Validate results of river bends modelled by Delft3D 4 Suite and D-Flow FM

Additional master thesis

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Preface

This report is the result of an additional thesis, executed at Deltares. The research is part of the master program Hydraulic Engineering at the Technical University Delft and belongs to the specialization River Engineering. I have done this for more insight into that specific part of Civil Engineering.

In this report, one can read about the validation of Deltares morphological modelling programs, Delft3D 4 Suite and its successor D-Flow FM with a structured and unstructured mesh on sharp bends. This is validated using laboratory flume results from the Delft Hydraulic Laboratory and the Laboratory of Fluid Mechanics. Also the differences between the two modelling programs are mentioned. By validating the model it is possible to test the improvements made over the last years, and -with the right parameters - the ability to make realistic predictions.

This subject was introduced by Kees Sloff and Willem Ottevanger of the department River Engineering of Deltares. They are continuously busy with the improvement and implementations of these kinds of models. I am grateful that Deltares gave me the opportunity to do research at such a beautiful and helpful location as Deltares and to have a little more insight about all the kinds of projects Deltares is working on. I am especially thankful for the help of Willem Ottevanger, who was always kind and patient.

Abstract

The use of rivers for navigation and the increased human activity along their banks generally requires river control and improvement measures. Most rivers have a natural tendency for continuous change of alignment, e.g. meandering and braiding rivers. Construction of bridges, towns, berths, etc. have required fixation of the river alignment at many places, changing the natural morphology of the rivers. This might lead to bank erosion, erosion around bridge pillars, sedimentation of navigation channels, etc. Adequate measures against this requires a reliable prediction of the morphological changes.
For simulating the morphological effects in bends there are two different major factors involved that have been described by several scientists: bed slope effects and spiral flow. For modelling morphological development of a river bend several tests have been done on two different cases that have been researched in a laboratory flume (Delft Hydraulics Laboratory (DHL) and Laboratory of Fluid Mechanics (LFM)) in the 80s. In this research the effects of the major characteristics on the bed development of the bend are examined. This has been done by varying the different input parameters that have influence on the secondary flow and the bed slope effects. Subsequently the varied input files are used to model the same bend with Delft3D 4 Suite, D-Flow FM with an unstructured grid and D-Flow FM with a structured grid. In this way the differences are shown between the different kinds of modelling of the same input parameters.

The parameters that have been tuned are A_{sh}, B_{sh} and C_{sh} for the bedload transport factor that is influencing the bed slope effect. The other parameter is E_{spir} that influence the amount of spiral flow in a bend. The last is α_{cal} that is a multiplication factor in the sediment transport formula from Engelund-Hansen in Delft3D 4 Suite. After optimising these parameters it was not possible to reproduce the flume experiments. Reason for this is probably a simplification in the numerical calculation because with similar parameters of Struiksmas modulation [6] in 1985, which reproduce the flume well, it was still not possible.

To improve the reliability of the model it is recommended to study the following aspects:

- Improvement of the inflow boundary conditions, to improve the way in which water and sediment flows into the system.
- Improvement of the numerical modelling, to create a model that can simulate the characteristics of the river bed in a better way.
- Look for test cases which are close to reality to see if the updates in the model are truly simulating the reality.

By improving these points, the morphological changes might be predicted in a better way than it is in the current situation. Also it will be possible to have less crashes during the run of simulations.

Contents

1 Introduction

To enable delta life Deltares has developed modelling software to describe and predict the direction and values of water, waves, sediment and morphology. It started with different models for different purposes and cases but slowly the functionalities of the different models were integrated. The most common version for two- and three-dimensional simulation of free surface water environment from Deltares is now Delft3D 4 Suite. To keep up with the latest techniques Deltares introduced D-Flow Flexible Mesh. This successor of Delft3D 4 Suite is capable of modelling with different shapes of grid cells besides modelling with curvilinear grids. Now is it possible to connect the familiar curvilinear meshes with the unstructured grid of triangles, pentagons and simple 1D channel networks, all in one single mesh. The advantages of this mesh are more modelling flexibility, decreased computational time and increased accuracy.

The new version creates different solutions compared to the Delft3D 4 Suite version because of a different calculation method. Deltares has existing models of large coastal, delta and river areas operational in the previous grid that have to work similar or better in the new flexible mesh. For that reason some research about the differences in the way of modelling is interesting. With some basic and fast calculating cases it is possible to test D-Flow FM latest settings with Delft3D 4 Suite results on irregularities and errors. The model can also be compared with tests done in laboratories, so model results can be tested on their quality of simulating reality. By removing errors on this small scale the total model can be improved on a larger scale.

In this additional thesis the different outcomes of specific modelling cases are researched. Besides has been tried to give explanations for these differences. In order to reduce the scope of this research, it focusses on the differences of Delft3D 4 Suite and D-Flow FM. Differences between Delft3D 4 Suite and D-Flow FM will be discussed for the following subjects:

- Helical flow (Secondary flow in transverse direction)
- Gravitational bed slope effects

The balance of forces associated to these two processes have to be in equilibrium to obtain a stable river bend. Hence, they are important for predicting the river course. After finding and describing the different ways of calculating those variables on simple cases it is possible to find out what these effects are on larger rivers, with more difficult systems. This forms the basis of this research and is therefore translated into the research question. During this additional thesis answers need to be found to this question. The research question is as follows:

How do secondary flow and slope effects influence the transverse river bed profiles in the D-Flow Flexible Mesh model compared to the older Delft3D 4 Suite model?

Those differences can arise due to different numerical calculations on different types of grids. To explain those differences, more insight is needed about the working of the grid and the computational processes. In addition, the ongoing hydraulically processes are important and need to be understood, as well as the relation between the variables. To find differences between the models, the same cases can be calculated with the different models and subsequently the variables can be plotted next to each other. It is possible to compare the outcomes of the following software:

- Delft3D 4 Suite
- D-FLOW FM with a structured mesh
- D-FLOW FM with an unstructured mesh

In this additional thesis differences have to be found, analysed and solved if possible. Research is done to find a simulation that reproduce two different kinds of flume experiments in the best way. The two cases used are from a sharp river bend which is a replica of the experiment that is done in 1980 in the Laboratory of Fluid Mechanics (LFM), to support research of Koch and an experiment of the Delft Hydraulics laboratory with a less sharp angle. To find the best reproductions of the flume experiment the inflow boundaries, grids and parameters for the sediment transport formula, secondary process and bed slope are changed.

2 Theory

The use of rivers for navigation and the increased human activity along their banks generally requires river control and improvement measures. Most rivers have a natural tendency for continuous change of alignment, e.g. meandering and braiding rivers. Construction of bridges, towns, berths, etc. have required fixation of the river alignment at many places, changing the natural morphology of the rivers. This can give rise to bank erosion, erosion around bridge pillars, sedimentation of navigation channels, etc. Adequate measures against this require a reliable prediction of the morphological changes.

2.1 Physical and theoretical background

River bends have tendency to start meandering, point bars arise on the inner bend and pools on the outer side. The deformation of a river bend is influenced by the interaction between the turbulent water motion and the sand particles [6]. Some time it was assumed that only the local conditions -such as water depth, bed shear stress, bend curvature and sediment properties- influenced the bed deformations. These parameters effect the balance that is created between up slope drag force by the spiral flow and the down slope gravitational force. Struiksma [6] assumed that this approach was too simple since non-local redistribution of flow and sediment effect the bed slope as well. Struiksma suggested that the lateral bed slope in a bend is also influenced by transitional effects due to differences in the conditions upstream and in the bend. This means that a significant part of the lateral bed slope is due to an overshoot effect induced by the redistribution of the water and sediment motion in the first part of the bend. [5]

The equilibrium bed topography of laboratory flumes and river bends with a simple geometry can be explained quantitatively on the basis of a linear analysis of the mathematical model for the steady state ($\frac{\delta z_b}{\delta y} = 0$) . The basic linear analysis is derived from straight rivers. This simplification provides a simple zero-order solution while the ruling phenomena are almost the same when curves are gentle. The magnitude of the bed and flow disturbance at the entrance to a circular bend can be estimated by the difference between the zero-order solution of the straight reach and the bend.

$$\frac{\delta z_b}{\delta y} = -A f_s \frac{h}{R} \tag{1}$$

In which A is the spiral flow coefficient, f_s the slope factor of grains, h the water depth, R the radius of the streamlines. The left side of the equation is the slope of the bed level in lateral direction. In this linear analysis the secondary flow inertia is neglected because the wavelength of the bed deformation is longer than the relaxation length of the secondary flow. Following, the longitudinal sediment transport rate is expected to be independent to the bed slope, which is permitted when the longitudinal slopes are small. For steady flow conditions the equilibrium bed level can be obtained when the sediment transport normal to the flow direction is zero. The normal flow sediment transport vanishes when the transversal component of the gravity force is compensated by the bottom shear force normal to the flow direction. This shear force depends completely on the way in which the spiral motion has been introduced [2].

The linear solution of the mathematical model is used to analyse the development of alternating bars and meanders in alluvial channels [5]. This analysis leads to the conclusion that the linear stability analysis, which often has been used to explain the development of meanders, only applies to fast migrating bed forms of the alternating bar type. Meanders migrate with a speed negligible compared to the celerity of bars predicted by the mathematical model. This implies that a steady state analysis applies to meanders. Results of a steady state analysis of the linear mathematical model are in fair agreement with meander lengths measured in natural rivers.

Lateral distribution of the flow and the sediment transport are highly significant for the bed development (wave length and damping) downstream of a local bed and/or flow disturbance. Change of curvature, for example by a river bend, can be considered as a bed level and flow disturbance caused by the change of secondary flow which tends to change the lateral bed slope [6].

When bends are curved more strongly, some first-order analysis is involved. This is done by superimposing small perturbations into the zero-order equation. By adding the perturbations to and removing

the second or higher order terms from the mathematical model the linear model is obtained.
The perturbation of the spatial depth is assumed to be harmonic and given by:

$$h' = \hat{h}e^{i(kx+k_w y)} \tag{2}$$

Where

- $\hat{h}$ is a complex number in which the absolute value gives the amplitude and the modulus the phase
- $i = \sqrt{-1}$
- k_w is the wave number in lateral direction
- k is the wave number in longitudinal direction

Inserting this harmonic perturbation into the linearised equation of the mathematical model results in a polynomial from which the wave number k can be obtained. This polynomial has two imaginary roots of different sign, in which the negative part causes the exponentially growing perturbation and the positive root cause damping. The growing perturbation vanishes due to the downstream boundary conditions. The damping perturbation, which is generally large, will damp out quickly and only be visible close to the inflow boundary. The complex roots are mainly dependent on the ratio between the adaptation length of the bed topography and main flow λ_s/λ_w [6].

In this way the bed topography in a long bend is described as a damped oscillation of the transverse bed slope, what physically can be explained by redistribution effects of flow and sediment. Behind the bend entrance the spiral flow will affect the lateral bed slope where the flow gradually to adepts. This redistribution of flow will again initiate pronounced sediment transport due to non-linear dependence of the sediment transport on main flow velocity. This implies that transverse sediment transport occurs which only can be established by an increase of the transverse bed slope (overshoot). The damped osculation is established due to this bed overshoot. This causes an overshoot of the flow velocity which will reverse the sediment redistribution process [5].

Thanks to the linear analysis , it can be found which parameters has large influence on the equilibrium state. The reach upstream of the entrance is influenced by the exponential growing part of the solution, i.e. the negative imaginary root of the equation. Subsequently, at the downstream side of the entrance, only the exponential damping and the two harmonic parts influence the solution. The power b of flow velocity (equal to five in the Engelund-Hansen equation) has large influence on the damping of waves. Increasing b results in less damping, longer waves for small values of $\frac{\lambda_s}{\lambda_w}$ and shorter waves for large values of $\frac{\lambda_s}{\lambda_w}$. In addition a calibration factor has to be introduced to obtain a realistic wave length and damping.

After comparing the experiments from the laboratory flumes with the mathematical model, it was found that two calibration coefficients that influence the model strongly. These coefficients have no relevant physical ground. The first coefficient shifts the main flow to the outer bank, and so allows better simulation of the flow velocities. It can be considered as the convective influence of spiral flow on the main flow. According to the linear analysis an increase of the lateral gradient of the velocity can lead to a larger height of the point bar. The lateral velocity has large effect on the simulated results , so it is important to be similar to the laboratory experiments. The lateral velocity gradient is influenced by a non-uniform distribution of the Ch/'ezy coefficient and/or the spiral motion on the main flow.

The second coefficient influences the direction of the sediment transport with reference to the main flow direction. This is in fact the whole sediment model that contains uncertainties. In the Engelund-Hansen formula that is used in this model, the sediment transport varies with the velocity to a constant power. However this is not for all sediment-transport formulas the case. The linear analysis shows that the wavelength damping rates are quite sensitive to changes of this exponent. This also holds for changes in the angle between the direction of sediment transport and the direction of the depth averaged velocity.

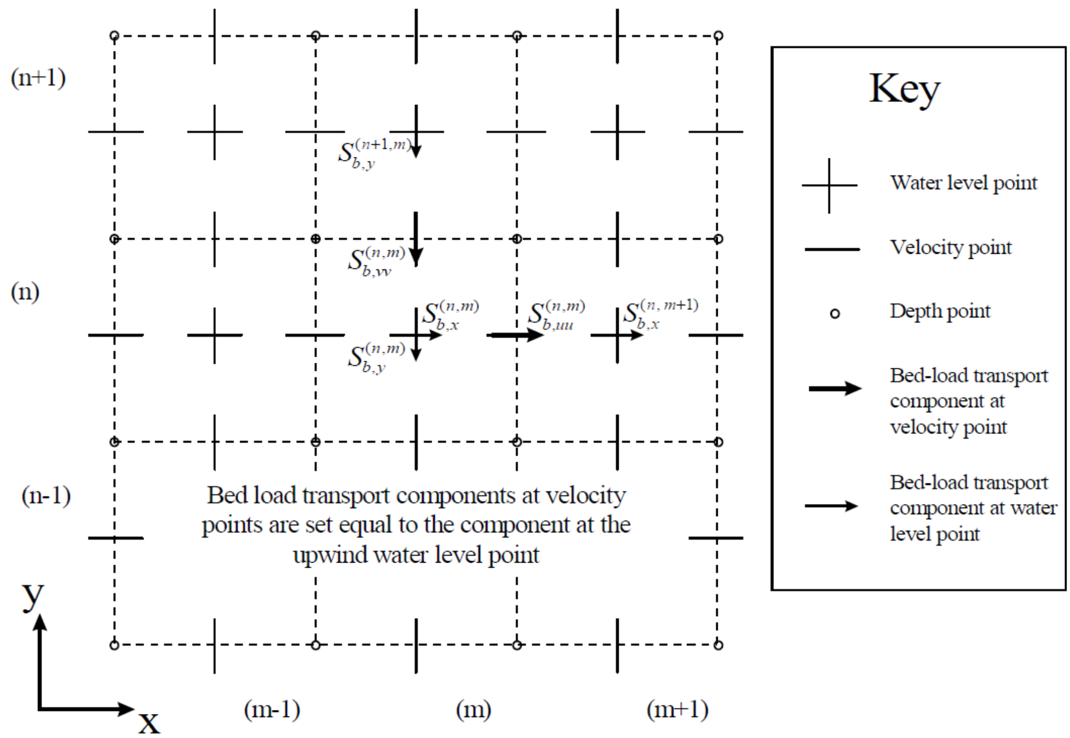
2.2 Computational understanding

To predict the topography of the river channel a mathematical model of the flow and sediment motion is used. This model is able to simulate reality in a computational manner what is less expensive than using for instance a physical-based laboratory scale model. To validate the mathematical model the results are compared with bed topographies of laboratory flumes. The laboratory equilibrium bed levels are quantitatively explainable with a linear analysis of the mathematical model. Besides, the linear analysis provides a good estimation for validating simple river equilibrium bed topography, contour and meander length estimation [6].

The flow in a river is three-dimensional, especially when there are bends which induce a spiral motion. Using a 3-D mathematical model of such flow requires much time and cost for repeated time-dependent morphological computations. For this reason depth-averaged equations are used to describe the flow. These equations are often applied to shallow flows, like rivers [4]. In this case the two-dimensional grid contains information about the depth and velocities of the simulated area.

The numerical method of Delft3D 4 Suite is based on finite differences [1]. To discretise the 3D shallow water equations in space, a curvilinear grid covers the model area. It is assumed that the grid is orthogonal and well structured. The numerical grid transformation is implicitly known by the mapping of the co-ordinates of the grid vertices from the physical to the computational space. The primitive variables water level and velocity (u, v, w) describe the flow. To discretise the 3D shallow water equations, the variables are arranged in a special way on the grid, see figure 1. The pattern is called a staggered grid. This particular arrangement of the variables is called the Arakawa C-grid. The water level points (pressure points) are defined in the centre of a (continuity) cell. The velocity components are perpendicular to the grid cell faces where they are situated. Staggered grids have several advantages such as: Boundary conditions can be implemented in a rather simple way. It is possible to use a smaller number of discrete state variables in comparison with discretisations on non-staggered grids, to obtain the same accuracy. However, the staggering (and mapping) of the different variables introduces some numerical diffusion on the simulated morphology.

Figure 1: A staggered grid



3 Results

In the last chapter we have analysed the influences of different parameters on the bed slope of a river bend. Several variables are made higher, lower or turned off. In this chapter the differences or similarities between the different models and between the models and reality are shown.

3.1 Simulations and reality

The outcomes of the models can be validated with the results of experiments in laboratory flumes. These experiments are done in the 80s by the Laboratory of Fluid Mechanics (LFM) curved channels and by the Delft Hydraulics Laboratory (DHL). The depth profile of these experiments can be compared with the graphs of the models. By adjusting some parameters it was tried to find a good match with reality. Then it was also tried to find an explanation for the found differences.

In the first experiment this model is based on an experiment that is executed by the LFM in four years before 1980 by Sutmuller, A.M. and Glerum, H.L. [7]. The research was part of Applied science water management rivers. It had the purpose to develop a numerical 3-dimensional water motion model, sediment transport model and make observations in models and prototypes to test the numerical models. Until then the research had contributed to publications of de Vriend (1976) and Koch (1980). The curved model was first used with a fixed bottom to research water flow and sediment transport models. Later tests started with a movable bottom of sand. The bend had a curvature of 180 degrees, a radius of 4.25 m and a width of 1.7 m. Other parameters and variables that follow out of those experiments are stated below in table 1.

Table 1: Parameters of the LFM and DHL curved flume

Variable			LFM	DHL (T2)
discharge	Q	(m^3/s)	0.17	0.061
Flume width	B	(m)	1.7	1.5
Water depth	h	(m)	0.20	0.1
Flow velocity	u	(m/s)	0.5	0.41
water surface slope	i_s	$(‰)$	1.8	2.03
Chézy coefficient	C	$(m^{\frac{1}{2}}/s)$	26.4	28.8
medium grain size	D_{50}	(mm)	0.78	0.45
gradation parameter	σ_g	$(-)$	1.15	1.19
sediment transport	s_t	(m^2/s)	13.10^{-6}	$6.9.10^{-6}$
Bend radius	R_c	(m)	4.25	12
Bend length	L_c	(m)	13.35	29.32
Froude number	F	$(-)$	0.36	0.41
Shield parameter	σ	$(-)$	0.28	0.27
-	L_c/B	$(-)$	7.85	19.55
-	B/h	$(-)$	8.5	15.00
-	B/R_c	$(-)$	0.40	0.13

Later in this research the DHL experiment was added to compare simulation results with the flume graphs. The research of the DHL consisted out of several tests with different parameters like water depth and sediment input. For this experiment, in 1985 already a simulation was done to reproduce the flume experiment. It is interesting if the new model can do the same modelling as it did in 1985. For this experiment a grid has been used with less lateral cells but with comparable dimensions.

The model was targeting Dutch rivers, so only bed load transport is considered significant, Froude numbers have to be small and bed forms have small influence compared to the influence of the bend. For the LFM-test 6 samples were tested. The first three were needed for testing and optimising the set-up, and the final three samples were distinctive in the amount of hours they were running and amount of sediment transport input. During the last three tests it appeared that the bed forms had more influence on the water flow than expected [7]. The length of the last three test were respectively 368, 1,204 and

2,124 hours (15.3, 50.2 and 88.5 days). In a straight flume the equilibrium position of the bed is reached at the moment that the sediment input during some time is the same as the sediment output over that same time. Due to the changing bed form over time the equilibrium time needs to be chosen such that it exclude the time dependent character. This is the same case for river bends where the sediment input over time needs to be the same as the output over time. This however does not always implies a static bed level. This bed level can always change over time [7]. On the first test it has been concluded that after 368 the equilibrium shape was not reached. For test 5 and 6 was concluded that the equilibrium was reached after 700 hours of flow.

The tests started with running the cases from the test bank of Deltares. But since this example has no physical experiments, with which it can be validated, the parameters have been changed to the parameters of table 1 also used by the LFM curved flume. For this case an extra boundary condition was added, namely the sediment transport that enters the upstream boundary. With this condition also a restart file is needed because otherwise the imported sediment flow would effected by the static water in the river bend. With the restart-file it is possible to start the simulation with an already flowing river, so the sediment can easier mix with the water. By setting the parameters of the test bank the same as the ones of the experiment in the lab, the results of the simulations can be validated. This is presented in the following section.

3.1.1 LFM-test

Koch The sharp bend tests in the LFM-flume before 1980 have already been simulated by Koch and Flokstra in 1980. At that time they were able to simulate the observed order of magnitude of the bed level variation quite well. The model results were however quite symmetrical while the flume results have a more asymmetric character. It is assumed that the asymmetry of the bed topography was not reproduced due to limited description of spiral motion following their own conclusions. [2]. The parameters used for this old simulation have not been noted so it is not possible to redo the test with the present model. The results of the model simulations are therefore compared with the flume results in a descriptive manner. The model results are showed in a graph with the longitudinal flow velocity and bottom depth. These graphs do not include the flume results. It is found that model II is most similar to the real situation, so this information can be used to give an impression of the expected bed shape.

Figure 2: velocity Koch modelling

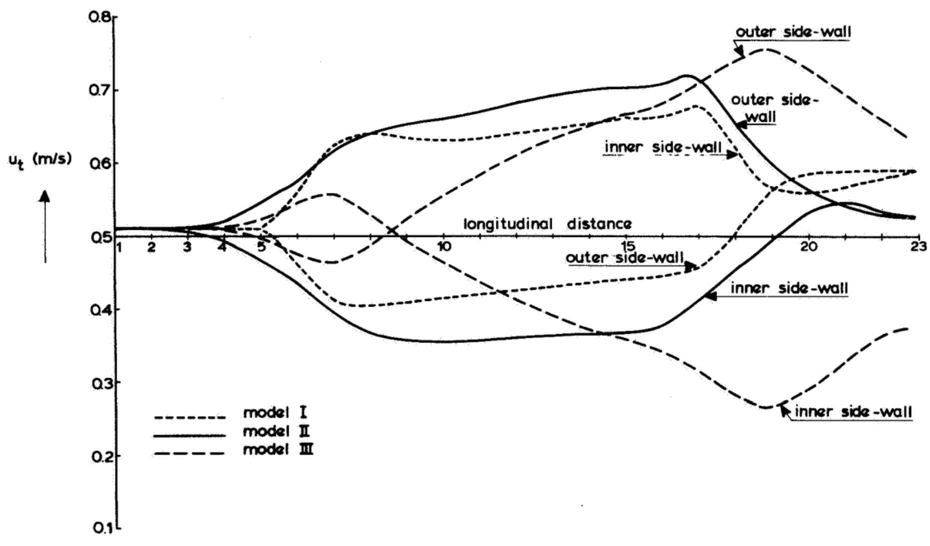
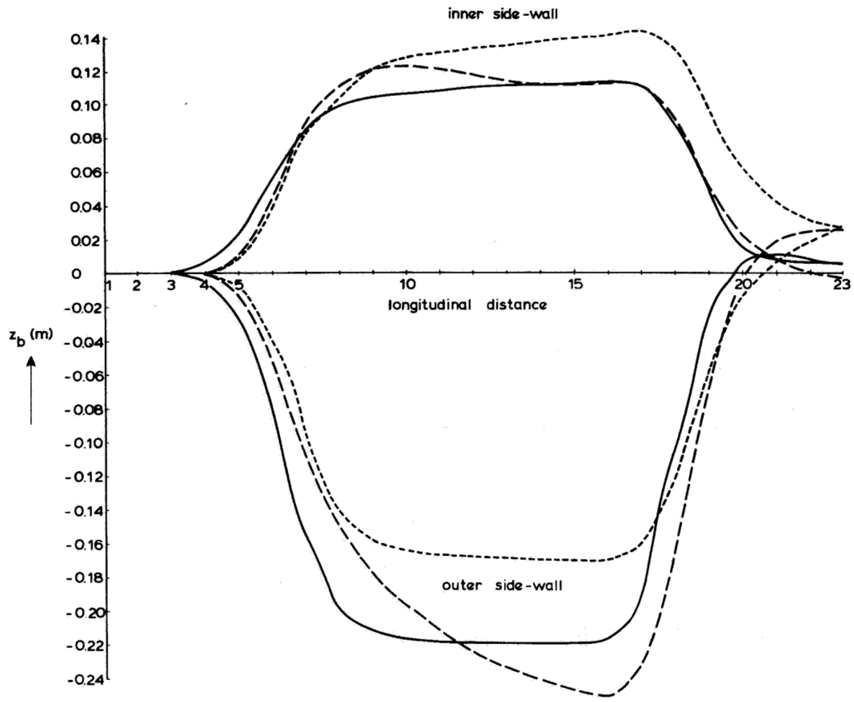


Figure 3: bed level Koch modelling



Struiksma In 1985 Struiksma researched the non-local effects on the lateral bed slope and compared those on different bends with varying radius. He found that the dimensions of the point bar play a significant role in determining the arc length of a river. According to this, the river bend which is discussed here belongs to the more sharp turns and is supposed to have only one clear point bar and pool length similar to the bend length. But because the width/depth ratio in this case is low, this effect disappears and the river bed shape becomes similar to the river bends with longer radius. Struiksma simulated several bends and mentioned the bend of the LFM laboratory but did not simulate this particular bend. In this thesis is tried to simulate the other bends by using the same parameters as for the LFM bend research. In the simulations the parameters of table 1 are used and the additional parameters that have been used for the Koch equation. Those parameters are not clearly defined with an A_{shield}, B_{shield} and E_{spir}. There are however other values given like a factor f_s, an ϵ which is a coefficient in the sediment transport formula and a β for the spiral flow inertia model. Besides, Struiksma speaks about a spiral flow intensity factor I, but is not further described or valued. Koch created the formula that formulated the way that sediment is transported on a transverse slope which is also used in the Struiksma's research, see equation 3.

$$\tan\varphi_s = \frac{\sin\varphi_\tau + \frac{1}{f_s\theta}\frac{\delta z_b}{\delta y}}{\cos\varphi_\tau + \frac{1}{f_s\theta}\frac{\delta z_b}{\delta x}} \tag{3}$$

In which φ_τ is the original direction of the sediment transport including the secondary effects and φ_s is the final direction the sediment will go, including both secondary flow and bed slope effects. $f(\theta)$ equals:

$$f(\theta) = A_{sh}\theta^{B_{sh}}(\frac{D_i}{h})^{C_{sh}}(\frac{D_i}{D_m})^{D_{sh}} \tag{4}$$

The last part of the formula with C_{sh} and D_{sh} are later added to involve the effects of aggregated sediments. The effect of this is not taken into account. Since it is given that the $f(\theta)$ is 1.5, the A_{sh} and B_{sh} can be determined. To create a similar formula as equation (3) the factors A_{sh} and B_{sh} needs to be 1.5 and 1 respectively. For the E_{spir} is chosen to start with 1 because this is standard in Delft3D 4 Suite. It is the factor to increase the effect if spiral-flow intensity on the transverse slope formula. The

E_{spir} is used to calculate the α_I in the bed-load transport direction ($\tan\varphi_\tau$) which is:

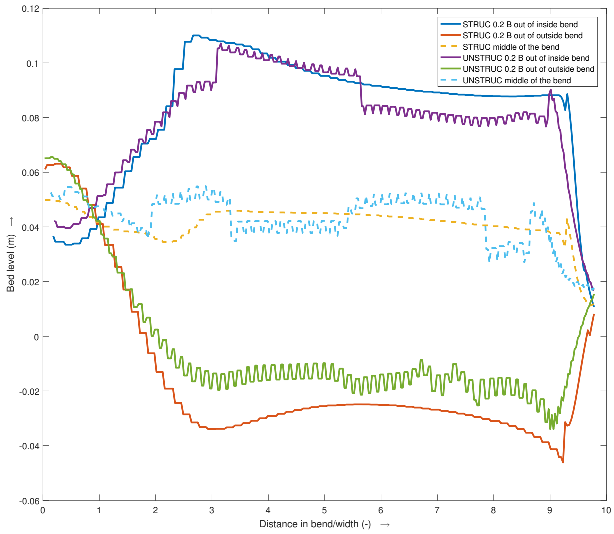
$$\tan\varphi_\tau = \frac{v - \alpha_I \frac{u}{U} I_s}{u - \alpha_I \frac{v}{U} I_s} \tag{5}$$

This α_I is similar to the A parameter that is used in the Struiksma simulations [6] plus E_{spir} added and is:

$$\alpha_I = \frac{2}{\kappa^2} E_s (1 - \frac{1}{2}\frac{\sqrt{g}}{\kappa C}) \tag{6}$$

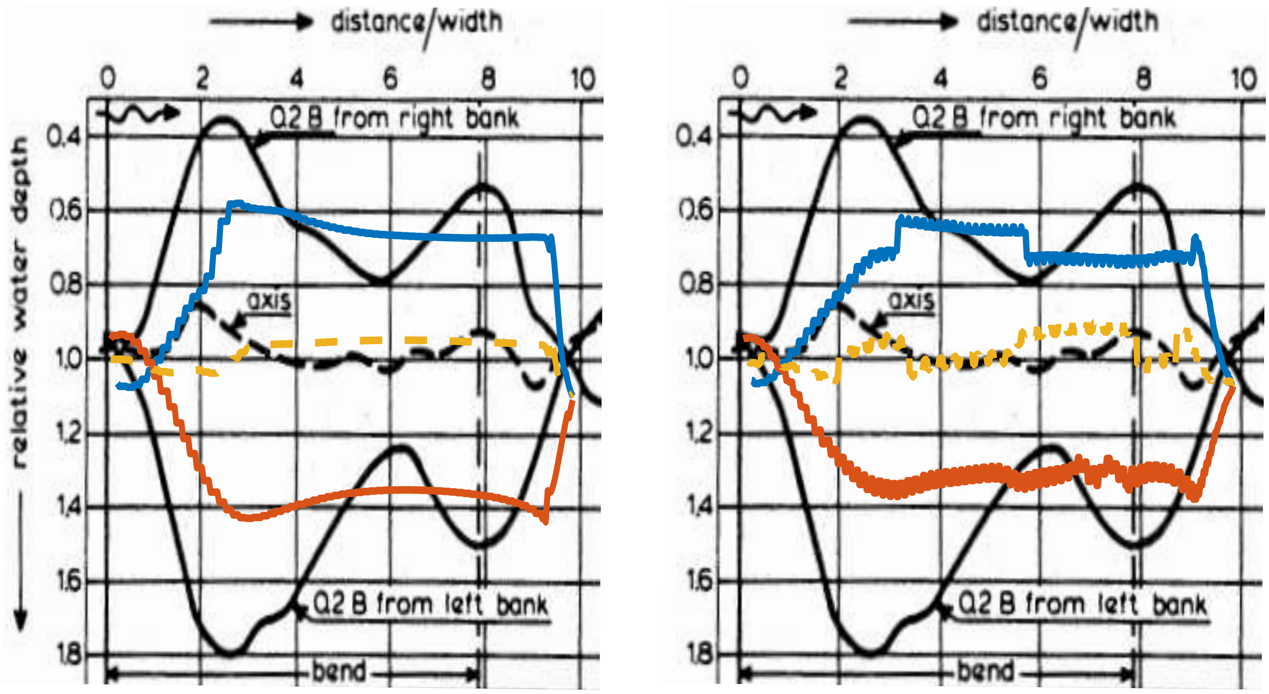
This formulates the direction that results of a stream in longitudinal u and transverse v direction minus the effects of the secondary flow times the scale of the flow (u/U, v/U in which U is the depth averaged velocity). But the simulations that are done with E_{spir}=1 to reproduce the Struiksma formula do not fit the experimental results. Therefore is the E_{spir} set to 0.4, what has been found iterative. Chézy is in the formula as well but will be kept constant.

Figure 4: Bed levels bend for structured and unstructured grid [dflowfm-x64-1.1.192.48215]



From this figure can be distracted that the mean bed level is increased with 5 cm during the run. This is different with the expectations from Koch displayed in figure 3. It is also found that the results, compared with the ratios of the LFM flume from Struiksma are not in the same shape, as shown in figure 5.

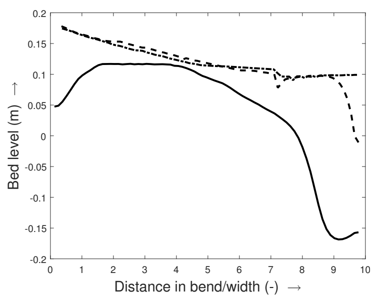
Figure 5: dimensionless depth profiles river bend [dflowfm-x64-1.1.192.48215]



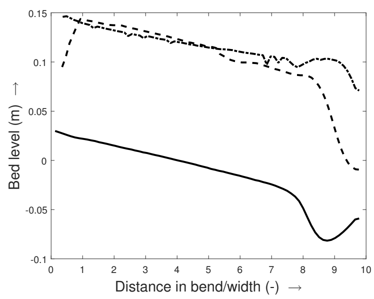
Also can the cross sections of the bed level on several places in the bend be used to compare the simulation with the flume results. Each parameter has a different effect on the equilibrium bed slope. In the figure below bed levels are plotted together with the equilibrium bed levels following from the LFM sharp bend experiment [7].

Since these parameters do not give a good result different parameters are used to compare the results of these with the reality. Used parameters are calculated by Talmon et al. [8] for bends quite similar to the one which is used here. The used parameters were successful for different kinds of bend specifications.

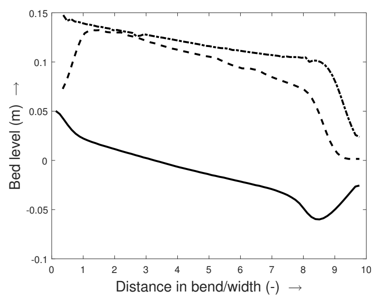
- A_{sh}=1.7 and B_{sh}=0.5
- A_{sh}=0.85 and B_{sh}=0.5
- A_{sh}=9, B_{sh}=0.5 and C_{sh}=0.3



(a) A_{sh}=9, B_{sh}=0.5 and C_{sh}=0.3



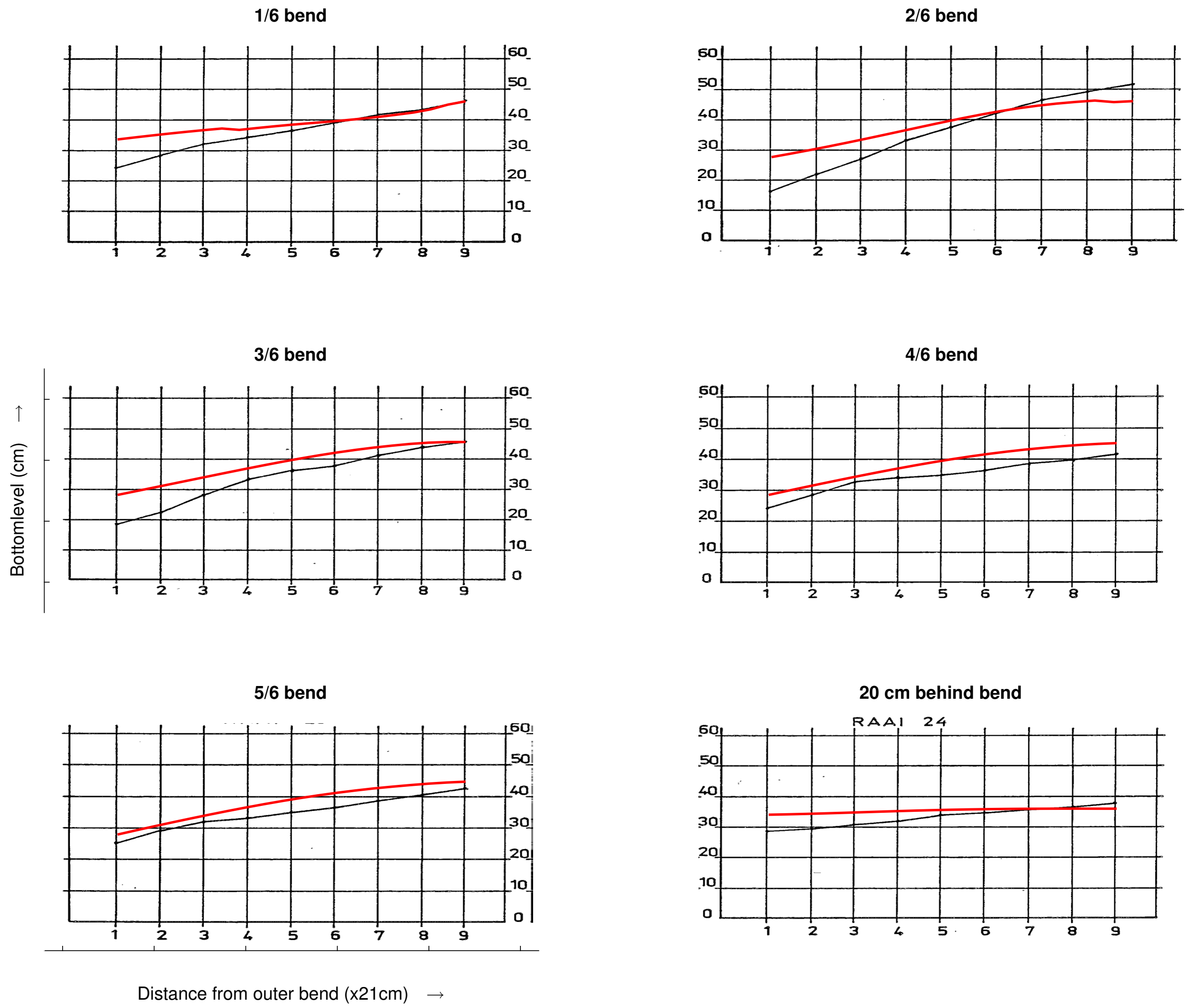
(b) A_{sh}=1.7 and B_{sh}=0.5



(c) A_{sh}=0.85 and B_{sh}=0.5

It appears that also these results do not fit the flume results properly. In fact, the parameters used by Struiksma [6] have a better shape than the ones showed above. When the parameters are varied it appears that using a B_{sh}=0.5 has a negative influence on the bed level shape of the bend. The inner side of the bend (dotted lines) has a wider shallow part since at all the examples the bed levels for the middle part (dashed lines) are nearly similar to the inner side bed level.

Figure 6: Cross sections with Koch parameters [dflowfm-build-linux64-1.1.192.48215]



3.1.2 DHL-test

For this test the inflow is divided over the inflow cells to create a uniform flow distribution over the width of the grid. For this case the equilibrium values are calculated and it is measured what the α_{cal} should be to fulfil the equilibrium conditions. For T2 of the DHL test appears that α_{cal} should be 1.15 instead of the 0.6 what has been used before for the simulations. With values of α_{cal} around 0.6 the simulation crashes most of the times. First a simulation is done with the initial values that have been suggested by Struiksma [6], A_{sh}=1.5, B_{sh}=1.0 and E_{spir}=0.4 and the calculated α_{cal}=1.15. For the equilibrium water depth it was found however that if the same values are used, the results are below those that have been obtained in 1985. When the water depth is added with a value of 0.012 the graph seems to be on the same level as it should be. The reason for this lower water level is unknown. After simulating this first test an alternative test is done with an increased A_{sh} and a reduced E_{spir}, both with a factor 2. This was also done by Struiksma to make the model fit better to the flume results. The result is visible in figure 8 and 9. There seems to be a small difference between the two simulations in the start and tail of the bend. With a factor two reduction and increase of the A_{sh} and E_{spir} respectively a small improvement is made compared to the flume results. The peak in the entrance is however still far underestimated.

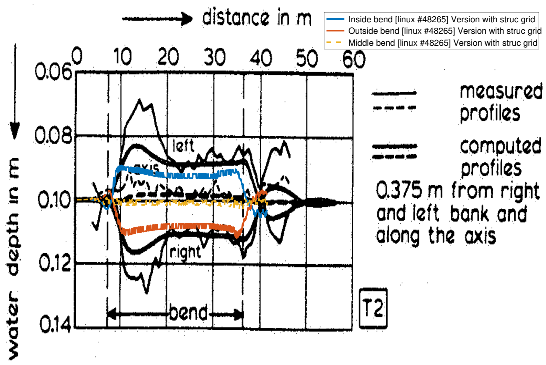


Figure 8: A_{sh}=1.5 and E_{spir}=0.4

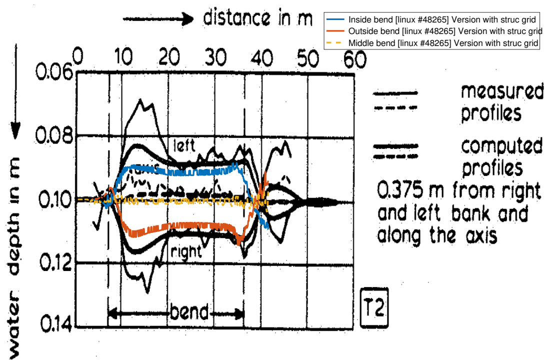


Figure 9: A_{sh}=3.0 and E_{spir}=0.2

The second measure Struiksma took was changing the exponent b in the sediment flow formula. Since this parameter is an important variable in the sediment transport he stated that it is also interesting to change this factor. Normally this factor is assumed to be 5, he simulated the bend with an exponent of 4 to the velocity parameter. The result of changing this factor is a much better fit with the flume results. To reproduce the effect of a changing b, which is not possible to change in the Delft3D 4 Suite or D-Flow FM settings, the α_{cal} is changed. By changing this parameter to a higher value the simulation reach a much better fit than it did before. Instead of α_{cal}= 1.16 is a value of α_{cal}=1.39 used, the results are shown below. By changing the α_{cal} to a higher number has no effect on the deviation of the water depth, the only result is a sinking equilibrium water level. The factor added to the total water depth needs to be increased to reach a better fit when the α_{cal} is increased. This scenario is a bit devious and therefore would a scenario with an Engelund and Hansen formula with b=4 be interesting for later research.

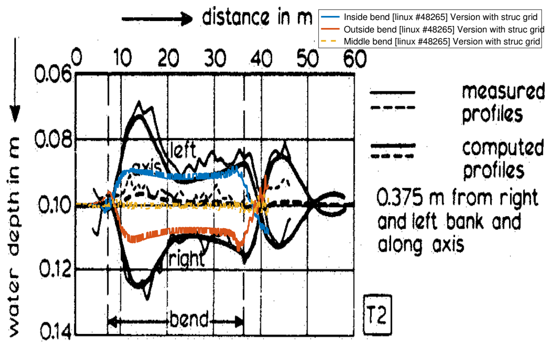


Figure 10: A_{sh}=1.5, E_{spir}=0.4 and α_{cal}=1.16

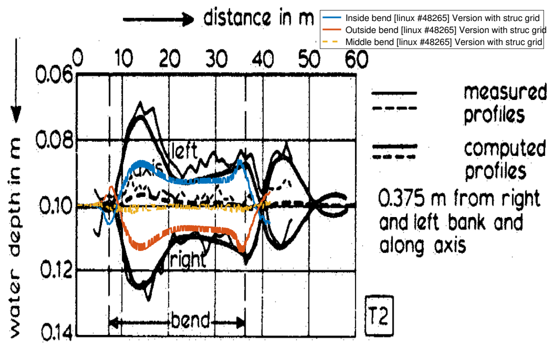


Figure 11: A_{sh}=3.0, E_{spir}=0.4 and α_{cal}=1.39

Still is there a difference of 1 centimetre with the flume results and the Struiksma simulation what is a difference of more or less 10% in the entrance of the bend. In the time for this research have several factors been changed but and tuned but was figure 11 the best fitting simulation.

3.2 Comparison of different models

In this chapter the effects of the different factors that influence the river bed profiles are shown. Each factor has a specific effect on the final equilibrium, which can be indicated by plotting graphs with changed variables. Theoretically the point bar and pools in river bends are created by local effects described by Koch [2] and by non-local effects described by Struiksma [6]. The local effects are created between the gravitational forces and the turbulent flow. The non-local effects are described by a mass-spring system, in which the extension is not dependent on time but on space. In this chapter the influences of different parameters on the equilibrium positions are shown. By varying some parameters the differences between them can be found. This is done with the different programs Delft3D 4 Suite, D-Flow FM with structured and unstructured mesh. To show the differences the variables are shown on specific places of the grid. These locations are the longitudinal inside and outside of the bend and several cross-section in the bend. The different kinds of grids are shown in figure 12 and 13.

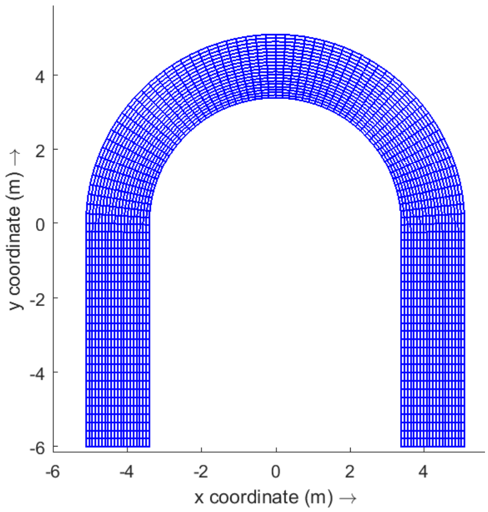


Figure 12: Curvilinear structured grid

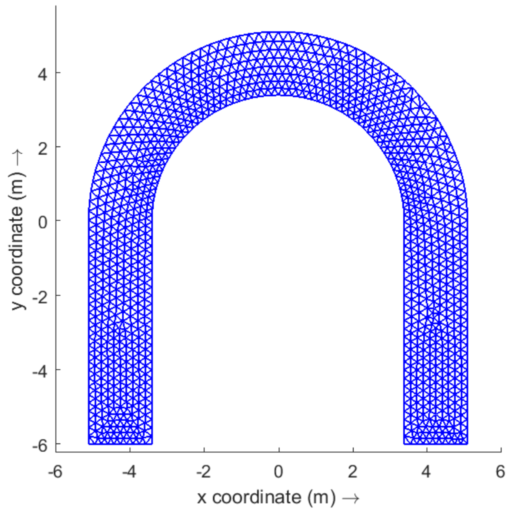


Figure 13: Unstructured grid

The standard is set with a bend with morphological, spiral flow and gravitational effects. The bend is presumed to be in an equilibrium state, just like the other examples. The bend starts with a flat bed and uniform velocity distribution at the inflow boundary. The simulations have already been done for the bend without morphological effects, so the water has an initial velocity and sediment content. In this way the inflowing sediments are better diffused over the whole surface instead of being blocked by the stagnant water. After some time the equilibrium situation with a point bar and pools is reached, visible in figure 14 and 15.

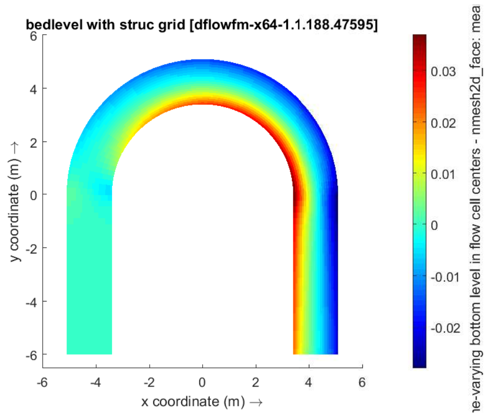


Figure 14: Curvilinear structured grid

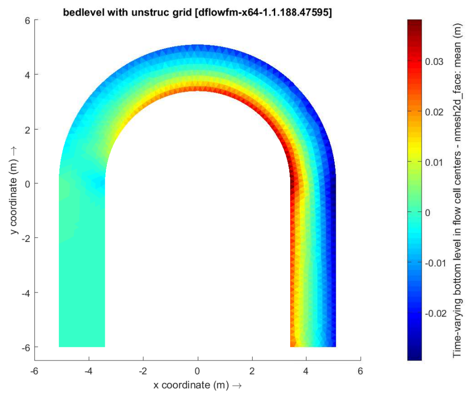
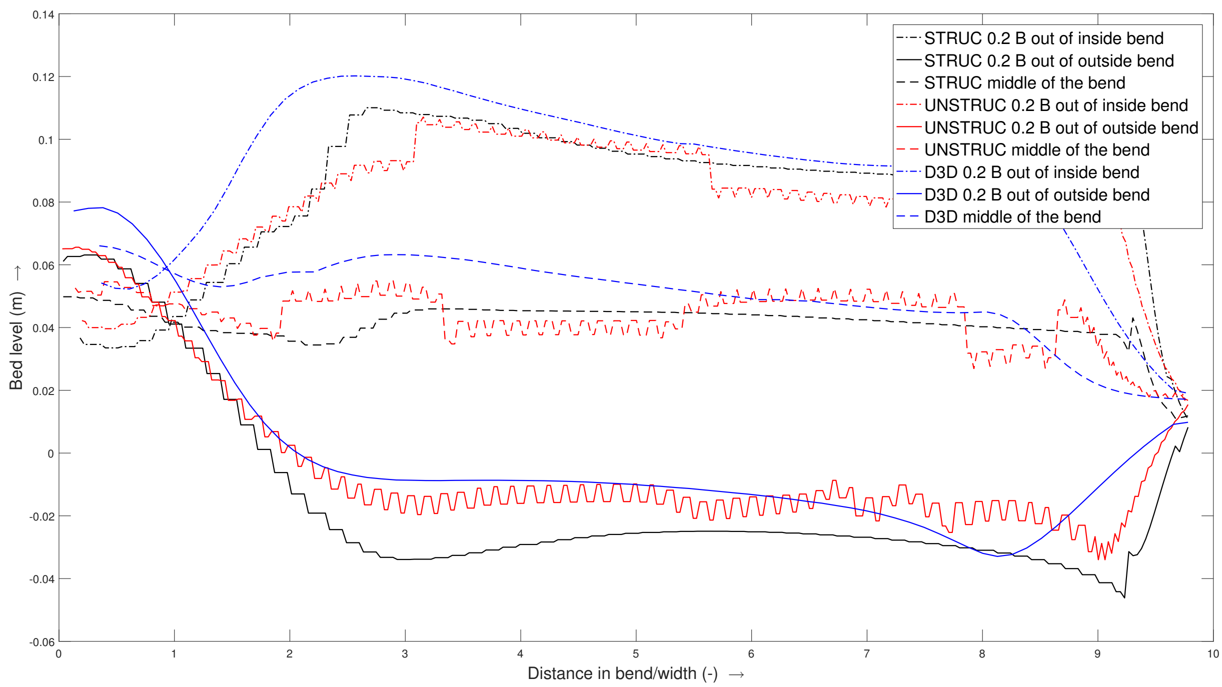


Figure 15: Unstructured grid

3.2.1 With all functions

To clarify the results the depth profiles are shown for both the in- outside of the bend. This is done for the Delft3D 4 Suite and Delft-FM structured mesh and unstructured mesh in figure 16. In this figure is visible how the models process the same parameters in different ways. It is visible that for both profiles an almost symmetrical path is created. One of the differences between the different models is the fluctuated path the D-Flow FM unstructured grid is following compared to the Delft3D 4 Suite and D-Flow FM with a structured grid graphs. These peaks arise due to the fact that the profiles are collected over multiple grid cells, which contain each different values for different variables. The variable for bed level is collected for each of the grid cells through which the line is passing. In the curvilinear grid only grid cells are passed in the longitudinal way instead of cells that vary in their transverse direction. The increasing fluctuation during the passage of the bend is explainable by the increasing difference in transversal bed slope between the unstructured grid cells.

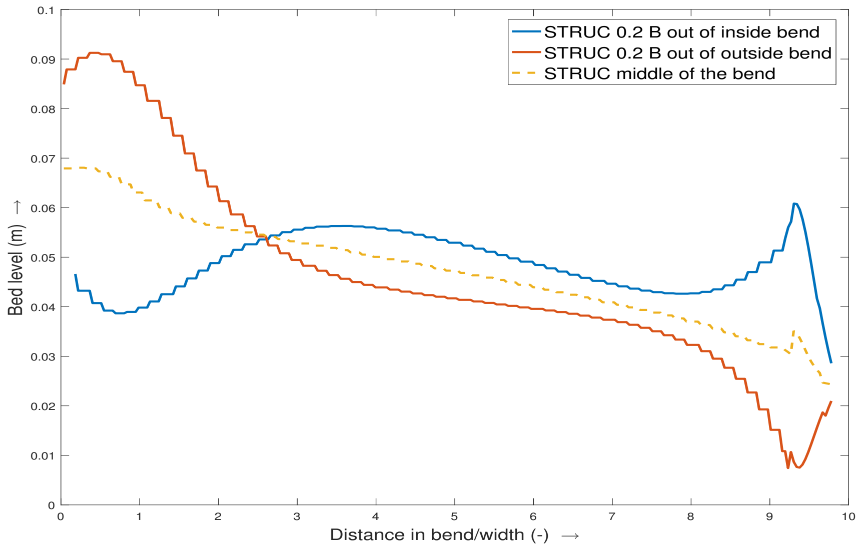
Figure 16: differences between different models [dflowfm-build-linux64-1.1.192.48215] [Version 6.02.06.6075]



3.2.2 Effect of Spiral Flow

First the effect of spiral flow or secondary flow is treated. This is influenced in Delft3D 4 Suite and D-Flow FM by the E_{spir} parameter, when this is turned off a clear difference is visible with the reference bed level. Only at the start and at the end of the bend erosion and aggregation is visible.

Figure 17: Bed level of inside bend without secondary flow



Around the entrance of the bend the transverse water surface slope will grow rapidly from zero until its final value in the bend. So, along the inner bank the longitudinal water surface slope will increase rapidly and cause an acceleration of the flow there. Along the outer bank the water surface slope decreases and the flow decelerates. In turn this ensures a gradual growth of the streamline curvature around the entrance. Due to the increasing velocity the bed level will erode on this point. On the exit of the bend the exact opposite occurs.[5]blz25

3.2.3 Effect of E_{spir} for spiral flow

Since the influence of the different parameters for the bedload transport factor is discussed, now the other major influence of the river bend bed profile is discussed. This is the secondary flow which is influenced in the model by E_{spir}. Below are graphs of a model with a reduced E_{spir} and no E_{spir}. It is visible that the change of secondary flow has only effect in the entrance and exit of the bend. In the middle of the bend this effect is constant. This is caused by the change of curvature in the bend. Since the water enters the bend straight the effect of the secondary flow is largest on the parts where the water curvature changed the most. This change of curvature leads to a damped wave with an overshoot when the damping is low. In the middle of the bend there is a constant curvature of the water flow so is the lateral bed slope mostly influenced by the gravitational influences.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- $A_{sh} = 1.5, B_{sh} = 1.0, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.1$
- $A_{cal} = 0.6$

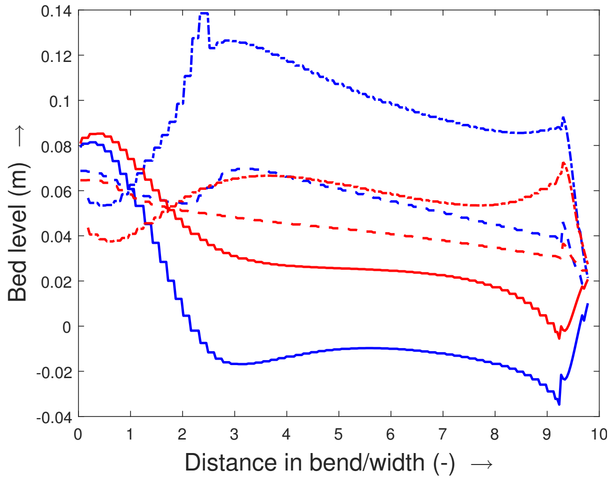


Figure 18: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

Below is the graph of a bend simulation with no secondary flow involved. It shows large deviations at the start and end of the bend, and only very small influences at the middle part of the bend.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- $A_{sh} = 1.5, B_{sh} = 1.0, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0$
- $A_{cal} = 0.6$

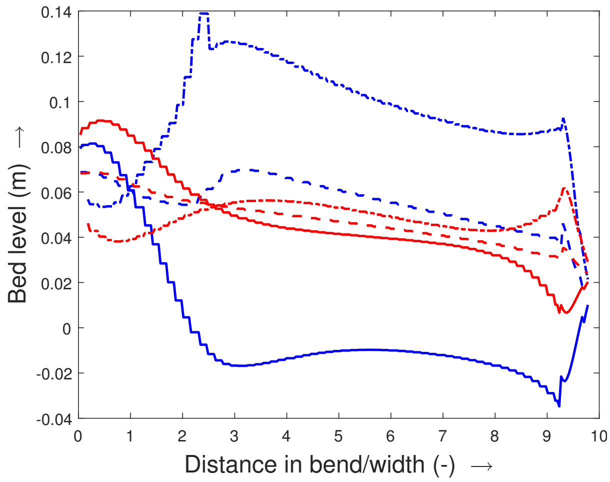


Figure 19: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

The difference between Delft3D 4 Suite and D-Flow FM

In the case of changing the E_{spir} it becomes clear that the same delay of the peak at the exit of the bend is established like the structured and unstructured grid models for the bedload transport factor. At the entrance of the bend especially the structured grid is similar to the Delft3D 4 Suite simulation; the D-Flow FM with unstructured grid simulation slightly underestimates the bed level change.

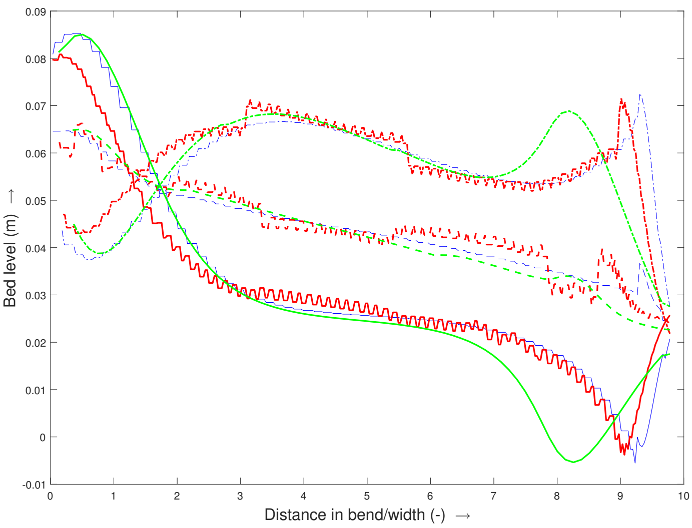


Figure 20: Changing E_{spir} in Delft3D (green), D-Flow unstructured (red) and structured (blue) [dflowfm-build-linux64-1.1.192.48265 and Delft3D 4 Suite version 6.02.06.6075]

3.2.4 Effect of Slope Effects

The other phenomenon that effects the bend bed level, besides spiral flow, is the transverse bed slope. Only few models for the influence of bed slopes on the sediment transport rate (i.e. not on the direction) have been proposed. These models suggest that this effect is caused entirely by a change of the critical Shields parameter. The forces acting on a sediment grain on a sloping alluvial bed are: drag, lift, gravitational, normal and friction forces. Almost all the models for the direction of the sediment transport (or the transverse bed slope) include at least the influence of the drag and the gravitational force, but in some of the models all the forces are considered. Two main groups of models can be distinguished, the models based on a "static approach" and the models based on a "dynamical approach". In the static models the forces on a resting grain are considered or the velocity of the grains is considered much smaller than the flow velocity near the bed. In the dynamical models the computation of the drag force is based on the relative flow velocity (i.e. relative to the moving grains). The model of Koch is used to formulate the bed slope effects. This formula is based on consideration of drag, friction and gravitational forces on a grain at the bed.

When spiral flow is included and the effects of the bed slope are turned off the following effect is visible. When the gravitational force is off, only the spiral flow influences the sediment in the bend. Since the spiral flow forces a sediment flow to the inner bend all the sediment will be transported this direction. Since gravity has no influence in pulling the sediment down the walls reach vertical shapes instead of sloping shapes. Just on the inside of the bend a bar is visible that has a vertically slope while the outside of the bend has a deep pool with vertical slopes. This pool arises because sand is moved to the inner side of the bend while there are no grid cells available to deliver sediment on the outside. Likewise all the sediment is continuously transported to the inner bend where it is piled up.

3.2.5 Effect of the bedload transport factor for the bed slope formulation

This section describes the effect of the bedload transport factor for the Koch formula in the transverse equilibrium bed slope. This factor is determined by different parameters influencing the effect of the Shield parameter or the effects of grain size. The formula for the bedload transport factor is in Delft3D

4 Suite formulated as following:

$$f(\theta) = A_{sh}\theta^{B_{sh}}(\frac{D_i}{h})^{C_{sh}}(\frac{D_i}{D_m})^{D_{sh}} \tag{7}$$

To see the different effects of each parameter, several simulations were done, with each one adjustment. The first plot is done with the following characteristics.

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

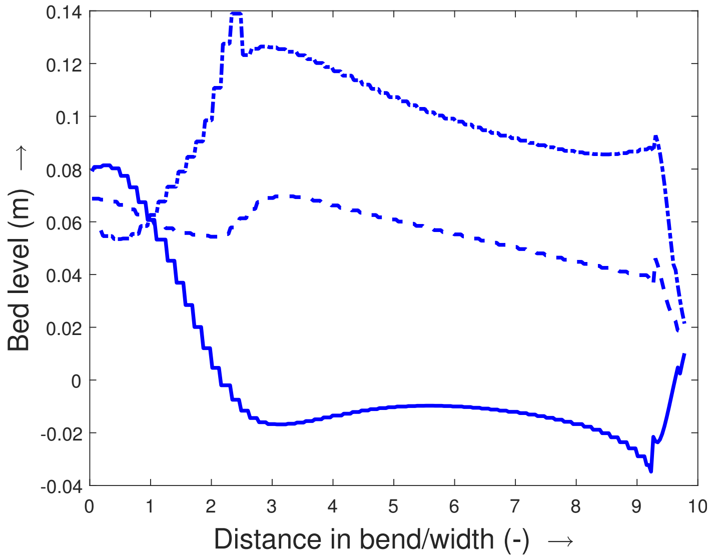
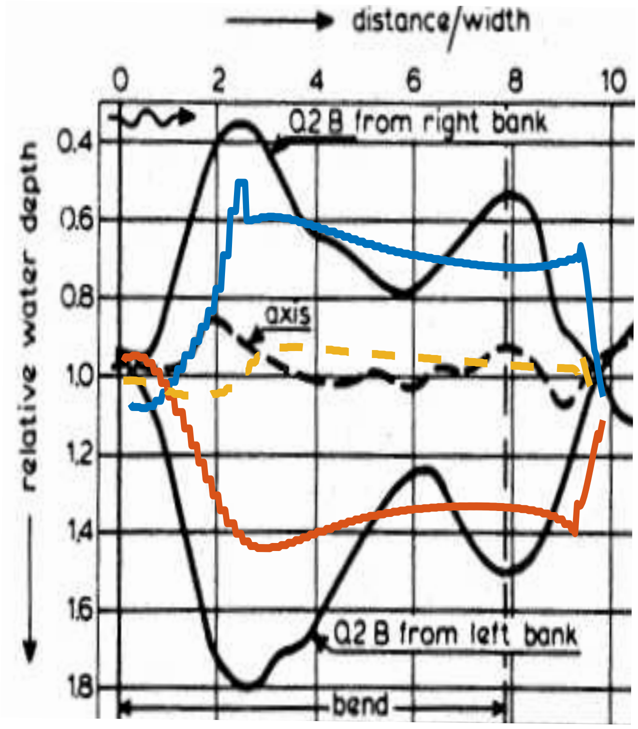


Figure 21: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

This are the same parameters that Struiksma uses in his research to simulate bends with the Koch formulation [6]. This parameters will be set as normal to see the differences with other parameters, in the other pictures this graph will be in the back with blue. To compare results, in sake of clearness only the structured grid simulation of D-Flow Flexible Mesh are plotted, because this shows the effect of D-Flow FM and has no jumpy character such as the unstructured grid. With this plot the following result is made in order to simulate the LFM-flume:

Figure 22: Compared with flume 186 [dflowfm-build-linux64-1.1.192.48601]



Changing the A_{sh} result in a change of a bedload transport factor multiplying the shields parameter in a linear way. In this case the A_{sh} is lowered to 0.6, the effect is visible in the figure below. By lowering the A_{sh} it is visible that the bed level has a lower amplitude. Also the bed level at the bend entrance less affected than it is with a A_{sh} of 1.5. At the outflow of the bend however, still a high amplitude in the longitudinal bed level is visible. The position of the middle bed slope (dotted) gives an impression of the transverse bed shape, in case of a middle bed level in the middle of the out- and inside bed level a more linear bed level is expected. In case of a deviation of the middle bed level of the mean between the in- and outside bed level a more curved transverse bed shape is expected. In this case the transverse bed slope is more linear than with a low A_{sh}. For a more similar bed level with the flume experiment a higher A_{sh} is needed than the initial 1.5 to create a stronger erosion. This can be explained with the Koch [3] formulation because the bedload transport factor influence the amount of bed slope effect on an inverse way. A higher bedload transport factor means less of the bed slope effects on the sediment transport direction. Low influence of the bed slope effects will result in a more skewed sediment transport that is the result of the secondary flow. An lower A_{sh} will increase the amount of the bed slope effects and will bring the sediment transport direction back to normal. When sediment is transported in a more straight direction there will be less sediment transport from the outside to the inside of the bend and thus will the equilibrium shape be less steep as it would be with an high transverse sediment transport angle.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- $A_{sh} = 0.6, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

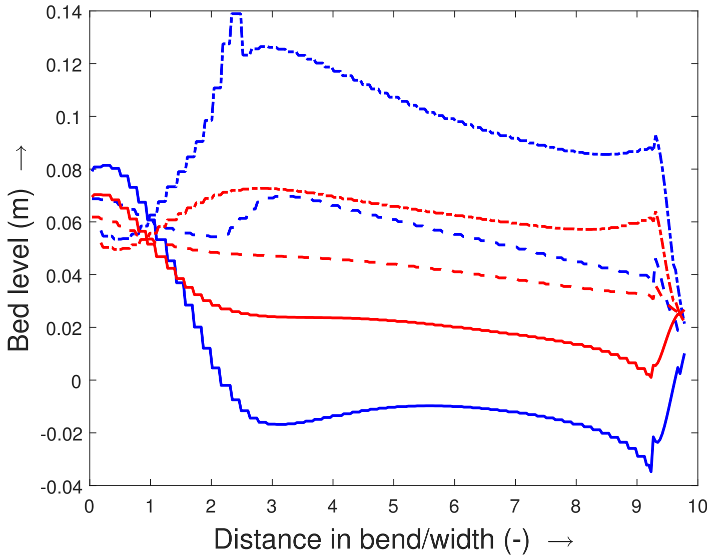


Figure 23: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

Subsequently the B_{sh} is changed, which is the exponent of the Shields parameter. The following differences are visible when they are plotted next to each other. The red graph with the reduced B_{sh} is plotted from the unstructured grid simulation because the structured run with the same parameters crashed. The plot makes the comparison of the graphs a bit harder but with the result of older simulations and this one it seems that the bed level in the entrance of the bend shifts to a lower level. In the end of the bend the bed level returns earlier to its original position. B_{sh} influence the effect of the Shields parameter that is changing with the flow through the bend. Shield is dependent on the flow velocity, Ch/'ezy, relative density of the submerged sediment and sediment diameter (see equation 8).

$$\theta = \frac{u^2 + v^2}{C^2 \Delta D_{50}} \tag{8}$$

Since only the velocity in u and v direction will change in the bend this will also change the Shield parameter in the bend. The B_{sh} will influence how this affects the transverse slope. A reason for the difference between the begin and end of the bend with a different B_{sh} could be due to a stronger influence of the shields parameter. The parameter from Shields is in this case a value below one. With a B_{sh} also below one the denominator of the bed slope will be higher and thus decrease the influence of the bed slope effects. In the first part of the bend it is possible that the effect of the low B_{sh} is visible, but due to a Shields parameter closer to one, the effect of a lower B_{sh} is vanishing.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- $A_{sh} = 1.5, B_{sh} = 0.8, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

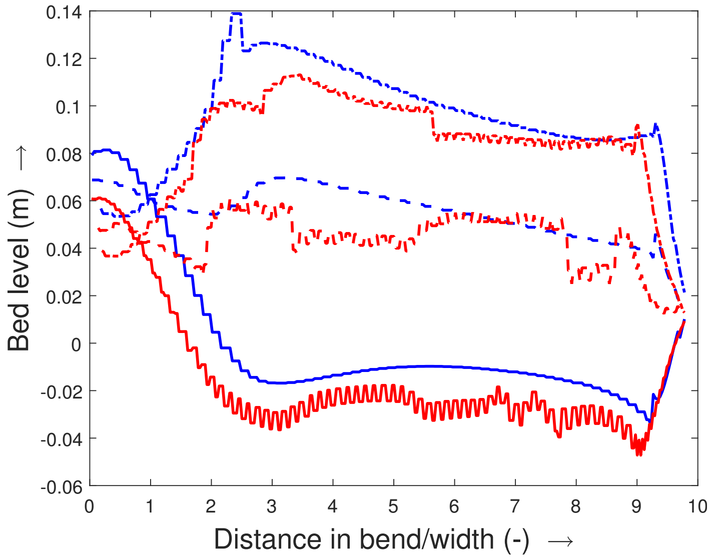


Figure 24: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

C_{sh} into thebedload transport factor simulation has the following effect on the bed shape. Since the parameters introduce the term $\frac{D_i}{h}$ the depth is influencing the bedload transport factor since the sediment diameter remains always the same. The parameters effect is comparable to that of bed forms. In this graph C_{sh} seems to have the same effect as A_{sh} since it reduces the amplitudes of the bed level deviation and thus reduces the dominator of the bed slope effect influence. Probably is the effect of the diameter divided by the depth quite small and is the variation of h not of much influence on the bed level variation.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- $A_{sh} = 1.5, B_{sh} = 1.0, C_{sh} = 0.3$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

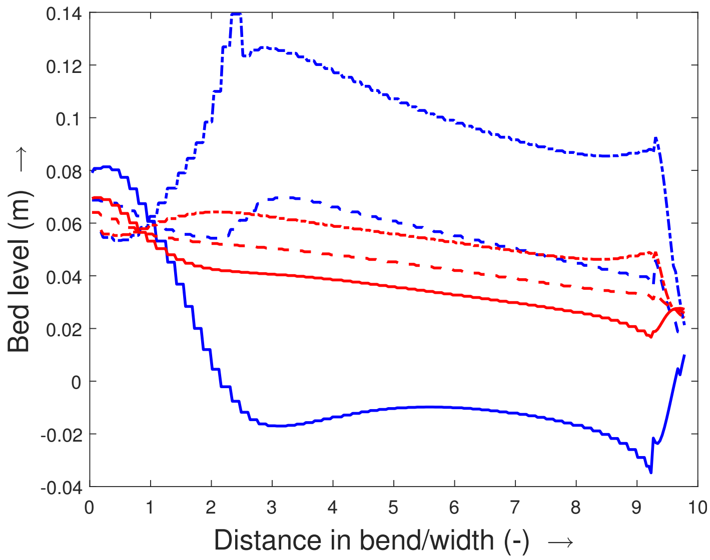


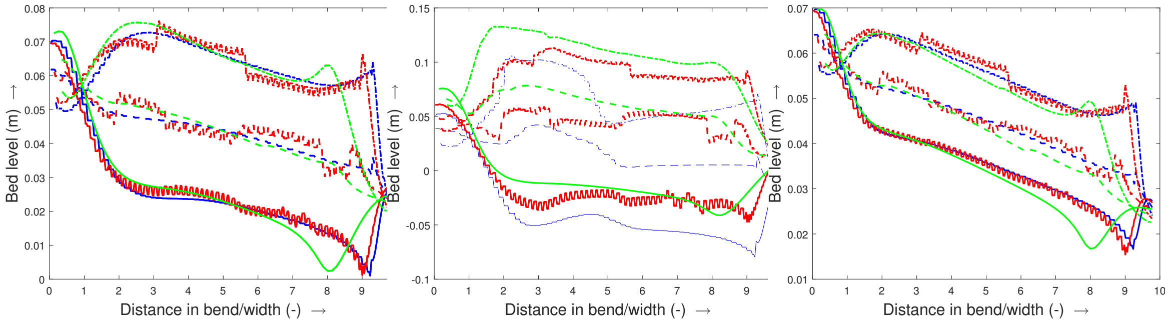
Figure 25: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

D_{sh} have been neglected in this case because in the flume experiments and simulations only one grain size (uniform sediment) was used, and since the D_{sh} parameter is the exponent of $\frac{D_i}{D_m}$ this will have no influence on the final equilibrium.

The difference between Delft3D 4 Suite and D-Flow FM

Due to the different grids and different modelling programs also differences arise between the results. When the models results are compared for the same set of parameters, the following graphs are made, in which the green line is Delft3D 4 Suite, red line is D-Flow FM with an unstructured grid and the blue line D-Flow FM with a structured grid.

Figure 26: changing bedload transport factor parameter in Delft3D 4 Suite (green), D-Flow FM with unstructured (red) and structured (blue) mesh [dflowfm-build-linux64-1.1.192.48265 and Delft3D 4 Suite version 6.02.06.6075]



(a) changing A_{sh} (b) changing B_{sh} (c) changing C_{sh}

For figure 26b there is a lot of difference between the graphs but this is due to a crashed simulation of the structured grid, mentioned earlier. This is the bed level during the development to an equilibrium and can be neglected (the reason of this crash is probably an error at the inflow boundary). For the other cases there seems to be a similar bed level except for the bend exit. For Delft3D 4 Suite the effect of the exit of the bend appears to start earlier than in D-Flow FM. The peak arises in an earlier stage and subsequently the bed level returns back to the initial bed level earlier. The slope of the Delft3D 4 Suite bed level is however less steep than the D-Flow FM model so they end up both on the same place. The difference between the structured and the unstructured grid does not look very significant (besides that it crashes when the B_{sh} is changed).

3.2.6 Effect the calibration factor in sediment formula

The simulation of the bend is also dependent on the way the sediment transport is interpreted. In this case we have used the Engelund-Hansen formulation which calculates the sediment transport with the following formula:

$$S = \frac{0.05 * \alpha * u^5}{C * \sqrt{g} * \Delta^2 * D_{50}} \tag{9}$$

In this equation the sediment transport is dependent on the velocity with an exponent assumed to be constant. The linear analysis of Struiksma [6] showed that the wave length and damping rate of the bed oscillations are quite sensitive to changes of this exponent. In this case not the exponent b is changed but the calibration factor that also influence the overall sediment transport. When this factor is reduced to 0.45 instead of 0.6 the simulations change bed level indeed. On the inside of the bend a higher and smaller peak in the bed level is visible than with the higher sediment transport factor. On the outside however this peak is not visible. The bed becomes a bit deeper and reaches this depth a bit earlier. This is hard to explain because a lower factor should result in a lower numerator and thus in less sediment transport. Apparently sediment is transported to a point at the inside of the bend due to high flow velocity, after which there is a drop of velocity and thus less sediment transport to transport the local accumulation further into the bend.

In blue

- $A_{sh} = 1.5, B_{sh} = 1, C_{sh} = 0$ and $D_{sh} = 0$
- $E_{spir} = 0.4$
- $A_{cal} = 0.6$

In red

- A_{sh} =1.5, B_{sh} =1.0, C_{sh}=0.3 and D_{sh} = 0
- $E_{spir} = 0.4$
- $A_{cal} = 0.45$

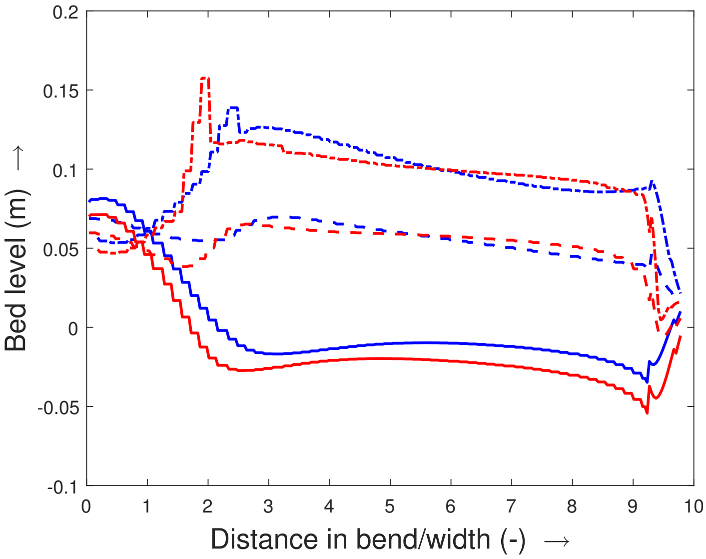


Figure 27: Bed levels bend for structured grid [dflowfm-build-linux64-1.1.192.48265]

The difference between Delft3D 4 Suite and D-Flow FM

In this case the differences are quite large compared to the differences of the E_{spir} and bedload transport factor. First of all it is visible that the peak at the entrance of the bend is only established for the structured grid simulation with D-Flow FM. This look like a good simulation of reality but is not calculated in the other models. The in- and outside bed levels are different for every model and it seems that the mean bed of the Delft3D 4 Suite model is higher than the D-Flow FM calculations. Apparently something is calculated differently in the sediment transport formula what causes differences between the models. It is possible that Engelund and Hansen does not predict the conditions well for a sharp bend like this one, since also the reduction of the A_{cal} has not the expected influence on the final bed shape, i.e. a more steep bed level shape.

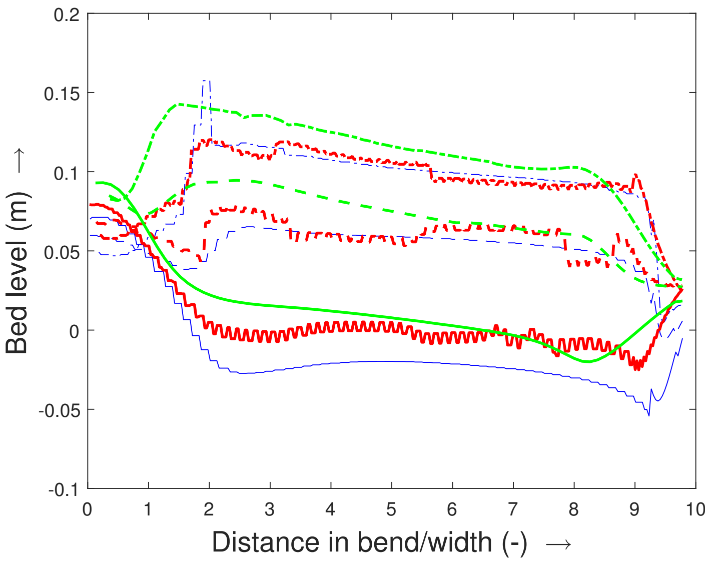


Figure 28: changing bedload transport factor in Delft3D 4 Suite (green), D-Flow FM with unstructured (red) and structured (blue) mesh [dflowfm-build-linux64-1.1.192.48265]

4 Analyses

During the construction of a model similar to the tested bend several obstacles avoid a direct good solution. In this part several obstacles are described and explained.

For simulation of the LFM-flume a sediment transport at the inflow boundary has been imposed. When no sediment was added the mean bed level started to decrease, taking a lot of time. For reaching an equilibrium, more than 10 days in the model were needed what also took a lot of calculation time. This explains a lower equilibrium bed level position which needs time to erode.

By adding the sediment to the bend at the inflow boundary a new problem arose due to accumulation at the inflow cells. This accumulation resulted in a bed level higher than the water level what is remarkable. The first part of solving this problem was to start with a bend that was already in a flowing condition instead of static water. The initial bed level was however still horizontal. By having an initial velocity, which contains sediment as well, it is possible to blend the incoming sediment better with the water in the bend. In D-flow this is possible by making a restart file of a non-morphological run. In this way a part of the problem was solved, meaning that the sediment did not stack up as high as it did before. However in the inflow edge at the outer side of the bend is still an accumulation visible. This is probably created by the bend that pushes the water to the outside of the bend.

This effect is still present at the inflow boundary. The inflowing water and sediment at this side has a little bit more resistance to flow in the system. Due to the resistance the water is probably deflected to the other side of the inflow boundary. Since a small effect of the curve is still observable at the inflow, also transverse sediment transport can be present and moving the particles into one direction. Since the edge has less water to move those particles downstream a circle arises with sediment transport to the edge and less capacity of this edge to move this sediment the result of such event is visible in figure 29, where the flow is entering right and flows to the left. Avoiding the skewed distribution of water and sediment resulted in inflow boundaries of only 1 cell wide. By imposing an inflow of water and sediment of only one cell the system is not able to divide the inflow over its length. After this adjustment no remarkable accumulation was found at the inflow boundary. The inflow distribution led to an update of the D-Flow FM by an added equilibrium flow intensity.

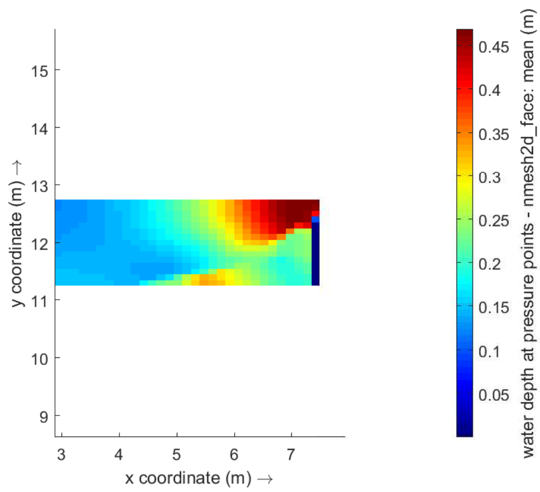
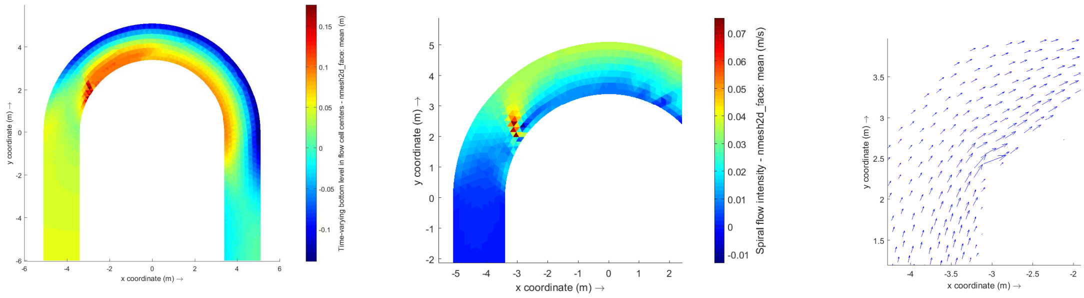


Figure 29: Inflow with one inflow boundary

Since the inflow at the boundary worked well, some more test could be done by varying the parameters. However, the D-Flow FM still crashed some times, which is likely caused by a cell on the begin and inside of the bend that has a lot of accumulation and reaches extreme heights (bed level above water level). In time this causes a peak in the longitudinal bed level and in cases a crash of the simulation. Below some characteristics of the system are shown. At the end of the research it remained unclear due to which influences this is caused. A possible reason could be that due to the shallow area that arises at the inside of the bend the water flow characteristics are different and give a wrong sediment transport.

Another issue is the equilibrium bed level that is simulated very different when parameters are changed. A change in shape is assumed but the heights are also quite different, sometimes lower than the original bed level and in some cases much higher than the initial bed level. The chosen conditions for the bend



(a) Bed level (b) Spiral flow (c) Flow velocity

are however for an equilibrium solution, so only a changing shape with little net erosion or accumulation would be expected.

The calibration factor in the sediment transport formula has large influence in the outcome for the water depth of the simulated flume. Striking is that the calibration factor in these experiments has an opposite influence for the LFM and DHL experiments. For the DHL simulation a much better result is found by increasing this factor. For the LFM lab however, are the water depths deviations decreasing are compared to the actual results. Here a smaller factor is more appropriate.

5 Conclusion

For simulating the morphological effects there are two different major factors involved that have been described by several scientists, bed slope effects and spiral flow. For modelling morphological development of a river bend several tests on two different cases were done. These considered cases are a laboratory flume at Delft Hydrological Laboratory (DHL), and a flume at Laboratory of Fluid Mechanics (LFM) in the 80s. In this research the effects of the major characteristics on the bed development of the bend have been simulated and examined. This has been done by varying the different input parameters that have influence on the secondary flow and the bed slope effects. Subsequently the varied input files have been used to model the same bend with Delft3D 4 Suite, D-Flow FM with an unstructured mesh and D-Flow FM with a structured grid. In this manner the differences were shown between the different kinds of modelling with the same set of input parameters.

It was found that Delft3D 4 Suite successor D-Flow FM is not as successful for river bend simulation as it was in the time of Struiksma. Major influence on this inefficiency is the inflow boundary condition that is been influenced by the downstream development of the flow. In many cases modelled with D-Flow FM, a turbulent part at the inflow boundary was the preface of sediment accumulation at the inflow boundary. Several measures have been taken to remove this accumulation, like adapted initial conditions with equilibrium flow conditions, a new parameter *equili* to the .mdu file responsible for equilibrium flow intensity and finally a divided inflow. The last measures resulted in more successful simulations, although in several cases they still failed. Remarkable was that the Delft3D 4 Suite did not crash or gave extreme fluctuations. Probably this is the result of a better processing of Delft3D 4 Suite on the inflow conditions than D-Flow FM. This conclusion is drawn because of crashes due to high fluctuations at the inflow boundary. When there was no crash there was sometimes strong turbulence at the same location, while Delft3D 4 Suite did not have this problem. How to solve the inflow boundary condition is unknown yet.

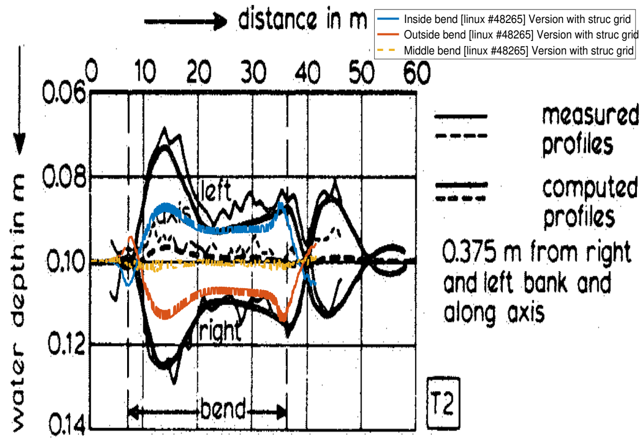
Remarkable is that the simulations done by Struiksma cannot be re-simulate comparably with the new software while the same input parameters are used. This is the case for both the Delft3D 4 Suite as the D-Flow FM with structured and unstructured mesh models. Struiksma [6] started with some initial parameters and adjusted them such that a good fit with the laboratory results was established. By following the same steps, increasing the spiral flow, reducing the shape factor and adjusting the sediment formula for the experiment T2 of the DHL, the same kinds of improvements as Struiksma were found but not with the same magnitude. For the other experiment (LFM) the effect of a change in the sediment transport formula had an opposite effect and gave a worse result than it did before. It was also notable that the effect of the exponent of the Shields parameter in the bedload transport formula β_{sh} had a better result when it was 1.0 while Talmon [8] found that in several cases he studied a squared Shields parameter gave a better fit. E_{spir} on the other side has to be 1.0 to create the same formula as is used in the Struiksma formula for calculating the coefficient in the bed shear stress direction model. With this value the simulation gave extreme deviations at the entrance and exit of the bend, what does not give a realistic result. With the factor 2 reduction for E_{spir} and increased bedload transport factor the bed level and water depth results are more realistic, but also quite straight on the longitudinal axis of the bend. The factor α_{cal} gave again a better water depth result to a laboratory reproduction but is still not close enough at the entrance of the bend. Apparently there are other factors that influence the bend which have not been investigated in this research.

Comparing the simulations which did not crash it appears that both the flexible mesh, structured grid with D-Flow FM and Delft3D 4 Suite gives roughly the same results. Mostly on the entrance and exit of the bend differences arise. Especially in the end of the bend, bed water depth is a lot more natural than the D-Flow FM simulation with a steep point at the in- and outside of the bend. Since the spiral flow is mostly changing at the entrance and exit of the bend, this is probably the reason for a different kind of dealing between the two models. α_{cal} gave mostly differences at the entrance of the T2 DHL experiment so this can also be the reason for influences at the beginning of the bend.

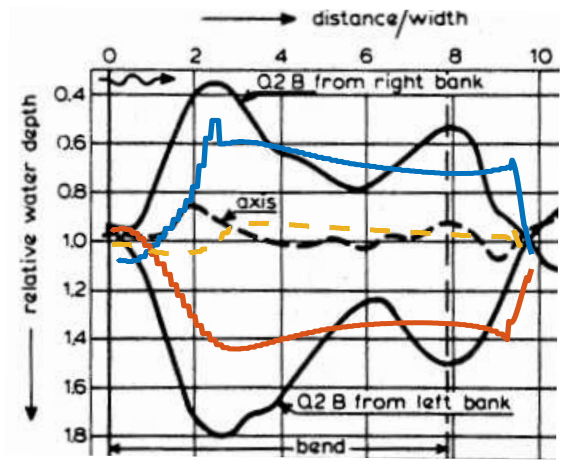
Since obtaining a similar result to the Struiksma modelling has not been reached during this research, the morphological simulation has space for improvement. Interesting is that it was possible with an earlier version of the modelling program. To create more reliable results some points have to be looked at, which are discussed in the next chapter recommendations.

6 Recommendation

In this research is tried to resemble as close as possible the laboratory experiment done in the 80s. This in order to test how well Delft3D 4 Suite and the new D-Flow FM models simulates them. The conclusion is that it is possible to reproduce the flume results roughly, but that some important details are not included. The influences at the entrance and the exit of the bend should be more pronounced in the model. The best test-simulation results which has been done in this test are shown below.



(a) Best DHL-flume simulation



(b) Best LFM-flume simulation

To do realistic modelling for these cases it is important that simulations reproduce flume results well. So more research into improving both Delft3D 4 Suite as D-Flow FM has a lot of value. When the work of Struiksma [6]], which worked quite well, is copied on the current model it appears to work less good as it did 30 years ago. With the variations done with the available parameters there are just small improvements achievable. The reason for this different result could therefore maybe be found in the numerical modelling part.

Recommended is also to improve the manner of input in the system. Many crashes arise due to accumulation or remarkable flows at the inflow boundary. This could partly be fixed by imposing inflow per cell, which was not necessary in Delft3D 4 Suite. This is not conductive for other users to implement every time they set up a model. Improving the inflow conditions can make the system more robust.

Limitations
In this research only the Engelund-Hansen method is used for the sediment transport formula, similar to the Struiksma research. Maybe different sediment transport formulas can improve the simulation. Certainly because the effect of A_{cal} was noticeable compared with the secondary flow and bed slope parameters.

References

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[2] C Flokstra and FG Koch. Numerical aspects of bed level predictions for alluvial river bends. *Delft Hydraulics Laboratory. Netherlands, Publication*, (258), 1981.

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[4] J Kuipers and Cornelis Boudewijn Vreugdenhil. *Calculations of two-dimensional horizontal flow*. Delft Hydraulics Laboratory, 1973.

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[6] N Struiksma, KW Olesen, C Flokstra, and HJ De Vriend. Bed deformation in curved alluvial channels. *Journal of Hydraulic Research*, 23(1):57–79, 1985.

[7] AM Sutmuller and HL Glerum. Beschrijving en evaluatie van metingen uitgevoerd in een bochtmodel met zandbodem. Technical report, TU Delft, Section Hydraulic Engineering, 1980.

[8] AM Talmon, N Struiksma, and MCLM Van Mierlo. Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes. *Journal of Hydraulic Research*, 33(4):495–517, 1995.

Appendix

I) Sediment transport formula formulation

Van Rijn

```
TrasaFrm    =    #flume.tra#        # Sediment transport formula
TraFrm      =     -1
 name       =     'Van Rijn (1993)'
 IopSus     =    0.0
 AksFac     =    1.0
 RWave      =    2.0
 RDC        =    0.01
 RDW        =    0.02
 IopKCW     =    1.0
 EpsPar     =    0.0
```

$$S = 8\alpha D_{50}\sqrt{\Delta g D_{50}}(\mu\theta - \xi\theta_{cr})^{3/2}$$

Engelund-Hansen

```
TrasaFrm                  = #flume.tra#            # Sediment transport formula
TraFrm                    = 1
Name                      = #Engelund-Hansen (1967)#
ACal                      = 1.392
RouKs                     = 0.08
SusFac                    = 0.0
```

$$S = S_b + S_{s,eq} = \frac{0.05\alpha q^5}{\sqrt{g}C^3\Delta^2 D_{50}}$$

where:

q	magnitude of flow velocity
Δ	the relative density $(\rho_s - \rho_w)/\rho_w$
C	Chézy friction coefficient
α	calibration coefficient (O(1))

The transport rate is imposed as bed load transport due to currents S_{bc}. The following formula specific parameters have to be specified in the input files of the Transport module: calibration coefficient α and roughness height r_k.
A second formula specific input parameter (r_k) is required for the Engelund-Hansen formula. This parameter, which represents the roughness height for currents alone in [m], is only used to determine the C value when the Chézy friction in the flow has not been defined. Generally, this parameter can thus be treated as a dummy parameter.

Meyer-Peter-Mueller

```
TrasaFrm          = #flume.tra#       # Sediment transport formula
TraFrm            = 2
Name              = #Meyer-Peter-Mueller (1948)#
ACal              = 4
```

Swanby / Ackers-White

```
TrasaFrm          = #flume.tra#       # Sediment transport formula
TraFrm            = 3
Name              = #'Swanby / Ackers-White'#
ACal              = 1.0
RouKs             = 1.0
```

General formula

```
TrasaFrm          = #flume.tra#       # Sediment transport formula
TraFrm            = 4
Name              = #General formula#
ACal              = 0.08
PowerB            = 2.5
PowerC            = 1.0
RipFac            = 1.0
ThetaC            = 0.047
```

The general sediment transport relation has the structure of the Meyer-Peter-Muller formula, but all coefficients and powers can be adjusted to fit your requirements. This formula is aimed at experienced users that want to investigate certain parameters settings. In general this formula should not be used. It reads:

$$S = \alpha D_{50}\sqrt{\Delta g D_{50}}\theta^b(\mu\theta - \xi\theta_{cr})^c$$

where ξ is the hiding and exposure factor for the sediment fraction considered and

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}}$$

in which q is the magnitude of the flow velocity.

The transport rate is imposed as bedload transport due to currents S_{bc}. The following parameters have to be specified in the input files of the Transport module: calibration coefficient α_b, powers b and c, ripple factor or efficiency factor μ, critical mobility parameter θ_{cr}.

Others

```
if (iform == -3) then
   name      = 'Partheniades-Krone'
   nparreq   = 3
   parkeyw(1) = 'EroPar'
   pardef(1)  = 0.0_fp
   parkeyw(2) = 'TcrSed'
   pardef(2)  = 0.0_fp
   parkeyw(3) = 'TcrEro'
   pardef(3)  = 0.0_fp
   naropt    = 4
   parkeyw(4) = 'TcrFluff'
   pardef(4)  = 0.0_fp
   parkeyw(5) = 'ParFluff0'
   pardef(5)  = 0.0_fp
   parkeyw(6) = 'ParFluff1'
   pardef(6)  = 0.0_fp
   parkeyw(7) = 'DepEff'
   pardef(7)  = -1.0_fp
  elseif (iform == -2) then
   name      = 'Van Rijn (2007): TRANSPOR2004'
   nparopt   = 7
   parkeyw(1) = 'IopSus'
   pardef(1)  = 0.0_fp
   parkeyw(2) = 'Pangle'
   pardef(2)  = 0.0_fp
   parkeyw(3) = 'Fpco'
   pardef(3)  = 1.0_fp
   parkeyw(4) = 'Subiw'
   pardef(4)  = 51.0_fp
   parkeyw(5) = 'EpsPar'
   pardef(5)  = 0.0_fp ! false
   parkeyw(6) = 'GamTcr'
   pardef(6)  = 1.5_fp
   parkeyw(7) = 'SalMax'
   pardef(7)  = 0.0_fp
elseif (iform == 5) then
   name      = 'Bijker (1971)'
   nparreq   = 9
   parkeyw(1) = 'CalBs'
   parkeyw(2) = 'CalBd'
   parkeyw(3) = 'CritCs'
   parkeyw(4) = 'CritCd'
   parkeyw(5) = '[dummy]' !don't remove: backward compatibility!
   pardef(5)  = 1.0_fp
   parkeyw(6) = 'RouKs'
   parkeyw(7) = 'WSettle'
   parkeyw(8) = 'Porosity'
   parkeyw(9) = 'TWave'
  elseif (iform == 6) then
   name      = 'Bailard'
```

```
  nparreq    = 10
elseif (iform == 7) then
  name       = 'Van Rijn (1984)'
  nparreq    = 4
  parkeyw(1) = 'ACal'
  parkeyw(2) = '[dummy]' !don't remove: backward compatibility!
  pardef(2)  = 1.0_fp
  parkeyw(3) = 'Aks'
  parkeyw(4) = 'WSettle'
  nparopt    = 1
  parkeyw(5) = 'BetaM'
  pardef(5)  = 0.0_fp
elseif (iform == 8) then
  name       = 'Van Rijn / Ribberink (1994)'
  nparreq    = 14
elseif (iform == 9) then
  name       = 'Partheniades / Krone'
elseif (iform == 10) then
  name       = 'Ashida & Michiue'
  nparreq    = 3
elseif (iform == 11) then
  name       = 'Soulsby / Van Rijn'
  nparreq    = 3
  parkeyw(1) = 'ACal'
  parkeyw(2) = 'RatioD90D50'
  parkeyw(3) = 'RouZ0'
elseif (iform == 12) then
  name       = 'Soulsby'
  nparreq    = 3
  parkeyw(1) = 'ACal'
  parkeyw(2) = 'ModInd'
  parkeyw(3) = 'RatioD50Z0'
elseif (iform == 13) then
  name       = 'Wang / Fredsoe'
  nparreq    = 2
  parkeyw(1) = 'VicMol'
  parkeyw(2) = 'ACal' ! Don't move up: historical order!
elseif (iform == 14) then
  name       = 'Ashida-Michiue (1974)'
  nparreq    = 5
  parkeyw(1) = 'ACal'
  parkeyw(2) = 'ThetaC'
  parkeyw(3) = 'PowerM'
  parkeyw(4) = 'PowerP'
  parkeyw(5) = 'PowerQ'
elseif (iform == 15) then
  if (name == ' ') name = 'External subroutine'
  nparreq    = 0
elseif (iform == 16) then
  name       = 'Wilcock-Crowe (2003)'
  nparopt    = 1
```

```
    parkeyw(1) = 'ACal'
    pardef(1)  = 1.0_fp
 elseif (iform == 17) then
    name       = 'Gaeuman et. al. (2009) lab calibration'
    nparreq    = 2
    parkeyw(1) = 'ThetaC0'
    pardef(1)  = 0.021_fp
    parkeyw(2) = 'Alpha0'
    pardef(2)  = 0.33_fp
 elseif (iform == 18) then
    name       = 'Gaeuman et. al. (2009) Trinity River'
    nparreq    = 2
    parkeyw(1) = 'ThetaC0'
    pardef(1)  = 0.03_fp
    parkeyw(2) = 'Alpha0'
    pardef(2)  = 0.3_fp
```

II) Run script on linux server

- Create your case map on
n:\My Documents\unix-h6\

- add to case map a *.sh file, containing:

```
#!/bin/bash
#$ -cwd
#$ -q normal-e3
#$ -m abe

./case/scripts/run_dflowfm.sh  **.mdu
```

With first the path to the run_dflowfm.sh file and then **.mdu for your name of the .mdu

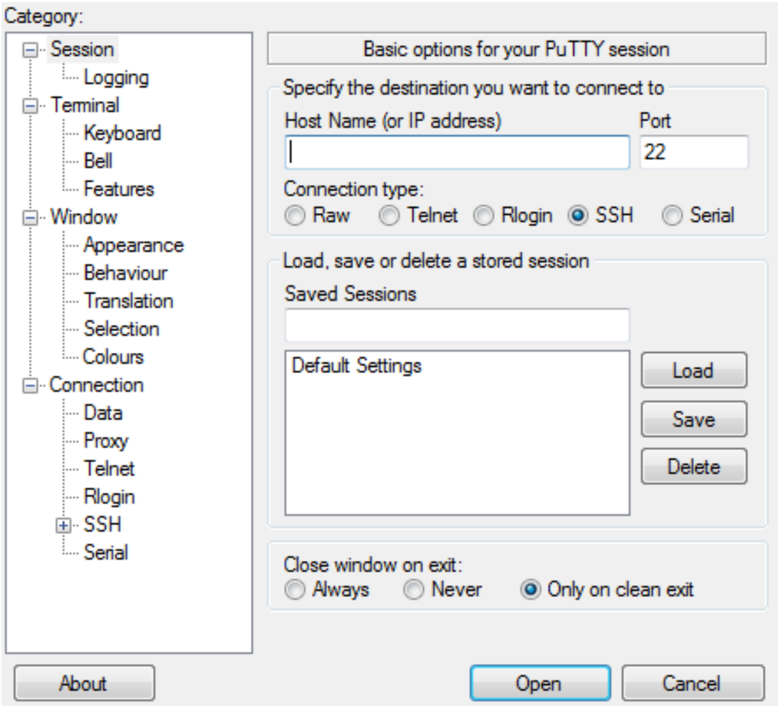
or .mdf file

- download for linux program bin_TB.tar.gz , for instance

  https://build.deltares.nl/viewLog.html?buildTypeId=DFlowFlexibleMesh_BuildFmDistributionsZipped_DflowfmBuildLinux64sedmor&buildId=lastSuccessful&tab=artifacts#!-6ro0z9z1132a

  unzip the file in n:\My Documents\unix-h6\

- Download putty from appstore



- Host name: h6.directory.intra
- Open
- Login with Deltares account
- Create directory to the case folder

cd ~/case

starting script:	*qsub *.sh*
stop script	*qdel *.sh*
overview runs	*qstat*
overview your runs	*qstat –u [user]*

extra:

move back one folder	*./..*
go to folder	*./foldername*