3      4
*------------------------------------------------------------------------------
* Record 11.2 --> Specification of Stop Parameter
* NOTE: has to be specified when Stop Criterion is 4 or 5
* Name  -  Comp.Option -  Rel.Time
*------------------------------------------------------------------------------
 'U1'       4      1.00000000000
*------------------------------------------------------------------------------
* Record 11.3 --> Start and Update type of controller after repeater check
* Start Type - Start Item  - Update Type - Update Item
*------------------------------------------------------------------------------
   3          0          3          0          1          1
*------------------------------------------------------------------------------
* Record 11.1 --> Specification of Stop Criterion
* Controller - Stop Criterion - No.of Exec./Stop Time - Level
*------------------------------------------------------------------------------
    2        2        1               0.000   4      1      2      3      4
*------------------------------------------------------------------------------
* Record 11.3 --> Start and Update type of controller after repeater check
* Start Type - Start Item  - Update Type - Update Item
*------------------------------------------------------------------------------
   3          0          3          0          1          1
*------------------------------------------------------------------------------
* Record 11.1 --> Specification of Stop Criterion
* Controller - Stop Criterion - No.of Exec./Stop Time - Level
*------------------------------------------------------------------------------
    3        2        1               0.500   4      1      2      3      4
*------------------------------------------------------------------------------
* Record 11.3 --> Start and Update type of controller after repeater check
* Start Type - Start Item  - Update Type - Update Item
*------------------------------------------------------------------------------
   3          0          1          3          1          1
*------------------------------------------------------------------------------
* Record 11.1 --> Specification of Stop Criterion
* Controller - Stop Criterion - No.of Exec./Stop Time - Level
*------------------------------------------------------------------------------
    4        3     2808000            0.000   4      1      2      3      4
*------------------------------------------------------------------------------
* Record 11.3 --> Start and Update type of controller after repeater check
* Start Type - Start Item  - Update Type - Update Item
*------------------------------------------------------------------------------
   3          0          3          0          1          1
*------------------------------------------------------------------------------
* Record 11.1 --> Specification of Stop Criterion
* Controller - Stop Criterion - No.of Exec./Stop Time - Level
*------------------------------------------------------------------------------
    5        3     2808000            0.000   4      1      2      3      4
*------------------------------------------------------------------------------
* Record 11.3 --> Start and Update type of controller after repeater
check
* Start Type - Start Item  - Update Type - Update Item
*------------------------------------------------------------------------------
   3          0          3          0          1          1
*------------------------------------------------------------------------------
* Record 12 --> Selection of Physical Processes and Time Intervals
* NOTE: has to repeated for all End Nodes
*------------------------------------------------------------------------------
* Record 12.1 --> Specification of Physical Processes
* NOTE: to select a physical process the Version Number has to be
*       specified if not set to 0
* End Node - WAVES - FLOW - TRANSPORT - BOTTOM
*------------------------------------------------------------------------------
   1     0     1      0      0       1 1 1 1
*------------------------------------------------------------------------------
* Record 12.2 --> Specification relative time intervals
* NOTE: has to be specified for active physical processes
* Phys.Process - Relative Start Time - Relative Stop Time
*------------------------------------------------------------------------------
        2       0      60
*------------------------------------------------------------------------------
* Record 12.1 --> Specification of Physical Processes
* NOTE: to select a physical process the Version Number has to be
*       specified if not set to 0
* End Node - WAVES - FLOW - TRANSPORT - BOTTOM
*------------------------------------------------------------------------------
   2     0     1      0      0       1 1 1 1
*------------------------------------------------------------------------------
* Record 12.2 --> Specification relative time intervals
* NOTE: has to be specified for active physical processes
* Phys.Process - Relative Start Time - Relative Stop Time
*------------------------------------------------------------------------------
        2       0      30
*------------------------------------------------------------------------------
* Record 12.1 --> Specification of Physical Processes
* NOTE: to select a physical process the Version Number has to be
*       specified if not set to 0
* End Node - WAVES - FLOW - TRANSPORT - BOTTOM
*------------------------------------------------------------------------------
   3     0     0      1      1       1 1 1 1
*------------------------------------------------------------------------------
* Record 12.2 --> Specification relative time intervals
* NOTE: has to be specified for active physical processes
* Phys.Process - Relative Start Time - Relative Stop Time
*------------------------------------------------------------------------------
        3       0     1440
        4       0     1440
```

The transport input file; md-tran.h12:

```
****************************************************
*
*                          INPUT FORM OF TRANSPORT MODULE
*
****************************************************
*
****************************************************
*            Description
****************************************************
*
*0
*
****************************************************
*            Module options
****************************************************
*
*Record 1: MODSDA
1
*Record 3: INSTF
```

```
.true.
*Record 5: NWAVE
.false.
*
****************************************************
*            Memory use
****************************************************
*
*Record 9: MAXFLT
300
*
****************************************************
*            Time parameters
****************************************************
*
*Record 13: IDTS, NTSI
5            3
*Record 15: ITPERQ
99999999
*
****************************************************
*            Spiral motion effects
****************************************************
*
*Record 17: LSECBO
1
*Record 18: ESPIR
1.00000
*Record 20: FYTA
1.00000
*Record 21: ASHLD, BSHLD
1.00000      0.500000
*
****************************************************
*            Bed characteristics
****************************************************
*
*Record 22: NVAST
.false.
*
****************************************************
*            Boundary conditions
****************************************************
*
*Record set 31:
*Record set 31.1: IBNDNR, IBNDTP
1            0
2            0
3            0
4            0
5            0
6            0
7            0
8            0
9            0
10           0
11           0
12           0
13           0
14           0
15           0
16           0
17           0
18           0
19           0
20           0
21           0
22           0
23           0
24           0
25           0
26           0
27           0
28           0
29           0
30           0
31           0
32           0
33           0
34           0
*
****************************************************
*            General sediment parameters
****************************************************
*
*Record 40: RHOS
2650.00
*Record 41: RNU
1.00000e-006
*Record 42: D50C
0.000450000
*
****************************************************
*            Sediment transport relation
****************************************************
*
*Record 46: IFORM
7
****************************************************
#7           van Rijn (1984)
****************************************************
*Record 47.7.1: ALF1
10.00000
*Record 47.7.2: D90
0.000570000
*Record 47.7.4: RKSC
0.200000
*Record 47.7.6: WS
0.0600000
*
****************************************************
#     End of specification of transport relation
****************************************************
*
*Record 48: ALFABD
1.00000
*Record 50: NSTAB
4
*Record 50a: BBTRS, PORSTA
5.00000      0.400000
*Record 51: ALFSTA
6.00000
*Record 53: NTYDA, CRNMAX
0            0.700000
*
****************************************************
*            Output definition
****************************************************
*
*Record 55:
OUTPUT DATA
*Record 56: MODDM
0
*
****************************************************
*            Time histories
****************************************************
*
*Record 57: NOUTHS
0
```

```
*Record 58: ITHISA, ITHISB, IDTHIS
0          2147483647          10800
*Record 59: NOSED
12
*Record 60: I, MC(I), NC(I)
1          61          12
2          24          7
3          30          32
4          30          27
5          2           11
6          15          25
7          17          7
8          33          14
9          21          36
10         22          15
11         24          3
12         30          14
*Record 61: NTRAU
4
*Record 62: MITX(I) NIT1(I) NIT2(I)
1          1           2           37
2          61          2           37
3          25          20          22
4          33          19          22
*Record 63: NTRAV
4
*Record 64: NITY(I) MIT1(I) MIT2(I)
1          22          26          29
2          22          30          33
3          19          26          29
4          18          30          33
*
****************************************************
*          Initial maps
****************************************************
*
*Record 67: NQUALT3
0
*Record 68: NQUALT4
0
*
****************************************************
*          Time-dependent maps of non-time averaged functions
****************************************************
*
*Record 69: NOUTFI
0
*Record 70: ITMPIA ITMPIB IDTMPI
0          2147483647          10800
*Record 71: NQUALT5
1
*Record 72: NQUALT6
1
*Record 73: NQUALT7
1
*Record 74: NQUALT8
1
*Record 75: NQUALT9
1
*
****************************************************
*          Maps of integral and averaged transports
****************************************************
*
*Record 79: NOUTFA
0
*Record 80: ITMPAA, ITMPAB, IDTMPA
0          2147483647          10800
*Record 81: NQUALT30
0
*Record 82: NQUALT31
0
*Record 83: NQUALT32
1
*Record 84: NQUALT33
1
*
****************************************************
*          End of input of the transport module
****************************************************
```

The bottom-input file; md-bott.h12:

```
****************************************************
*
*                    INPUT FORM OF BOTTOM MODULE
*
****************************************************
*
****************************************************
*          Description
****************************************************
*
*0
0          0          0          0
0.400000              0
0  2147483647  1440   0  2147483647   10080  2
1          1          1          1
12
'endbend'   61         12
'hwchannel' 24         7
'outbend'   30         32
'inbend'    30         27
'begin'     2          11
'shallow'   15         25
'punt'      17         7
'wilgen'    33         14
'droog'     21         36
'gras'      22         15
'rand'      24         3
'pioniers'  30         14
1          4
2          4
3          4
4          4
5          4
6          4
7          4
8          4
9          4
10         4
11         4
12         4
13         4
14         4
15         4
16         4
17         4
18         4
19         4
20         4
21         4
22         4
23         4
24         4
25         4
26         4
27         4
28         4
```

29	4		33	33	4
30	4	4			
31	4				
32	4				

The files above are the ones used for the reference scenario and the research scenarios that turned out to be not entirely correct. The final improvements are given below. These replace the parts marked in grey above:

h12.mdf:

```
Flpp  = 0.000000 1.00 8.94096e+006
```

morf.h12:

```
* Record 12.2 --> Specification relative time intervals
* NOTE: has to be specified for active physical processes
* Phys.Process - Relative Start Time - Relative Stop Time
*--------------------------------------------------------------------------
        2        0        10

* Record 12.2 --> Specification relative time intervals
* NOTE: has to be specified for active physical processes
* Phys.Process - Relative Start Time - Relative Stop Time
*--------------------------------------------------------------------------
        3        0      0
        4        0      1440
```

md-tran.h12:

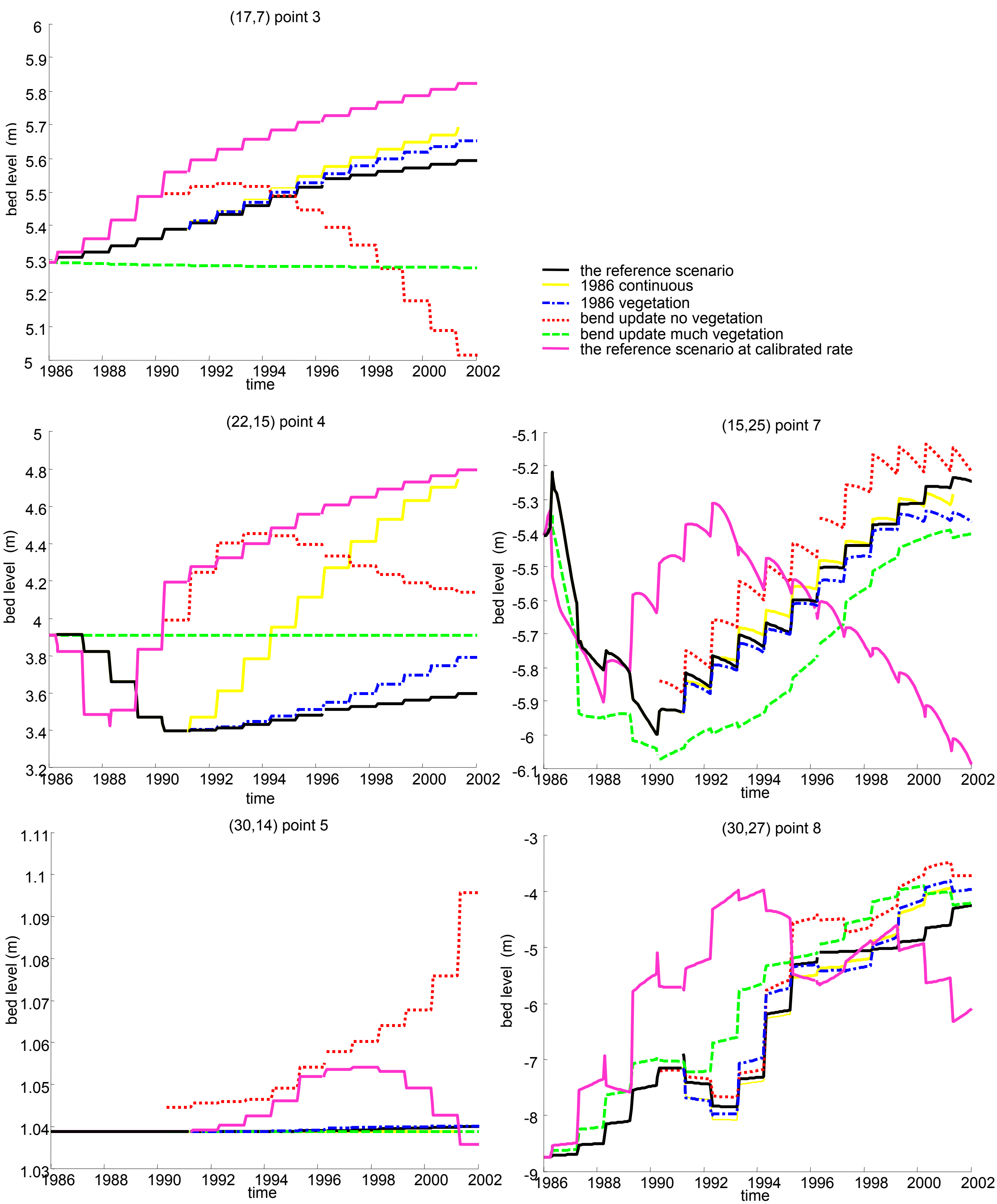
```
*Record 3: INSTF
.false.

*Record 13: IDTS, NTSI
1              0
```

md-bott.h12:

```
0   2147483647   43200   0   2147483647   43200   2
1              0              1              0
```

Annex 5 Bed level graphs



Annex 6 Flow velocities and sediment transports in observation points

Table A6.1 Depth averaged flow velocities and sediment transports at observation points for all research scenarios.

Observation point number	Reference scenario in 1986	Reference scenario in 2002	Reference scenario at low discharge	1986 continuous	1986 vegetation	bend update much vegetation	bend update no vegetation
Depth averaged flow velocity (m/s)							
3	0.26	0.25	Dry	0.38	0.23	0.11	0.81
4	0.96	0.60	Dry	0.99	0.74	0.34	0.94
5	0.28	0.45	Dry	0.32	0.51	0.26	0.73
6	0.28	0.16	Dry	0.33	0.17	0.27	0.57
7	1.97	1.90	0.96	1.86	1.86	1.91	1.84
8	1.76	1.92	0.67	1.99	1.98	1.95	1.93
Sediment transport (m^2/s)							
3	2.5E-15	7.3E-14	Dry	No value	3.8E-13	3.7E-16	2.9E-06
4	1.9E-04	1.8E-07	Dry	No value	1.9E-06	8.4E-17	6.2E-06
5	3.0E-17	3.9E-09	Dry	No value	1.0E-17	2.6E-17	7.5E-07
6	3.2E-17	6.7E-18	Dry	No value	4.2E-08	3.0E-17	1.6E-07
7	1.7E-04	6.7E-05	3.4E-06	1.7E-06	1.1E-04	1.2E-04	1.0E-04
8	7.7E-05	8.5E-05	4.0E-07	1.6E-05	1.5E-04	1.4E-04	1.5E-04

- The location of the observation points can be found in Figure 4-7.
- All values have been derived from the communication-file since the transport history files do not give useful output; some time step is included in that output.