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Contact person
Aukje Spruyt

Direct number
+31(0)88 335 7961

E-mail
Aukje.Spruyt@deltares.nl

Subject
Setting up a 1D-morphological model of the Waal in D-Flow FM

1 Introduction

Within the project ‘Ruimte voor Levende Rivieren’ from the WWF, the goal is to investigate if large scale river intervention measures for increasing the storage and discharge capacity of the rivers (by widening or lowering flood plains, removing obstacles and using water storage and retention areas) can contribute to stopping or slowing down the bed degradation in the river Waal. With exploratory calculations the influence of (combinations of) proposed measures on the sediment transport and long-term bed development of the Waal is investigated (Barneveld et al. 2018).

This memo describes the set up the 1D morphological model of the river Waal in D-Flow FM that can be used to perform these long term simulations and the first results obtained with this model. Furthermore a short description is given of the necessary adjustments in the software that were needed to be able to set up and run this model.

The following persons were involved in this part of the project:
Willem Ottevanger, Kees Sloff, Iris Niesten, Aukje Spruyt, Mohamed Nabi (Deltares), Andries Paarlberg, Carolien Wegman, Hermjan Barneveld (HKV), Marcela Busnelli (RHDHV).

This work is a follow up of (and contributes to) the RiverLab and is performed in cooperation with RWS, HKV and RHDHV.

2 Software development

To make the D-Flow FM 1D code fully suited for setting up a 1D morphological model of the river Waal the following functionalities have been implemented and tested:

1. Discharge/waterdepth dependent roughness
2. Summerdikes
3. Bed level update of cross sections
4. Morphological boundary conditions
5. Output parameters

These functionalities and the available testcases are described in more detail in the sections below.

The most recent version of the D-Flow FM 1D software used for this memo is:
- D-Flow FM Version 1.2.1.62280

2.1 Discharge/waterdepth dependent roughness

Within river models it is desirable to be able to define the roughness (both in the floodplain and the main channel) as a function of the discharge or water depth. This functionality was already available for the D-Flow FM 2D part of the code but now also has been implemented in the 1D part.

The roughness within a roughness section can now be defined as
- constant
- a function of water level h
- a function of discharge Q.

Testcase:
- c61_wl_q_dependent_roughness

2.2 Summerdikes

ZW Cross Sections or Tabulated Cross sections are mainly used in the modeling of rivers. ZW Cross Sections can incorporate a summer dike with additional flow and storage area. The part of the floodplain behind the dike does not play a role in the computation until the waterlevel exceeds the crest level of the summer dike. When a summer dike floods, the extra area is added to the cross section. To prevent the flow area from taking part in the flow process too easily, D-Flow1D uses a transition height above the crest level to ’scale’ the flow into the floodplain. When the water level falls below crest level, the extra area is gradually removed again from the cross section, modeling the water behind the summerdike to flow back slowly into the river until the flood plain is dry again.

Testcases:
- c71_no_summerdike
- c72_with_summerdike

2.3 Bed level update

The bed level in the ZW-cross sections has to be updated due to morphological changes. Only the part in the main channel is adapted, the flood plain level remains unaltered.

Testcases:
- c31_shoal_ds_IBedCond0_us_IBedCond1
- c81_crosssec_update_aggradation

2.4 Morphological boundary conditions

Besides hydrodynamic boundary conditions, also morphological boundary conditions must be prescribed in a morphological computation. Be aware that the boundary condition is actually prescribed in a so called ‘ghost cell’ just outside the domain. Therefore the results at the real boundary might slightly deviate from the condition that is given.
The following options are now available (both for uniform and graded sediment):

1 no bed level constraint :`IBedCond=0`
2 bed level fixed: `IBedCond=1`
3 depth specified as function of time: `IBedCond=2`
4 depth change specified as function of time: `IBedCond=3`
5 bedload transport rate prescribed (volume rate of bed material): `IBedCond=4`
6 bedload transport rate prescribed (volume rate of stone): `IBedCond=5`

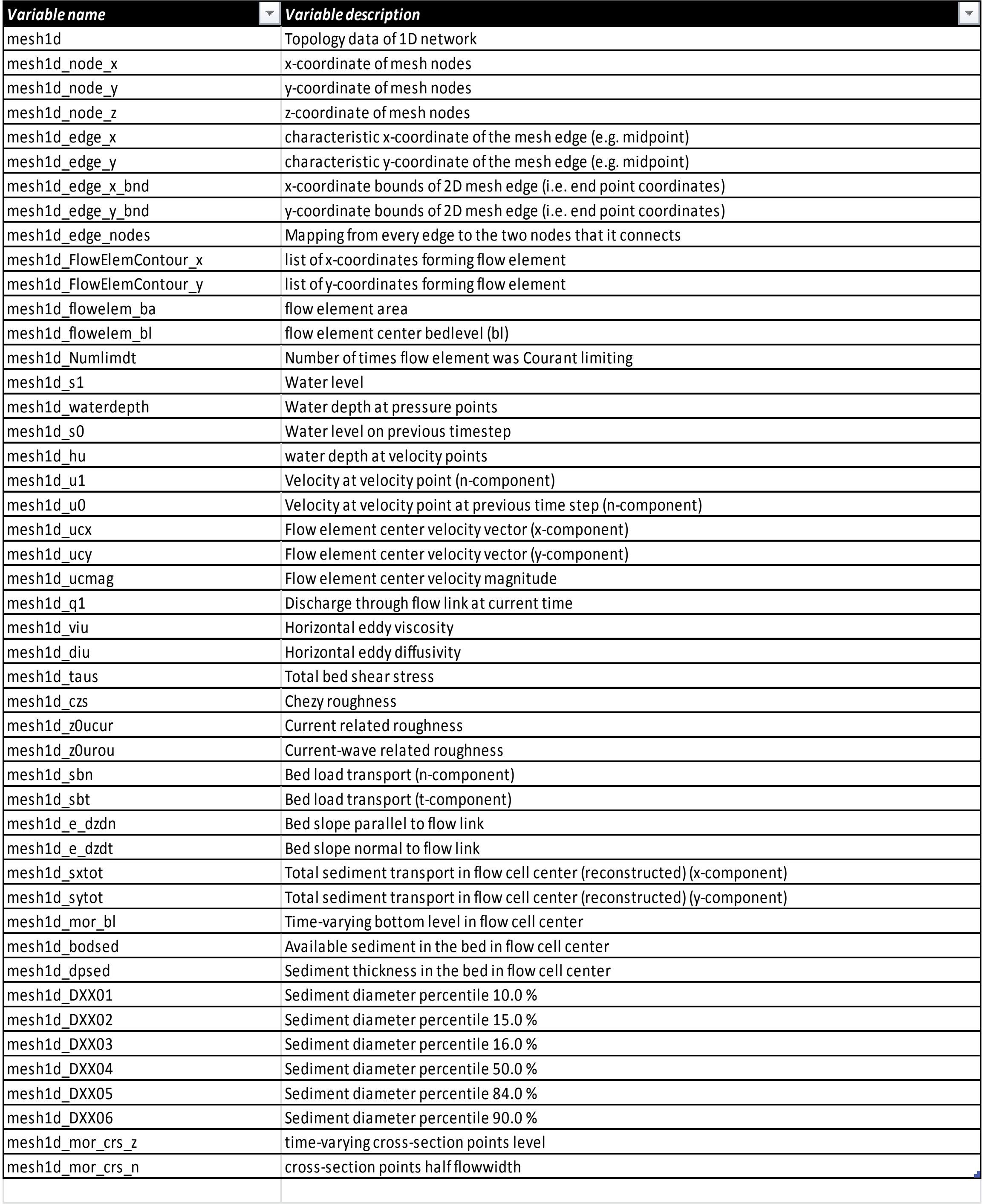
Testcases:

- c05_1D_boundary_condition_iBedcond2_icmpcond2\
- c06_1D_boundary_condition_iBedcond3_icmpcond2\
- c07_1D_boundary_condition_iBedcond4_icmpcond2\
- c08_1D_boundary_condition_iBedcond4_icmpcond0_graded\
- c09_1D_boundary_condition_iBedcond2_icmpcond2_graded\
- c21_equilibrium_slope_ds_IBedCond1_us_IBedCond4\
- c22_equilibrium_slope_ds_IBedCond1_us_IBedCond5\
- c23_equilibrium_slope_ds_IBedCond0_us_IBedCond4\
- c24_equilibrium_slope_ds_IBedCond0_us_IBedCond2\
- c25_equilibrium_slope_ds_IBedCond0_us_IBedCond3\
- c26_equilibrium_slope_ds_IBedCond1_us_IBedCond4_morfac10\
- c27_equilibrium_slope_ds_IBedCond1_us_IBedCond1\
- c28_equilibrium_slope_ds_IBedCond0_us_IBedCond0\

2.5 Output parameters

Several extra output parameters for the map-file are now available to better analyse the (morphological) results. These are given in Table 2.1. The output in the his-file (timeseries) is the same as in 2D (Deltares, 2018).

Table 2.1 Overview of 1d mapoutput of FM1D simulations



Variable name	Variable description
mesh1d	Topology data of 1D network
mesh1d_node_x	x-coordinate of mesh nodes
mesh1d_node_y	y-coordinate of mesh nodes
mesh1d_node_z	z-coordinate of mesh nodes
mesh1d_edge_x	characteristic x-coordinate of the mesh edge (e.g. midpoint)
mesh1d_edge_y	characteristic y-coordinate of the mesh edge (e.g. midpoint)
mesh1d_edge_x_bnd	x-coordinate bounds of 2D mesh edge (i.e. end point coordinates)
mesh1d_edge_y_bnd	y-coordinate bounds of 2D mesh edge (i.e. end point coordinates)
mesh1d_edge_nodes	Mapping from every edge to the two nodes that it connects
mesh1d_FlowElemContour_x	list of x-coordinates forming flow element
mesh1d_FlowElemContour_y	list of y-coordinates forming flow element
mesh1d_flowelem_ba	flow element area
mesh1d_flowelem_bl	flow element center bedlevel (bl)
mesh1d_Numlimdt	Number of times flow element was Courant limiting
mesh1d_s1	Water level
mesh1d_waterdepth	Water depth at pressure points
mesh1d_s0	Water level on previous timestep
mesh1d_hu	water depth at velocity points
mesh1d_u1	Velocity at velocity point (n-component)
mesh1d_u0	Velocity at velocity point at previous time step (n-component)
mesh1d_ucx	Flow element center velocity vector (x-component)
mesh1d_ucy	Flow element center velocity vector (y-component)
mesh1d_ucmag	Flow element center velocity magnitude
mesh1d_q1	Discharge through flow link at current time
mesh1d_viu	Horizontal eddy viscosity
mesh1d_diu	Horizontal eddy diffusivity
mesh1d_taus	Total bed shear stress
mesh1d_czs	Chezy roughness
mesh1d_z0ucur	Current related roughness
mesh1d_z0urou	Current-wave related roughness
mesh1d_sbn	Bed load transport (n-component)
mesh1d_sbt	Bed load transport (t-component)
mesh1d_e_dzdn	Bed slope parallel to flow link
mesh1d_e_dzdt	Bed slope normal to flow link
mesh1d_sxtot	Total sediment transport in flow cell center (reconstructed) (x-component)
mesh1d_sytot	Total sediment transport in flow cell center (reconstructed) (y-component)
mesh1d_mor_bl	Time-varying bottom level in flow cell center
mesh1d_bodsed	Available sediment in the bed in flow cell center
mesh1d_dpsed	Sediment thickness in the bed in flow cell center
mesh1d_DXX01	Sediment diameter percentile 10.0 %
mesh1d_DXX02	Sediment diameter percentile 15.0 %
mesh1d_DXX03	Sediment diameter percentile 16.0 %
mesh1d_DXX04	Sediment diameter percentile 50.0 %
mesh1d_DXX05	Sediment diameter percentile 84.0 %
mesh1d_DXX06	Sediment diameter percentile 90.0 %
mesh1d_mor_crs_z	time-varying cross-section points level
mesh1d_mor_crs_n	cross-section points half flowwidth

3 Model setup

This section describes the set-up of a 1D model of the river Waal in D-Flow FM. First the hydrodynamic setup is explained and after that the extension to include the morphology. Within the ‘Ruimte voor Levende Rivieren’ project also a SOBEK-RE model is used. This latter model is used as a basis for the morphological part and the results of the FM-1D model are compared with the results from SOBEK-RE.

3.1 Hydrodynamics

The FM-1D model of the river Waal is based on the existing SOBEK3-model of the Rhine branches: sobek-rijn-j17_5-v1 (available through the Helpdesk Water), see Figuur 3.1. The SOBEK3-model is cut to only contain the river Waal and then exported to a DIMR[1]-configuration (existing only of ASCI-files) within the interface of SOBEK3. These files can be used to run the SOBEK3-model in command-line mode, but the same files can be imported in D-Flow FM. In this way the 1D network, cross sectional profiles, discharge dependent roughness etc. from an existing SOBEK3-model can be used within D-Flow FM. This also gives the opportunity to create the basics of D-Flow FM 1D model using the existing user interface for SOBEK3.

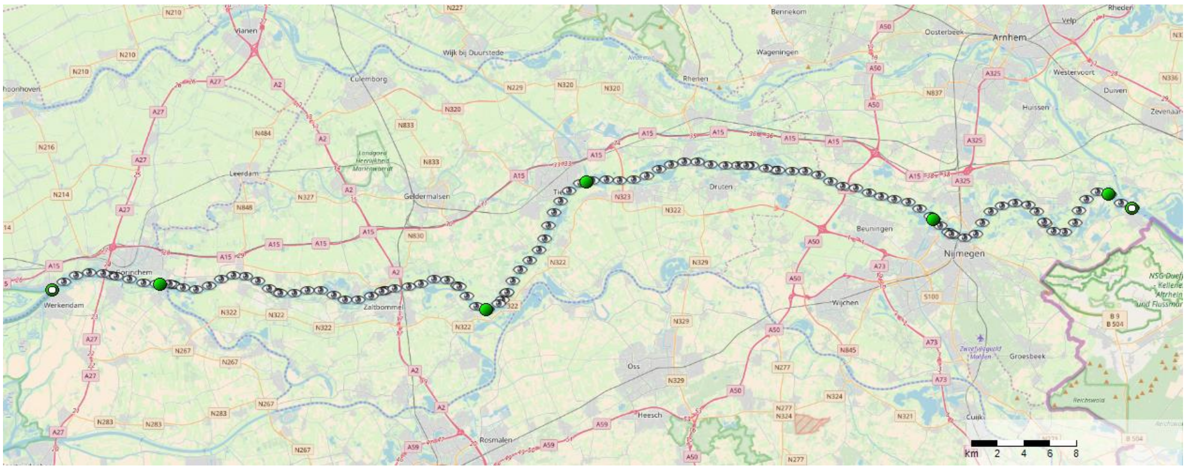


Figure 3.1 SOBEK3-model of the river Waal.

To avoid any undesirable effects of bends, the model is straightened in D-Flow FM. Since in 1D the equations are performed in only one direction, this has no effect on the results. Also the boundary conditions have to be added separately, since they cannot (yet) be imported from the SOBEK3-configuration.

In the final model the cross-sections are taken over from the SOBEK-RE model, to be able to do a fair comparison on the results. The roughness in the main channel remains however the same as in the (calibrated) SOBEK3-model.

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[1] DIMR = Deltares Integrated Model Runner

3.2 Morphology

To implement modelling of sediment transport and morphological processes of graded sediment in the Waal, the settings of the SOBEK-RE-model are taken over as good as possible.

The required files for the initial sediment distribution and the morphological settings in D-Flow FM are similar to Delft3D4 (DVR-model), however the spatially varying input files such as varying diameter in the length and in the different under layers have to be defined in so called “sample files” and thus as x,y and z. The initial bed composition is based on grain size distributions of the bed measured in 1995 (see Sloff, 2006) and 17 sediment fractions are used (equal to the SOBEK-RE model). In the morphological model, the subsurface is divided into a number of layers with a fixed thickness and position. These layers form part of the bookkeeping system with which the composition of the material can be made variable. The thickness of the transport layer is kept constant at 1.0 m and 10 underlayers are used with a thickness of 0.4 m. The composition of the underlayers is initially equal to that of the top layer. In the calculations fixed layers are defined at the location of the three non-erodible layers in the Waal (bottom groynes at Erlecom and fixed layers at Nijmegen and St. Andries).

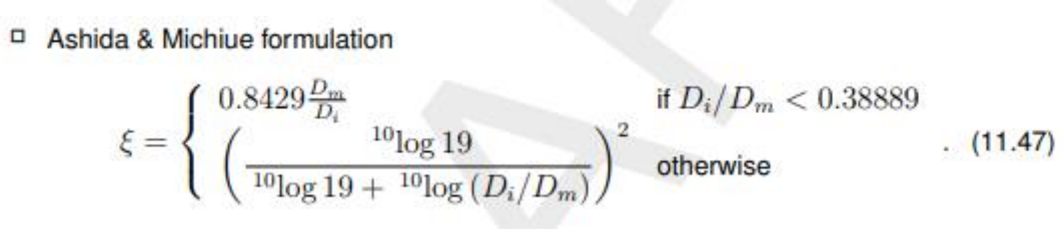
The general transport formula (similar to Meyer-Peter and Mueller) is used to calculate sediment transport:

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

The following coefficients are applied:

α (ACal)	= 0.40	Calibration coefficient
b (PowerB)	= 0	Power b
c (PowerC)	= 1.5	Power c
μ (RipFac)	= 0.7	Ripple factor or efficiency factor
θ_c (ThetaC)	= 0.025	Critical mobility factor

The hiding exposure as in Ashida & Michiue is used (the formulation is almost identical expect the hardcoded factor in FM and Delft3D is 0.38889 whereas this factor is 0.4 in the Sobek RE code).

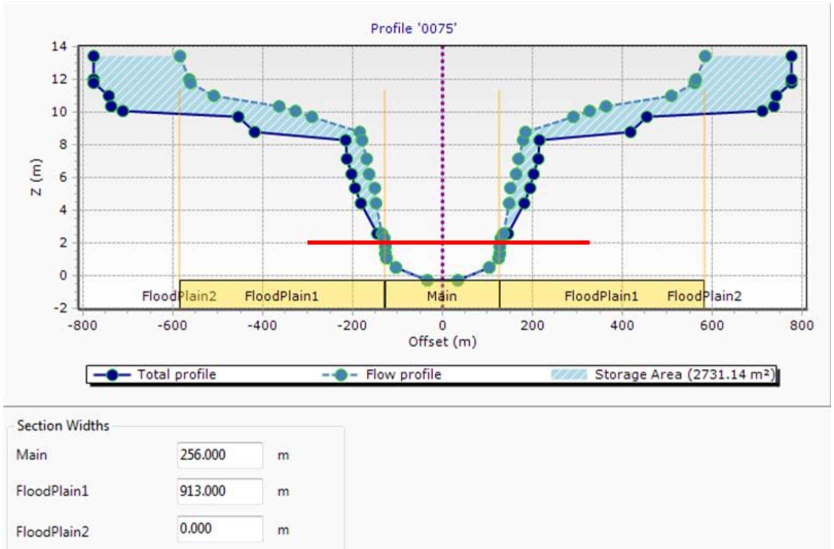


☐ Ashida & Michiue formulation

$$\xi = \begin{cases} 0.8429\frac{D_m}{D_i} & \text{if } D_i/D_m < 0.38889 \\ \left(\frac{{}^{10}\log 19}{{}^{10}\log 19 + {}^{10}\log\left(D_i/D_m\right)}\right)^2 & \text{otherwise} \end{cases} \quad . \quad (11.47)$$

In D-Flow FM it is not possible to use a steady state solver, as is the case in SOBEK-RE. Therefore a morphological acceleration factor is used (Morfac) with a value of 10.

WAQ2Prof generates the width of the summer bed (main channel width) based on the section 1 polygon (main channel) from Baseline, see Figure 11. In SOBEK-RE, however, sedimentation stops once the summerbed is completely filled. This corresponds to a maximum possible sedimentation to the red line in Figure 11.

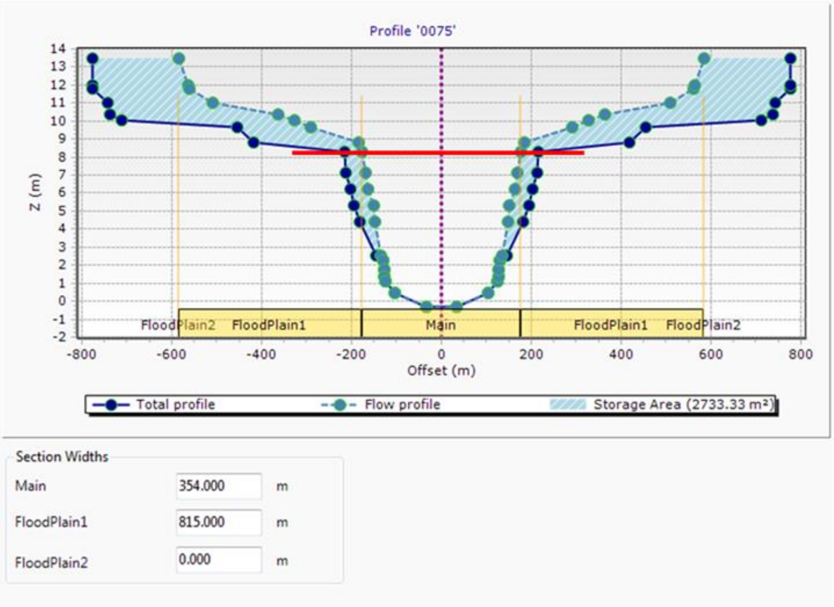


Section Widths

Main	256.000	m
FloodPlain1	913.000	m
FloodPlain2	0.000	m

Figure 3.2 Original cross-sectional output from WAQ2Prof

In order to ensure that enough sedimentation can take place (and that this does not limit the calculation), the width of the main channel has been adjusted manually for the morphological simulations. For this purpose, the shape of the cross section was taken into account and the boundary of the main channel was set at the location where the profile of the total flow width suddenly increased, see Figure 12.



Section Widths

Main	354.000	m
FloodPlain1	815.000	m
FloodPlain2	0.000	m

Figure 3.3 Adjusted cross section, with a larger main channel width.

This allows much more sedimentation, see the adjusted level of the red line in this section. figure. It also means, however, that the summer bed roughness is applied to a larger part of the profile in the morphological simulations. The same main channel width is used for both the reference and the variants.

4 Results

4.1 Hydrodynamics

In this section we look at the hydrodynamic performance of the D-Flow FM model of the Waal, compared to other models. For this analysis we used the original main channel width. For the hydrodynamic analysis, a discharge is imposed upstream derived from the corresponding WAQUA model, see Figure 13. This corresponds to the existing calculations that are used as input for WAQ2Prof to generate the profiles. Downstream a Qh-relatie is imposed: qh_Werkendam_j15_5.

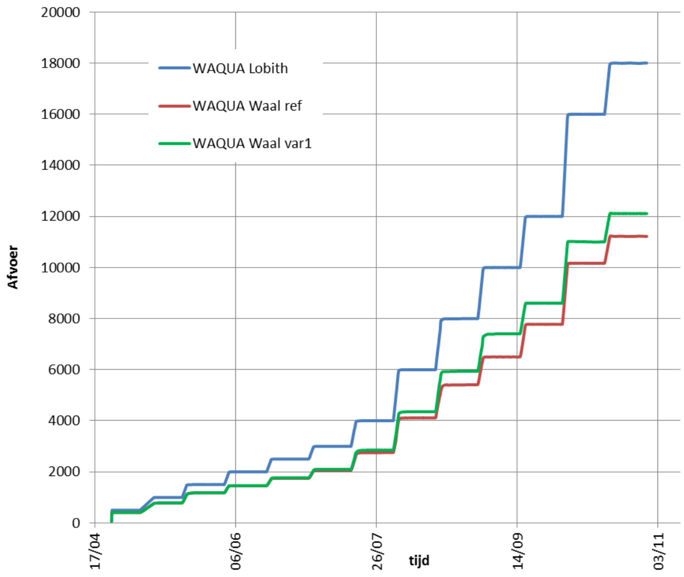


Figure 4.1 Upstream discharge for the hydrodynamic analysis.

The water levels along the Waal for different discharge levels at Lobith and for the different models are shown in Figure 4.2. It can be seen that the water levels calculated by the D-Flow FM 1D model are higher than those of the other models. The differences compared to the 2D-WAQUA-results are relatively large, especially for low discharges. This can be explained by the fact that the D-Flow FM model uses the main channel roughness from the SOBEK3-model, but has a different numerical scheme and is not calibrated for water levels (yet).
The kink in the water levels at low discharges at kilometer 925 is probably caused by a large change in profiles around the fixed layer at St. Andries. This is also slightly visible in the SOBEK-RE results.

As a test we also looked at the results where we used the (much lower) main channel roughness coming from the SOBEK-RE model, see Figure 4.3. It can be seen that the water level then become much lower (up to 60 cm difference), but are still higher than the water levels computed by the SOBEK-RE model.

It was not in the scope of this project to calibrate the model, also because of the fact that for the determination of morphological effects a good description of the (effects on) discharge distribution of main channel / flood plain is more important than the exact prediction of water levels. However it is recommended to pay attention to the hydrodynamic calibration in a possible future project with this D-Flow FM model.

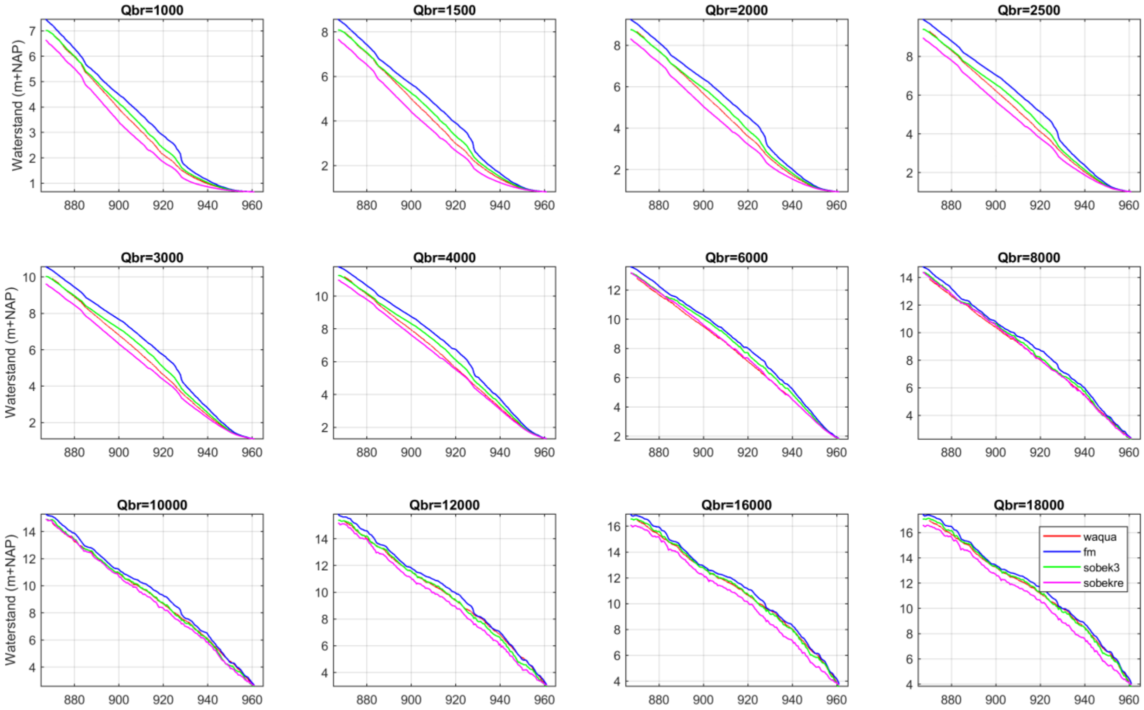


Figure 4.2 Water levels along the Waal for different discharge levels (at Lobith) and different models. Main channel roughness FM-model from SOBEK3-model.

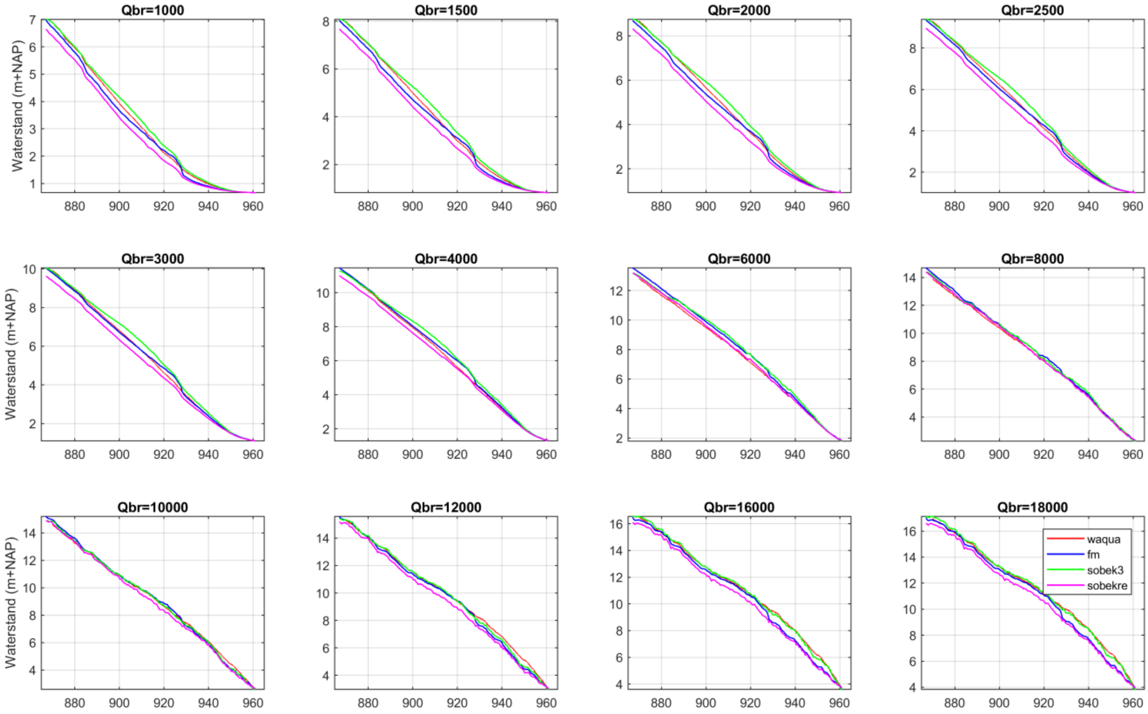


Figure 4.3 *Water levels along the Waal for different discharge levels (at Lobith) and different models. Main channel roughness FM-model from SOBEK-RE-model.*

Figure 4.4 shows the fraction of main channel discharge relative to the total discharge along the Waal for different discharge levels and the different models. For the 1D-models, the original width of the main channel was used here, so that it corresponds with what has been applied in the 2D-WAQUA model.

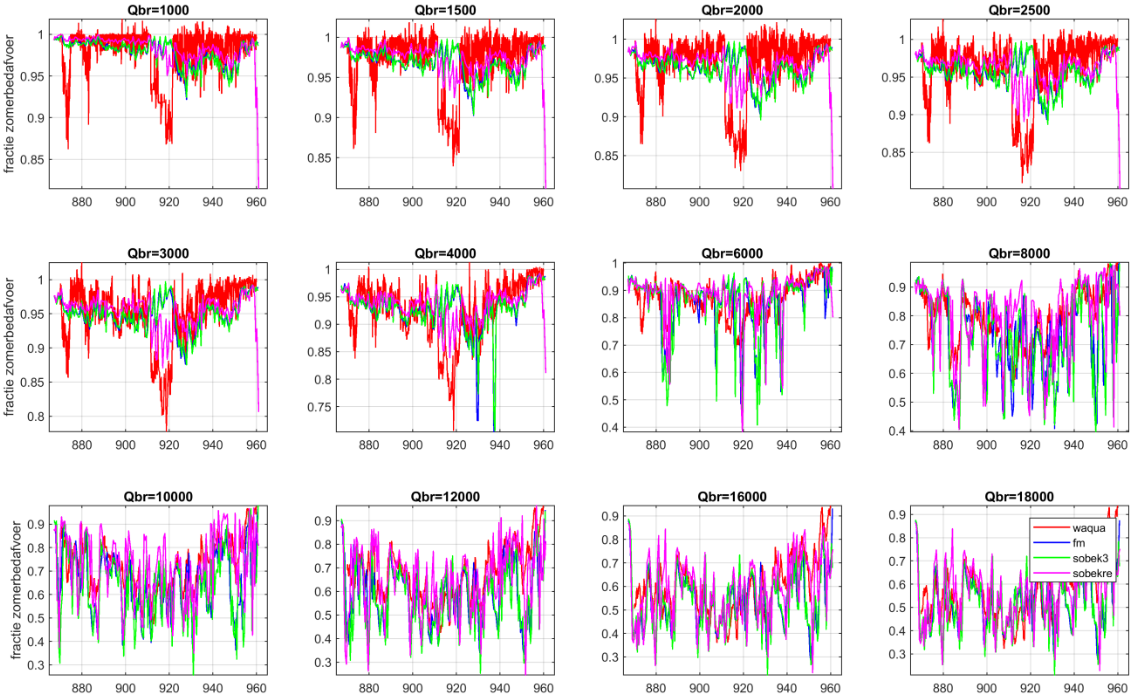


Figure 4.4 *Fraction of discharge through the main channel in relation to the total discharge along the Waal for different discharge levels and different models.*

What stands out here is that the general trends are fairly similar, but that large differences can occur locally. These differ per model and discharge level. The results of the D-Flow FM model compare relatively well with that of the SOBEK3-model. The 'dip' at low discharges around river kilometer 920 is caused because of the presence of longitudinal dams. These longitudinal dams are included in the 2D model (WAQUA) and the 1D models in a different way. That is why you see the dip less pronounced in the 1D models.

4.2 Morphology

In this section we look at the morphologic performance of the D-Flow FM model of the Waal, compared to the SOBEK-RE model. To determine the reference situation, the morphological model has been run for 100 years. An average discharge hydrograph is used for the morphological simulations. The discharge hydrograph is an annual average hydrograph derived from Sieben (2014) as used in the DVR II model (Ottevanger et al, 2015). The Upper Rhine discharge was translated into a Waal discharge on the basis of Sloff et al. (2009). The shape of the hydrograph is shown in Figure 4.5 and the used discharge levels and the number of days in Table 4.1. The values and the shape are given for both the Upper Rhine (Lobith) and the Waal (upper edge model) and are used for each year.

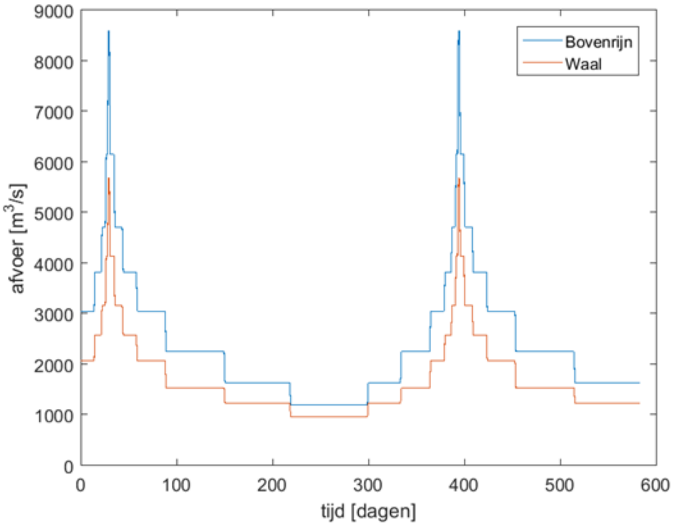


Figure 4.5 Average discharge hydrograph for the morphological simulations.

Table 4.1 Discharge hydrograph for the morphological simulations

Discharge Boven-Rijn (m^3/s)	**Discharge Waal (m^3/s)**	**Number of days**
3053	2066	15
3824	2580	7,3
4717	3163	4,3
6151	4137	2,3
8592	5678	2
6151	4137	4,7
4717	3163	8,7
3824	2580	14,7
3053	2066	30
2250	1533	61,5
1635	1237	68,5
1203	957	81
1635	1237	34,5
2250	1533	30,5

A morphological boundary condition has been used as the starting point, whereby a degradation of 2 cm per year is imposed on the boundary (for 100 years). This value was chosen because the current morphological trend shows a degradation of about 2 cm per year on the Upper-Waal. It has now been assumed that this trend will continue over the next 100 years.

The initial average bed level and that at every ten year of the 100 year simulation are shown in Figure 4.6.

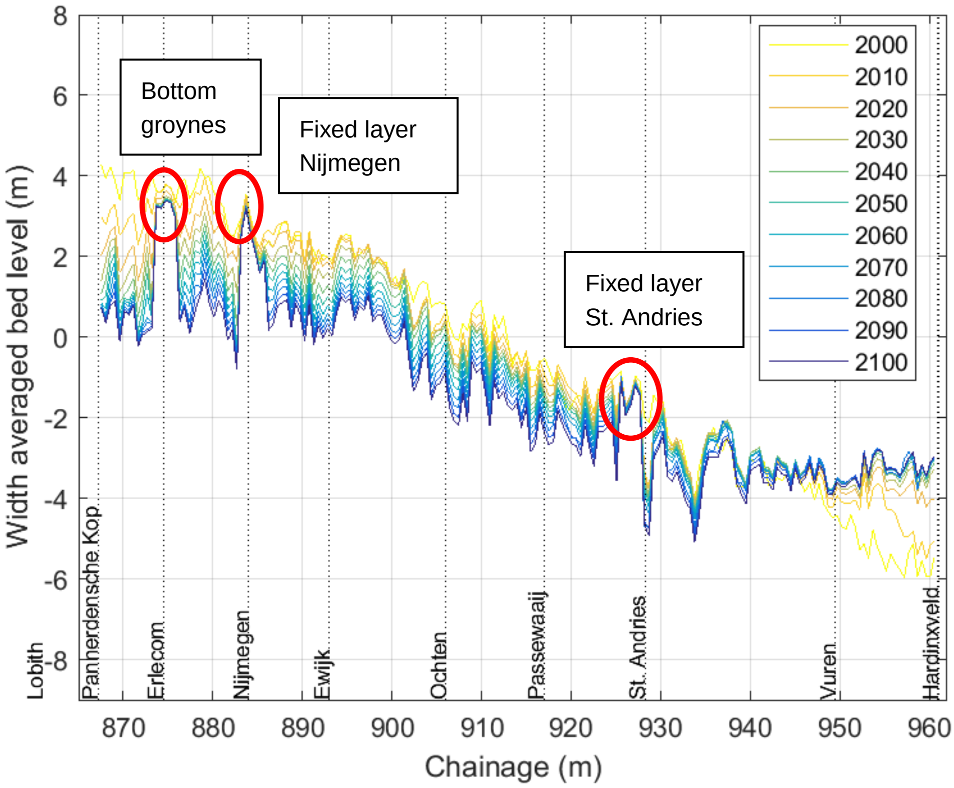


Figure 4.6 Average bed level for reference, as initial state and after every 10 years. The three ellipses indicate the location of the bottom groynes and the fixed layers near Nijmegen and St. Andries.

The bed erosion in the most upstream section is approximately 3,5 meters, which is higher than the imposed degradation of 2 cm/year. The erosion decreases in downstream direction. Between river kilometer 925 and 945 there is a stretch where there is almost no erosion or sedimentation to be seen anymore. On the downstream trajectory we see increased sedimentation, up to 3 m, relative to the initial situation. These results are in line with the current erosion and sedimentation trends in the Waal.

On this basis, we would like to determine the required sediment supply (for all 17 fractions) and impose this as boundary condition as was done with the SOBEK-RE model. In order to ensure that the average erosion on the upstream route (not just on the edge) is on average about 2 cm per year, it may be necessary to multiply this sediment supply by a factor. However, at this moment the sediment transport per fraction is not written to the output file yet. This will be included in an updated version of the software.

In Barneveld et al (2018) a basic variant (variant 1) of the SOBEK-RE model is made which includes lowering of floodplain, removal of summerdikes (and other high line elements in the floodplain), lowering of non-lowered groynes. This results in new profiles and floodplain roughnesses, which have been taken over in the D-Flow FM model as well. With this variant a 100 year morphological simulation has been performed and compared to the reference model. The results of the mean bed level for every decade are shown in Figure 4.7 and the difference with the reference model in Figure 4.8. For comparison also the difference between variant and reference computed with SOBEK-RE are shown in Figure 4.9.

The difference in mean bed level at the initial situation between reference and variant is caused by the fact that the initial profiles differ from each other. The initial difference is the same both in the D-Flow FM model and the SOBEK-RE model. The only exception is the peak near Passewaaij in D-Flow FM. This is at the location where there was originally a connection node (which is removed) and needs further investigation.

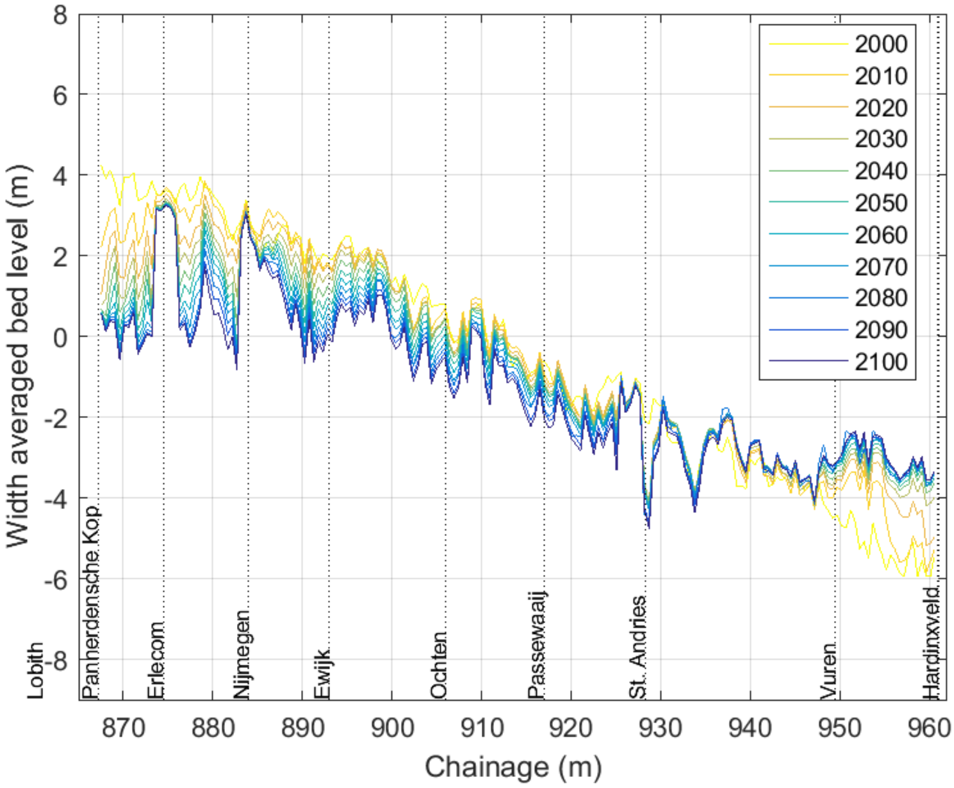


Figure 4.7 *Average bed level for variant 1, as initial state and after every 10 years.*

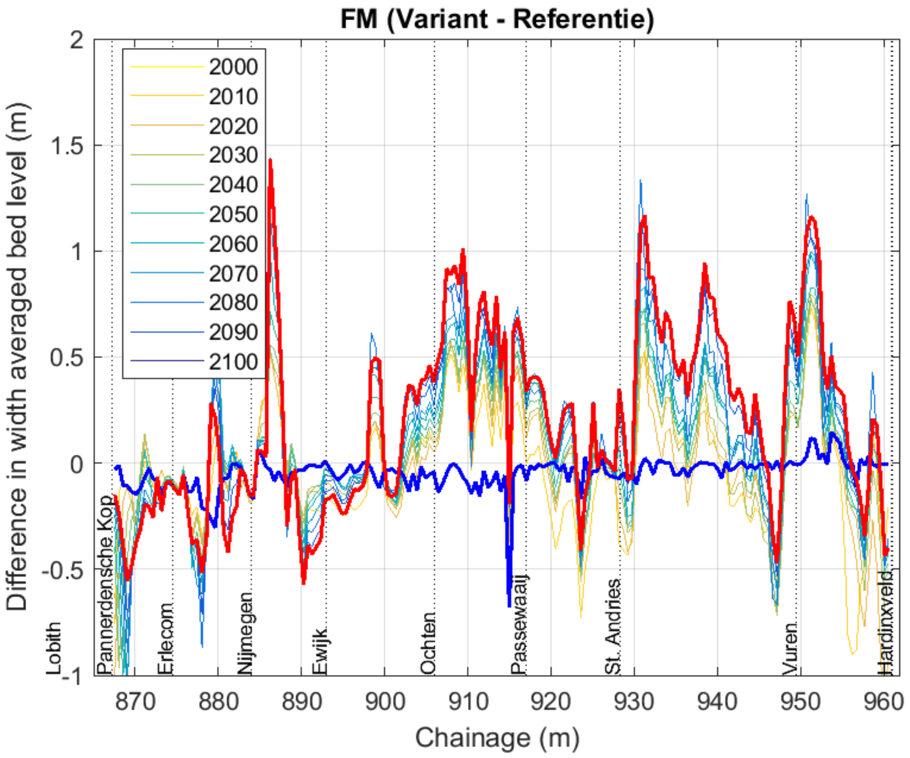


Figure 4.8 *Difference in mean bed level between variant 1 and reference, as initial state and after every 10 years. The initial situation (blue line) and situation after 100 year (red line) are emphasized.*

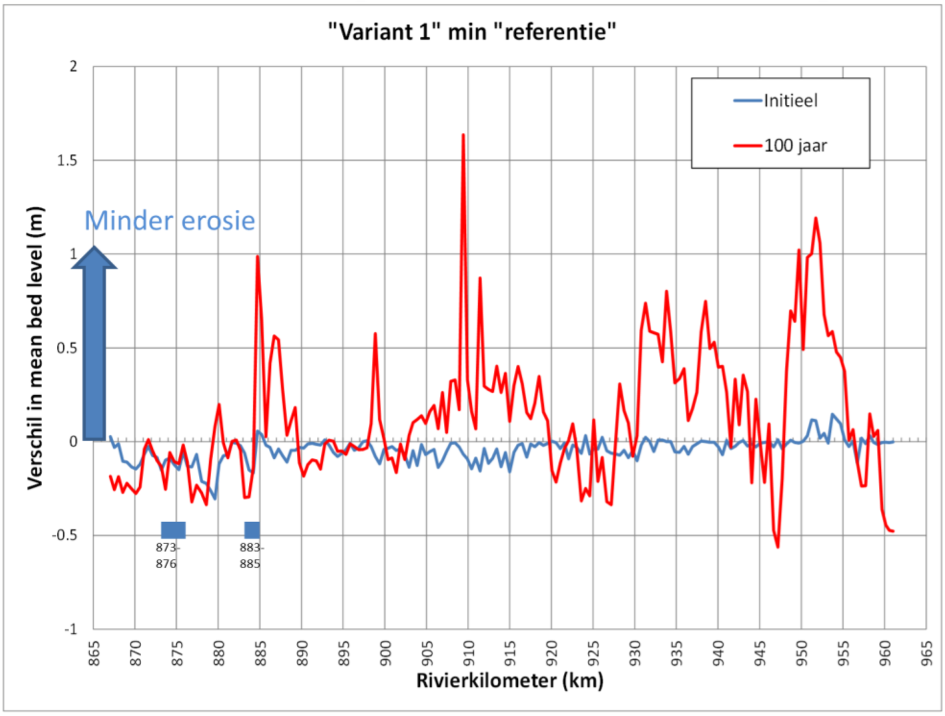


Figure 4.9 *Difference in average bed level between variant 1 and reference, as initial state and after 100 years, computed with the SOBEK-RE model. Bron: Barneveld et al. (2018)*

Taken into account that the computed water level in the D-Flow FM model is higher than in SOBEK-RE and that the sediment boundary condition is different between the models, the general trends are quite comparable. Locally there are still quite some differences (especially in the Upper-Waal), but the general conclusions from the SOBEK-RE model hold also for the results from the D-Flow FM-model:

Upper-Waal
- No reduction of the erosion (even more erosion in variant then reference)

Fixed layer Nijmegen (km 883-885)
- Downstream fixed layer significant decrease in erosion

Downstream from about 900 km
- Both reduction erosion and increased erosion.
- Overall pattern is similar between D-Flow FM and SOBEK-RE.

5 Conclusions and recommendations

This memo describes the set up the 1D morphological model of the river Waal in D-Flow FM that can be used to perform these long term simulations and the first results obtained with this model. To make the D-Flow FM 1D code fully suited for setting up a 1D morphological model of the river Waal the following functionalities have been implemented and tested:

1. Discharge/waterdepth dependent roughness
2. Summerdikes
3. Bed level update of cross sections
4. Morphological boundary conditions
5. Output parameters

When using the roughness in the main channel coming from the existing SOBEK3-model, the computed water levels along the Waal are higher than those of the other models. This can be explained by the fact that the D-Flow FM model uses a different numerical scheme. When using the main channel roughness coming from the SOBEK-RE model, the water levels become much lower (up to 60 cm difference), but are still higher than the water levels computed by the SOBEK-RE model. For the determination of morphological effects a good description of the (effects on) discharge distribution of main channel / flood plain is more important than the exact prediction of water levels. The discharge distribution between main channel and flood plain of the D-Flow FM model is comparable to that of the existing SOBEK3-model. However it is recommended to pay attention to the hydrodynamic calibration in a possible future project with this D-Flow FM model.

A morphological simulation of 100 year is performed with D-Flow FM model for both the reference case and a variant which includes flood plain and groyne lowering and removal of high line elements in the floodplain. Taken into account that the computed water level in the D-Flow FM model is higher than in SOBEK-RE and that the sediment boundary condition is different between the models, the general trends are quite comparable. Locally there are still quite some differences, but the general conclusions from the SOBEK-RE model hold also for the results from the D-Flow FM-model.

It is however recommended to write the sediment transport per fraction to the output file and impose this as boundary condition upstream and to check the initial difference in mean bed level between reference and variant at rkm 915.

6 Literature

Barneveld, H., A. van Hove, A. Paarlberg, R. Daggenvoorde, A. Spruyt, A. Fujisaki, K. Sloff, W. Ottevanger (2018): Effect grootschalige rivierverruiming op bodemerosie Waal (concept). HKV-Deltares rapport: PR3633.20 (HKV), 11202191-003 (Deltares)

Deltares (2018): D-Flow Flexible Mesh User Manual - for D-HYDRO Suite 2018, Version: 1.5.0, October 5, 2018

Ottevanger ,W., S. Giri, & C.J. Sloff (2015): Sustainable fairway Rhinedelta II : effects of yearly bed stabilisation nourishments, Delta Program measures and training walls, Deltares rapport 1209175, April 2015

Sieben J. (2014) Notitie afvoerhydrograaf.

Sloff, C.J., A. Paarlberg, A. Spruyt & M.F.M. Yossef (2009) : Voorspelinstrument duurzame vaardiepte Rijndelta : continued development and application of morphological model DVR,
Deltares rapport