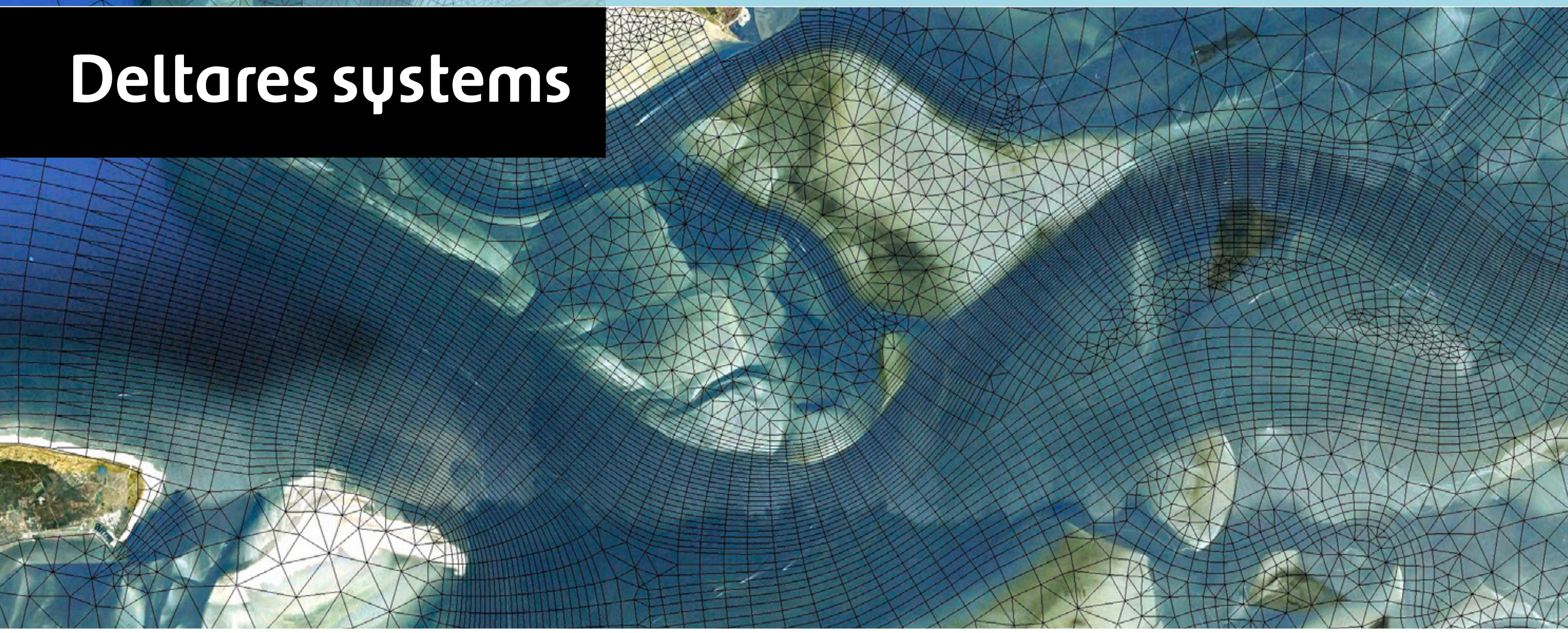
1D/2D/3D Modelling suite for integral water solutions

Delft3D Flexible Mesh Suite

Deltares systems



D-Flow Flexible Mesh

Deltares

Enabling Delta Life

Validation Document

Riverlab

Validation Document

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1 Introduction

This validation document describes the test cases that are performed to test the new software functionalities in D-Flow FM, which are implemented as part of the activities within the Riverlab in 2017. Within this project the focus is on implementing basic functionalities for hydrodynamics and morphology in 1D.

The validation document consists of different chapters, each containing a set of test cases:

- Hydraulics 1D & 2D: comparing hydrodynamic functionalities between (quasi) 1D and a real 1D-network within D-Flow FM.
- Morphology 1D & 2D: comparing morphological functionalities between (quasi) 1D and a real 1D-network within D-Flow FM.
- Tabulated profiles from SOBEK 3: testing the hydrodynamic functionalities with tabulated profiles imported from SOBEK3.
- Morphology 1D & SOBEK3: testing the hydrodynamic functionalities with tabulated profiles imported from SOBEK3.

The implementation of the functionalities in the software and testing of these functionalities is performed with a team of people. The main contributions were made by: Software implementation: Bert Jagers, Jan Noort, Willem Ottevanger (Deltares), Software testing: Andries Paarlberg (HKV), Stef Boersen (RHDHV), Carolien Wegman (HKV), Marcela Busnelli (RHDHV), Amgad Omer (Deltares)

2 Hydraulics 1D & 2D

2.1 Bélanger surface profile with zero bed slope

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Arthur van Dam		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

The purpose of this validation case is to examine the performance of D-Flow FM for a schematized channel flow simulation. For stationary flow through a river with a rectangular cross-section, the Bélanger surface profile equation can be utilized to compare the numerical solution with.
In the D-Flow FM test bench, a case is available where a numerical approximation of the surface profile based on the Bélanger equation is implemented. For use in further test cases we test a Matlab-version of this implementation for bed slope $i_b \geq 0$ The case for flat bed slope ($i_b = 0$) is of specific interest, since for a number of test cases, it is convenient to use a flat bed (without a bed slope).

Linked claims

Claims that are related to the current test case are:

- ◇ Water levels in 1D-model are identical to Quasi2D-model for flat bed.
- ◇ Water levels are identical to semi-analytical solution.
- ◇ Matlab implementation of Bélanger approximation is equal to that in D-Flow FM.

Approach

Base case: `/DSCTestbench/cases/e02_dflowfm/f03_advection/c010_belanger/`
This case is set-up for arbitrary bed slopes ($i_b \geq 0$). Here we investigate how the Matlab code performs w.r.t. the D-Flow FM code for the case with a horizontal flat bed ($i_b = 0$) and a bed slope of $i_b = 4\text{x}10^{-4}$ m/m.

A straight channel with a rectangular cross-section is defined. Given an inflow discharge Q, a channel width B, a bottom slope i_b and a Chézy friction factor C, the distance between the free surface profile and the bed profile can be described by the Bélanger equation for d as the water depth:

$$\frac{\mathrm{d}d}{\mathrm{d}x} = i_b \frac{d^3 - d_e^3}{d^3 - d_g^3} \tag{2.1}$$

with d_e the equilibrium depth and d_g the limit depth (associated with $\mathrm{Fr} = 1$) following:

$$d_e = \left(\frac{Q^2}{B^2 g}\right)^{1/3} \quad \text{and} \quad d_g = \left(\frac{Q^2}{B^2 C^2 i_b}\right)^{1/3}. \tag{2.2}$$

Given a certain inflow discharge Q_{in} and a certain outflow water level condition h_{out}, the surface profile can hence numerically be estimated in the most simple way as:

$$\frac{d_i - d_{i-1}}{\Delta x} = i_b \frac{d_i^3 - d_e^3}{d_i^3 - d_g^3}, \tag{2.3}$$

having $d_i = h_{out} + i_b L$ at the outflow boundary. This, in fact *semi-analytical*, solution can be used for comparison.

For zero bed slope we use a slightly different formula for the estimation of the surface profile, which is independent of the equilibrium depth:

$$\frac{d_i - d_{i-1}}{\Delta x} = -\frac{c_f d_g^3}{d_i^3 - d_g^3}, \tag{2.4}$$

where:

$$c_f = \frac{g}{C^2} \tag{2.5}$$

Model description

Relevant files for the case with zero bed slope are:

- ◇ MDU-file: belangerflat1d2d_rst.mdu
- ◇ Grid-file: 5001d2dflat_net.nc
- ◇ External forcings file: flat.ext

For the case of non-zero bed slope, the bed levels are set *inside* D-Flow FM (only implemented for 2D) by using a 2D-grid file with NaN-values and specifying the bed slope directly in the

- ◇ MDU-file: belanger_AP_rst.mdu
- ◇ Grid-file: 5002dmis_net.nc

The 1D and 2D channels have equal length, see figure below.

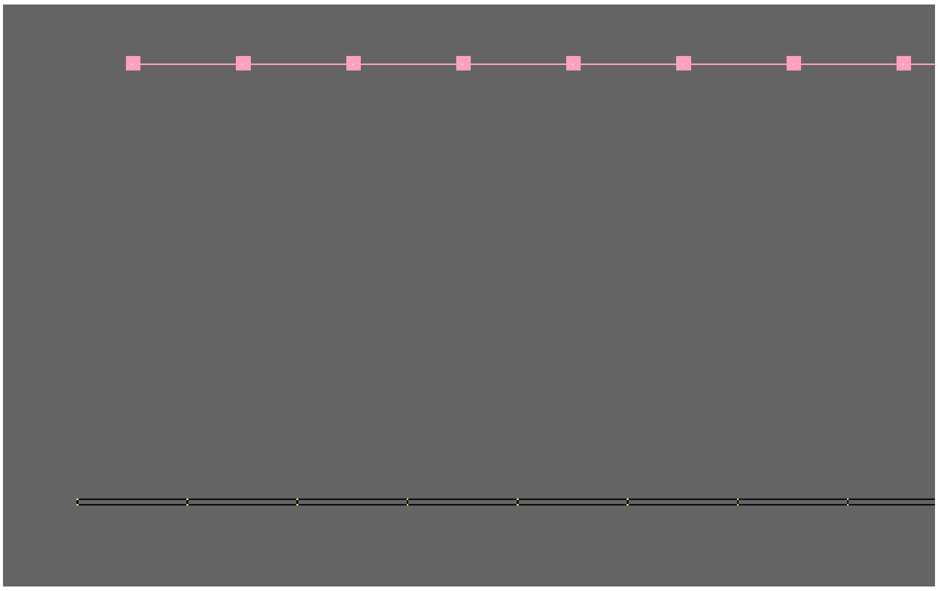

Figure 2.1: *Figure of the layout of the model*

The 2D computational domain has the sizes $L \times B = 100$ km $\times$ 20 m. The grid consists of 200×1 cells. The cell size is 500×20 m^2 everywhere. The bed slope i_b is 0. The inflow discharge is $Q = 600$ m^3/s. The Chézy coefficient is $C = 60$ m$^{1/2}$/s. The outflow water *level* is set equal to -0.12600 m (w.r.t. reference); the water *depth* at the downstream boundary is approximately 10 meters (differs per bed slope). Recall that the water depth is computed as the difference between the upstream water level (computed at the *cell center*) and the bed level at the velocity point (computed at the *cell face*), invoking a $\Delta x/2$ spatial shift. In the computational model, the bed level at the outflow boundary is equal to -10 m+NAP. Therefore, the specified water level holds at a distance $\Delta x/2$ outside the grid (mirrored location).

The case is run for 1 day, starting from a restart-file, to ensure a numerically converged solution.

Results

In D-Flow FM, the semi-analytical solution is implemented. When running the model in the interactive GUI, the deviations from the semi-analytical solution are shown on the screen, which are, for the case of a zero bed slope, approximately:

- ◇ 2D @upstream: 0.0157 m = 1.57 cm
- ◇ 1D @upstream: 0.0220 m = 2.22 cm
- ◇ 2D @ 80 km: 0.0224 m = 2.24 cm
- ◇ 1D @ 80 km: 0.0296 m = 2.96 cm

For the case of non-zero bed slope, the difference are sligthly larger, with a maximum of approximately 5 cm at the upstream boundary. In all cases, D-Flow FM is slightly lower than the analytical solution.

The result from D-Flow FM for the water *depth* is shown in the figures below in combination with its semi-analytical equivalent (here found with a Matlab code). The semi-analytical solution is based on the equation for the Bélanger surface profile.
Note!: to correctly reproduce the semi-analytical solution, Δx should be chosen small enough (here 1 m).

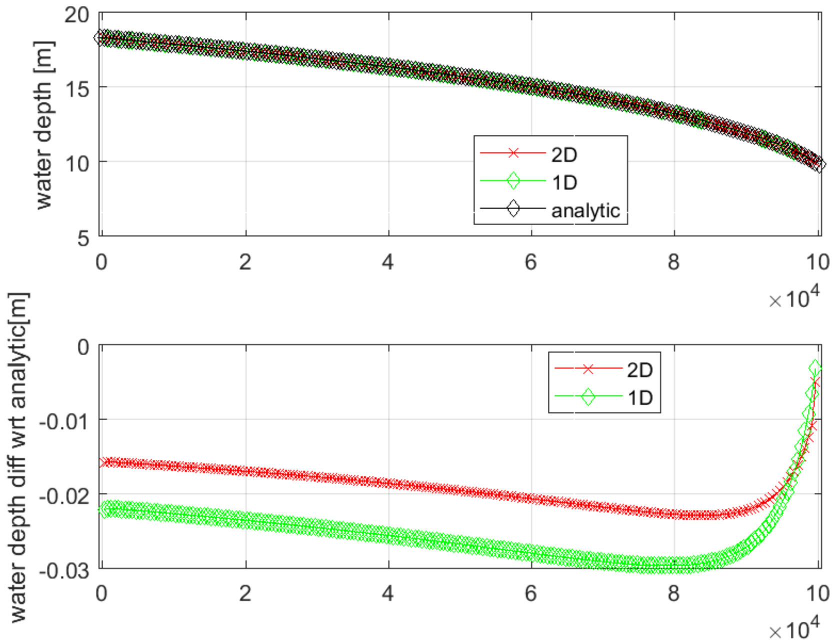

Figure 2.2: *Comparison of the numerical solution and the semi-analytical solution for the water depth for zero bed slope ($i_b = 0$).*

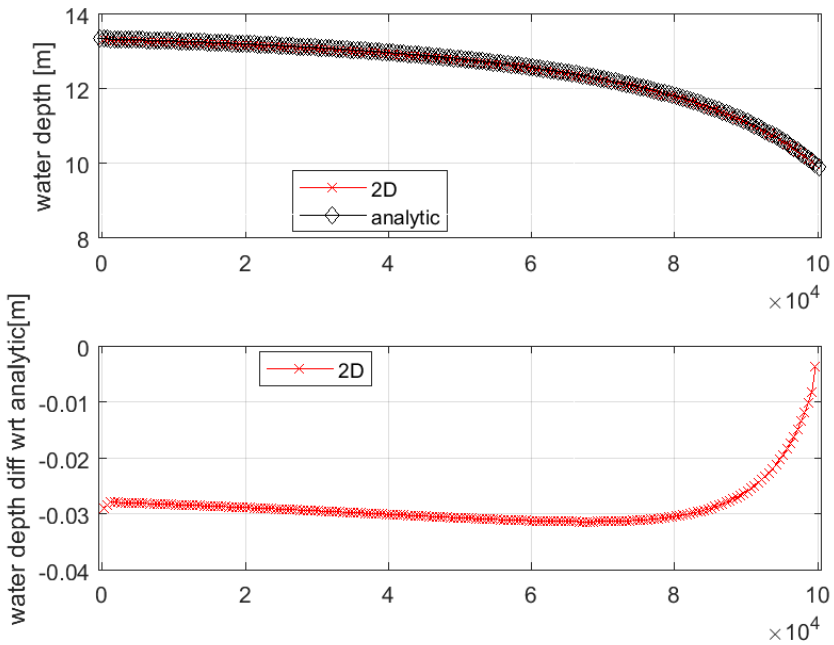

Figure 2.3: *Comparison of the numerical solution and the semi-analytical solution for the water depth for $i_b = 4\text{x}10^{-4}$ m/m.*

The difference in water depth compared to the analytical solution are equal to the difference computed in D-Flow FM. From validation document: root-mean-square difference between the numerical outcome from D-Flow FM and the semi-analytical solution is in the order of 10^{-3} m (for a channel of 100 km).

Conclusion

Water levels in the 1D-model are identical to those in the Quasi2D-model for the case of zero bed slope. For non-zero bed slope ($i_b = 4\text{x}10^{-4}$) the surface profiles found with D-Flow FM and Matlab are nearly identical.
This gives confidence to use the Matlab-code for $i_b \geq 0$ for further test cases.

2.2 Straight channel with zero bed slope (hydraulics)

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Arthur van Dam		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

The purpose of this test case is to test hydraulics for simple rectangular channel (so not-tabulated) with a zero bed slope. This is needed for correct interpretation of 1D-simulations including sediment transport and morphology. Computed water levels in 1D are compared with 2D (which is already validated) and a semi-analytical solution for the surface profile. By comparing flow velocities between 1D and 2D, we gain insight whether roughness and bed shear stress are modeled correctly in 1D.

Linked claims

◇ Water levels in 1D-model are identical to 2D-model for zero bed slope.
◇ Water levels are identical to semi-analytical solution of the surface profile.
◇ Flow velocity (and thus bed shear stress) in 1D-model are identical to Quasi2D-model for zero bed slope.

Approach

We start from an existing 2D test case which included sediment transport (switched off morphological changes). In D-Flow FM various options are available to specify the bed level, using so-called bedleveltypes. For morphology we use option 1, but for testing purposes also other zk-types are included. We test for three bedlevtypes: 1 (faces), 3 (zk) and 6 (faces via zk). For the 2D-grids we use the centerline values to compare with the 1D-results.

Model description

The figure below shows the computational domain, containing both the 1D and the 2D grid. The 2D channel (3 cells wide, cell edges 0.1 m long, aspect ratio = 1) and 1D channel (0.3 m wide) are of equal length (30 m). Pressure points are at identical locations for the centerlines of the models. The bed level is set 0 for the entire domain.

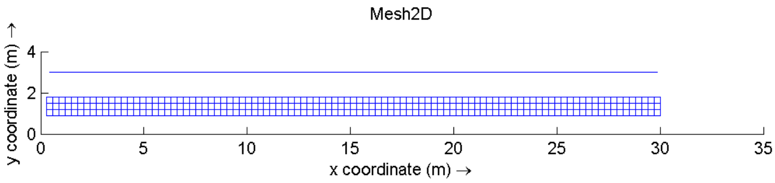

Figure 2.4: *Figure of the layout of the model.*

The model is forced with a constant discharge at the upstream boundary, and a constant water level at the downstream boundary. The discharge is 0.08 m^3/s for the 1D channel and 0.24 m^3/s for the 2D channel (since it has a width of 3 cells). The water level at the downstream boundary (and because of the zero bed level also the water depth) is 0.35 m.

For the semi-analytical solution of the water surface profile with zero bed slope (and validation of it), see 'c99_belangerflat1d2d' (Bélanger-equation).

Results

Below are the results for water depth (Bedlevtypes: 1 (faces), 3 (zk) and 6 (faces via zk)) and flow velocity (only bedlevtypes: 1 (faces)).

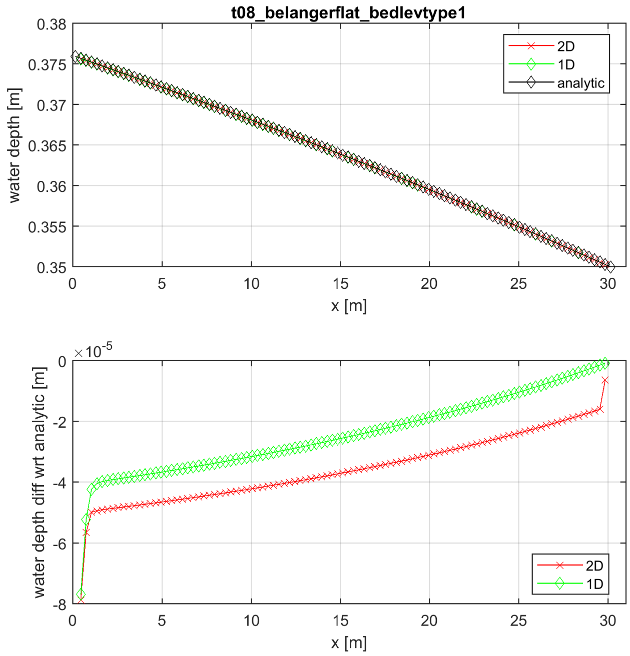

Figure 2.5: *Water depth (top) and difference with semi-analytical solution (bottom) for bedlevtype=1.*

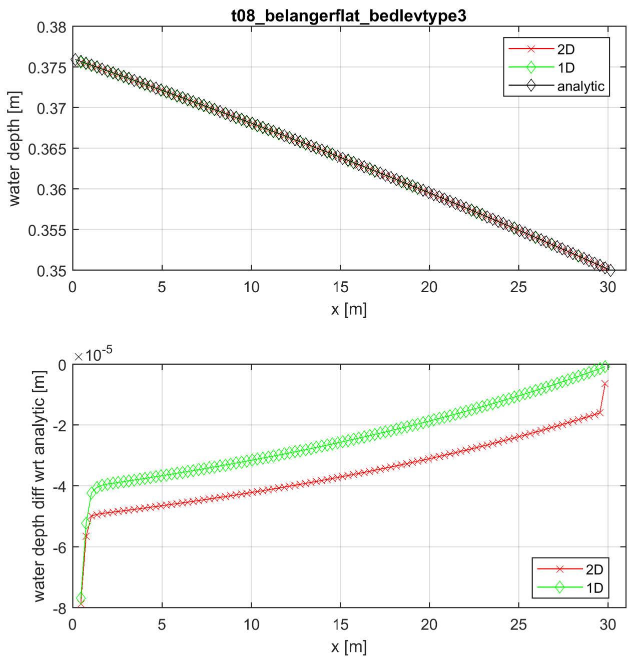

Figure 2.6: *Water depth (top) and difference with semi-analytical solution (bottom) for bedlevtype=3.*

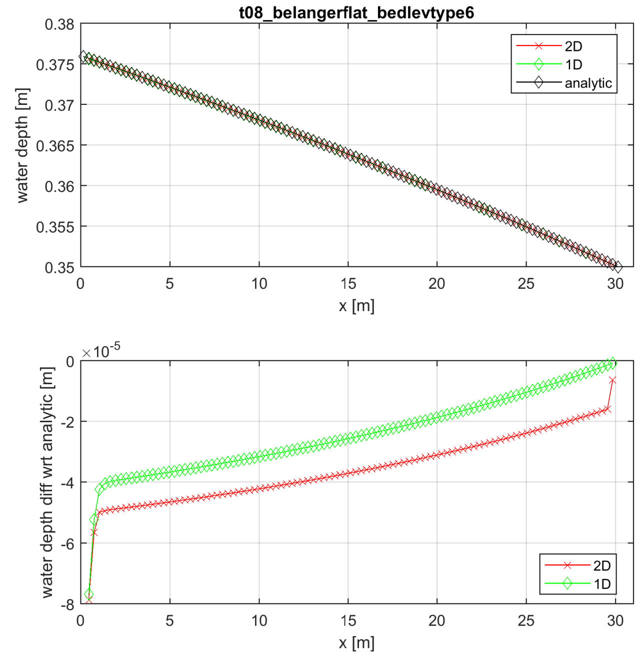

Figure 2.7: Water depth (top) and difference with semi-analytical solution (bottom) for bedlevtype=6.

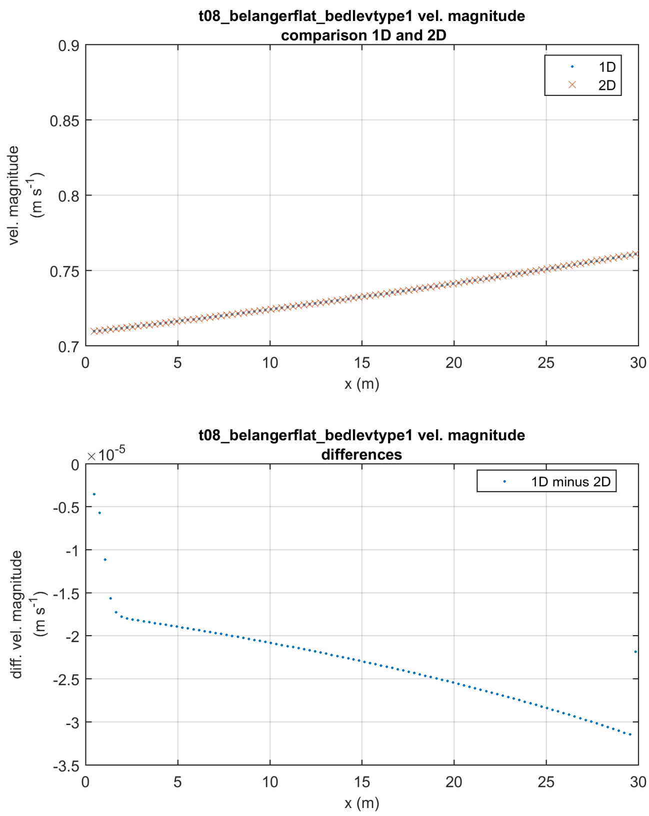

Figure 2.8: Flow velocity comparison in 1D and 2D for bedlevtype=1.

Analysis of results

- ◇ Water level: 1D is closer to analytical solution than 2D.
- ◇ Differences with analytical solution are small.
- ◇ Identical results for the considered bedlevtypes.
- ◇ Very small differences in flow velocity between 1D and 2D.

Conclusion

Differences in water level and flow velocities are small enough to use for test cases including morphology.
The water surface profile near the upstream boundary is different between 1D and 2D; this might need some attention in the future.

2.3 Straight channel with sloping bed (hydraulics)

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Stef Boersen		Aukje Spruyt	

Version information

Date of study : 08 Dec 2017
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Location : https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f28_mor1d_bakprof_hydraulics/c10_straight_bakprof_1Dvs2D_with_bedslope
SVN revision : -

Purpose

The purpose of this test case is to test hydraulics for simple rectangular channel (so non-tabulated) with a non-zero bed slope ($i_b > 0$). This is needed for correct interpretation of 1D-simulations including sediment transport and morphology. Computed water levels in 1D are compared with 2D (which is already validated) and a semi-analytical solution for the surface profile. By comparing flow velocities between 1D and 2D, we gain insight whether roughness and bed shear stress are modelled correctly in 1D. For 2D, we also test the effect of aspect ratio.

Linked claims

- ◇ Water levels in 1D-model are identical to 2D and Quasi2D-model for non-zero bed slope.
- ◇ Water levels are identical to semi-analytical solution of the surface profile.
- ◇ Flow velocity (and thus bed shear stress) in 1D-model are identical to 2D and Quasi2D-model for non-zero bed slope.
- ◇ Claims above are independent of aspect ratio (in 2D).

Approach

We start from an existing 2D test case which included sediment transport (switched off morphological changes). In D-Flow FM various options are available to specify the bed level, using so-called bedleveltypes. For morphology we use option 1, but for testing purposes also other zk-types are included. In this test case we consider two bedlevtypes: 1 (faces) and 3 (zk). For zero bed slope (REF), we showed that bedlevtype 6 gives identical results to 3. For the 2D-grids we use the centerline values to compare with the 1D-results and the semi-analytical solution. For certain cases there appear to be deviations from the analytical solution; this might be to using an aspect ratio $>> 1$, therefore we also test for aspect ratio $= 1$.

Model description

The figure below shows the computational domain, containing the considered grids. All channels have a constant bed slope of $4\text{x}10^{-4}\text{m/m}$ (dz 0.01188 on L = 29.7 m = $4\text{x}10^{-4}\text{m/m}$). Pressure points are at identical locations for the centerlines of the models. The effective length of the channels is 30 m (xleft=0.3m, xright=30m, considering the Δx/2 boundary location gives an effective length of 30 m).

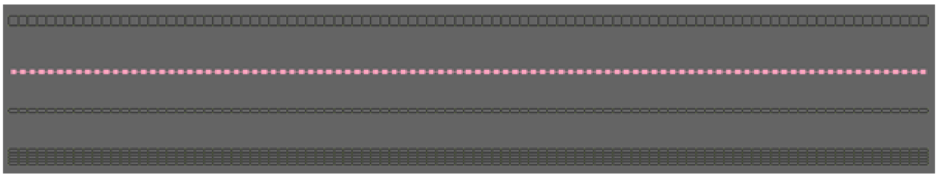

Figure 2.9: *Figure of the layout of the model.*

Explanation of different channels (counting from bottom to top):

1 2D grid, 3 cells wide, 0.3 m long x 0.1 m wide, so aspect ratio = 3 ("2D")
2 2D grid, 1 cell wide, 0.3 m long x 0.1 m wide, so aspect ratio = 3 ("Quasi2D_ar3")
3 1D channel, 0.1 m wide (so width equal to grid 2), 30 m long ("1D")
4 2D grid, 1 cell wide, cells 0.3 m long x 0.3 m wide, so aspect ratio = 1 ("Quasi2D_ar1")

To create sample xyz-files for the bed levels including the required bed slope, we used Matlab/createbedslope.m. For bedlevtype=3, the samples have to be interpolated to the zk-nodes in the network-file. For bedlevtype=1 (tiles), the xyz-file has to be added to the MDU-input file, as well, where it is important to have samples are each grid point. Another important aspect is that for bedlevtype=1 (so bed levels specified in pressure points), the velocities are still calculated at the (upwind) u-points (h_u). To be able to compare results for both bedlevtypes, the input bed level has to be shifted half a grid cell, because for the bed level in the u-point the maximum depth of the surrounding tiles is used. This is taken into account in the aforementioned Matlab-script (for straight 2D channels with constant bed slope).

In D-Flow FM the boundary conditions can be specified in different ways. For river models, it is a common choice to use a discharge upstream and a water level downstream. This is our first test. We use a constant bed roughness Chezy coefficient $C = 45$. The downstream water level is chosen 0 m (w.r.t. an arbitrary reference level). This boundary condition holds half a grid cell *outside* the grid, so the water level we need to specify is $0 - (dx/2) * ib = 0 - (0.3/2) * 4\text{x}10^{-4} = -6\text{x}10^{-4}\text{m}$. The bed level at the downstream boundary = -0.40188 (netnode), so the water depth (h) is 0.40188 m. The discharge is estimated such that in equilibrium for steady uniform flow, the water surface slope (i_w) should be equal to the bed slope (i_b). For this case we have (with discharge Q and constant channel width B): $Q = BhC\sqrt{(hi)}$, or the specific discharge (q): $q = hC\sqrt{(hi_b)}$ = 0.2293 m^2/s.

During testing, it turned out to be difficult to ensure perfectly steady uniform flow using an upstream discharge. Since we use Chézy for bed friction, theoretically, there should be an equilibrium between the pressure gradient and bed friction. Therefore, we also considered tests where we force the model with two water level boundaries, such that the pressure gradient is identical to the bed slope, i.e. $i_w = i_b$. To determine the upstream water level boundary condition, we also need to take into account the shift of half a grid cell at the boundary: $(L) * ib + (dx/2) * ib = 29.7 * 4\text{x}10^{-4} + (0.3/2) * 4\text{x}10^{-4} = 0.01188 + 6\text{x}10^{-5} = 0.01194\text{m}$.

Results - upstream discharge

The following figures show the water level and flow velocity (the latter only for bedlevtype=1). For this case we only considered aspect ratio = 3. Since the discharge is chosen such that the water depth should be equal to the downstream water depth in the domain, we use that as approximation for the "analytical solution".

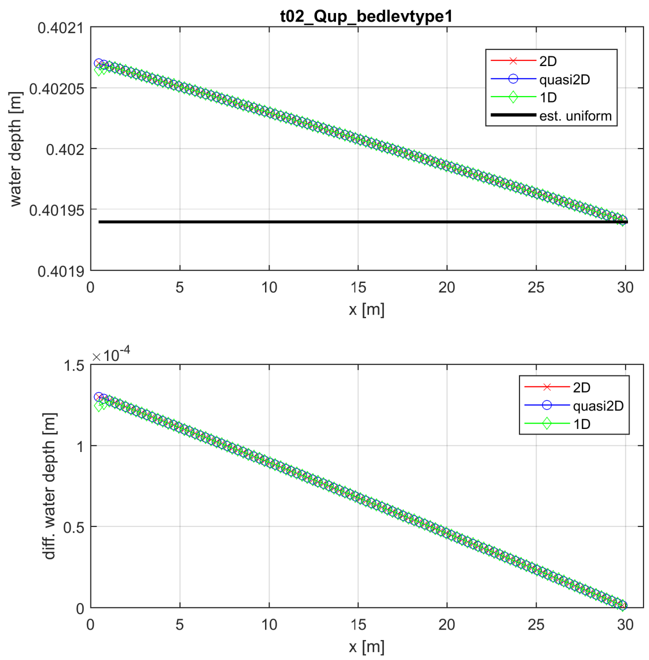

Figure 2.10: *Water depth (top) and difference with "uniform depth assumption" (bottom) for bedlevtype=1, upstream forcing: discharge.*

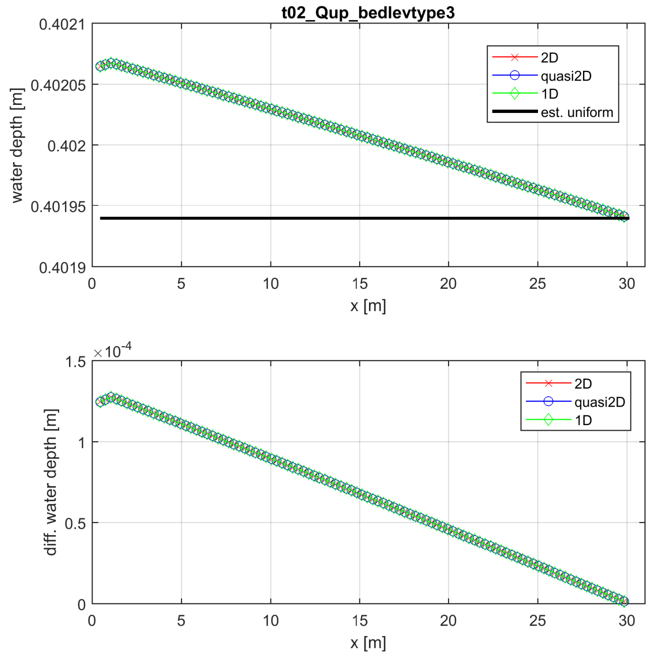

Figure 2.11: *Water depth (top) and difference with "uniform depth assumption" (bottom) for bedlevtype=3, upstream forcing: discharge.*

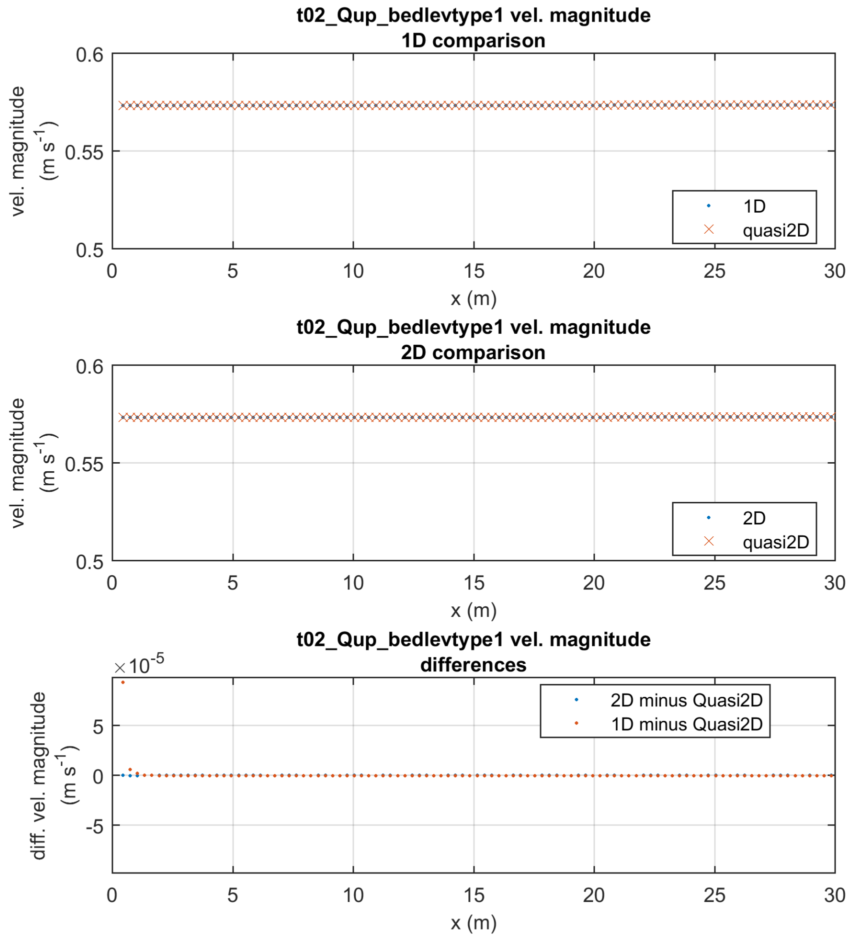

Figure 2.12: *Flow velocity comparison in 1D and 2D for bedlevtype=1, upstream forcing: discharge.*

Analysis:

- ◇ No difference in water level for 1D and 2D (for 2D centerlines).
- ◇ No difference for bedlevtype=1 and 3.
- ◇ The water level on the downstream boundary is correct.
- ◇ There appears to be a (small) backwater effect ("opstuwing") towards the upstream boundary of the model. It is not entirely clear where this difference originates from, since the dicharge is chosen such that the water depth upstream should be equal to downstream. Possible reasons are related to the fact that the discharge is not calculated with sufficient accuracy (decimals), or with the fact that in D-Flow FM, a discharge boundary is internally recalculated to a velocity, which might introduce some (rounding?) error?
- ◇ There is a "jump" in 1D at the upstream boundary in the first 3 computational cells in the domain. The difference is small, and not further considered herein.
- ◇ Differences in flow velocity between 1D and 2D are very small, with maximum differences at the inflow boundary, where the water levels also deviates from the semi-analytical solution.

Results - Pressure gradient (including aspect ratio)

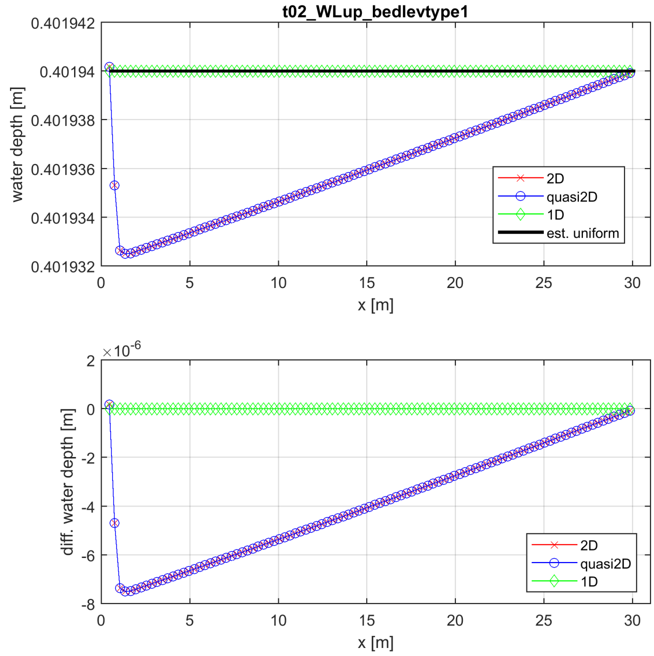

Figure 2.13: *Water depth (top) and difference with "uniform depth assumption" (bottom) for bedlevtype=1, upstream forcing: water level (pressure gradient).*

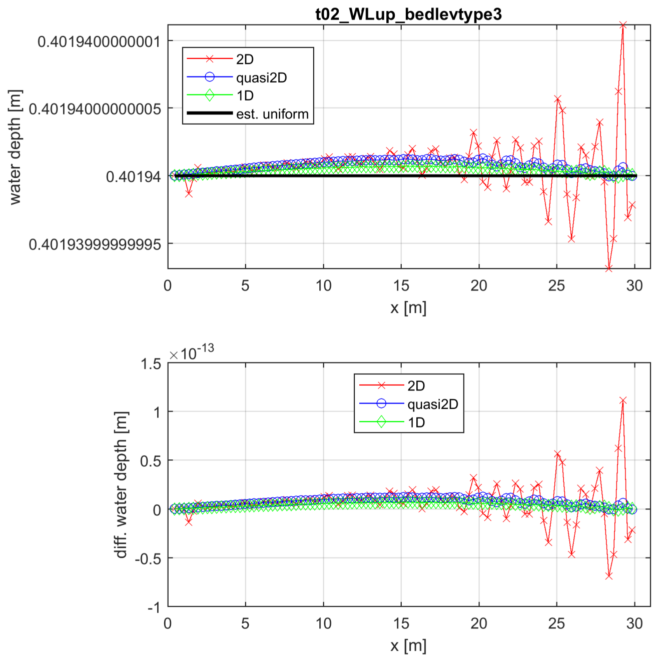

Figure 2.14: *Water depth (top) and difference with "uniform depth assumption" (bottom) for bedlevtype=3, upstream forcing: water level (pressure gradient).*

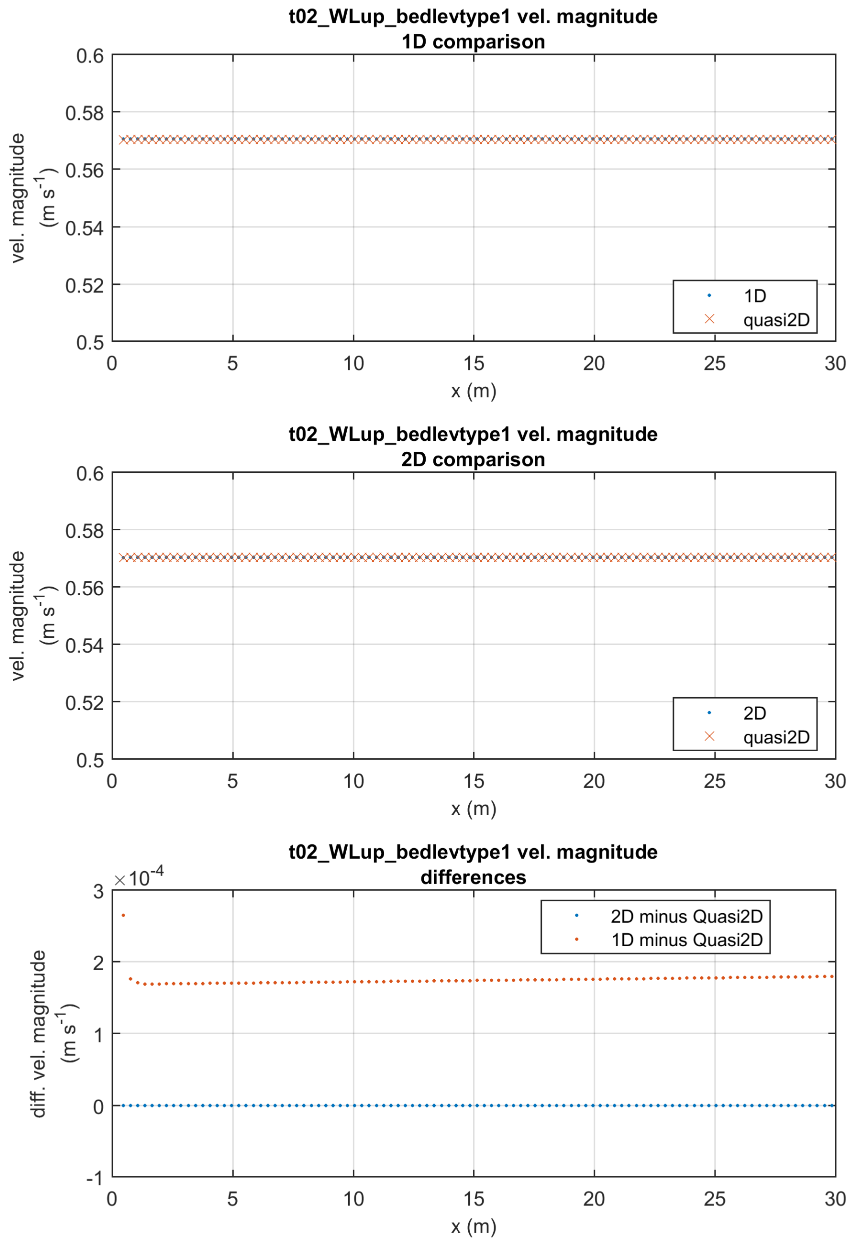

Figure 2.15: *Flow velocity comparison in 1D and 2D for* bedlevtype=1*, upstream forcing: water level (pressure gradient).*

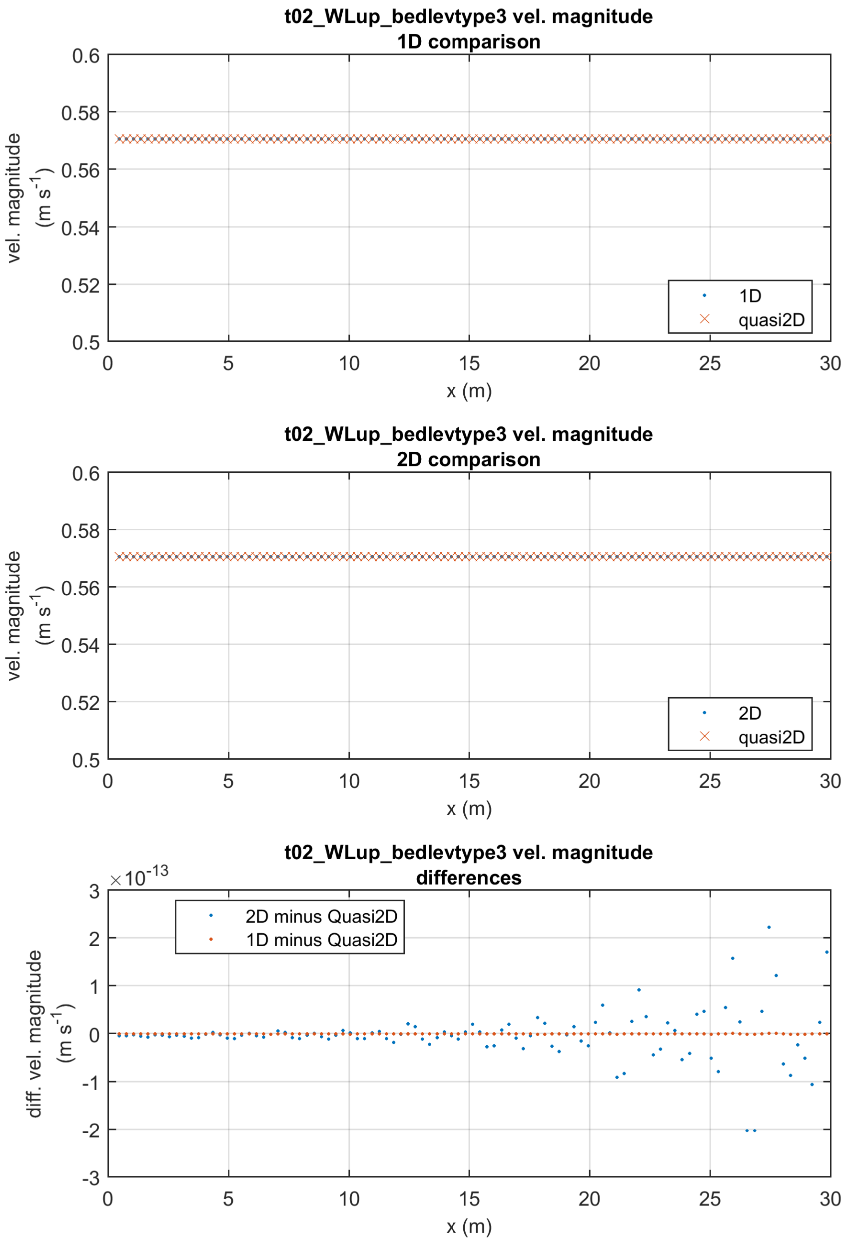

Figure 2.16: *Flow velocity comparison in 1D and 2D for* bedlevtype=3*, upstream forcing: water level (pressure gradient).*

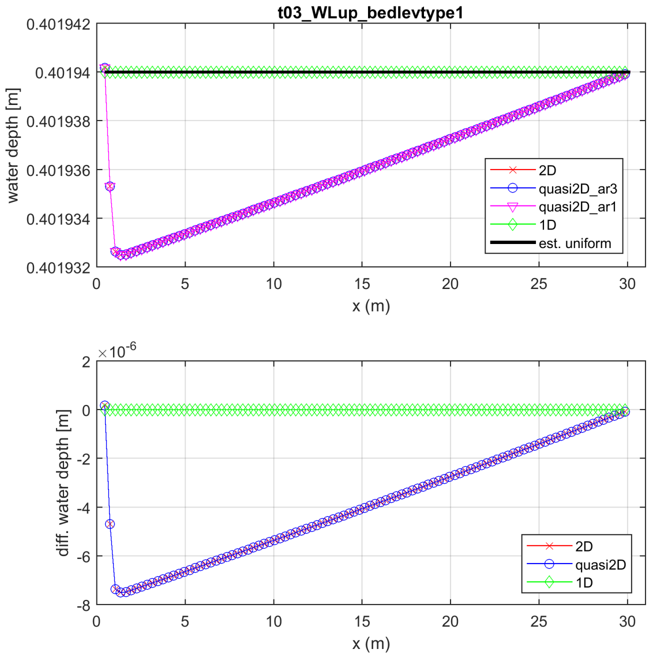

Figure 2.17: *Water depth (top) and difference with "uniform depth assumption" (bottom) for bedlevtype=1, upstream forcing: water level (pressure gradient). This includes aspect ratio = 1 for the 2D grid.*

Analysis:

- ◇ The water level on the downstream boundary is correct.
- ◇ For bedlevtype=3 the computed water levels are identical and as expected (constant water depth along the channel). Note that the fluctuations in the figure are in the orde of 10^{-13}.
- ◇ For bedlevtype=1, the above results only hold for the 1D channel.
- ◇ For 2D also with a pressure gradient as forcing, there is a striking difference for the first three grid points in the domain. It should be noted that for an upstream discharge, this was the other way around.
- ◇ The boundary effects (e.g. at the first 3 cells) is still present for an aspect ratio of 1 (see last figure).
- ◇ The are no differences in flow velocity for this case between 1D and 2D for bedlevtype=3. For bedlevtype=1 (which is relevant for morphology), there is expected to be no differences for 1D, but for 2D there are differences near the upstream boundary of the model, perhaps related to the treatments of the upstream boundary condition in 2D? (in the figure, it appears there is a difference for 1D, but this is because we compare velocities in 1D to velocity computed in 2D, what causes the differences here.)

Conclusion

For bedlevtype=3 and a pressure gradient as model forcing, the results in 1D and 2D are equal to each other and the surface profile is virtually indentical to a semi-analytical solution of the surface profile. However, for bedlevtype=1, which is used for morphological simulation, the are differences in water level and flow velocity, especially near the upstream boundary of the model. The differences are small though, and knowing these (small) differences, we can continue with the morphological validation cases.

2.4 Straight channels in 1D and 2D: including 90 degree bends

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Arthur van Dam		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

There is an important difference between SOBEK3 and D-Flow FM. In SOBEK3, the flow equations are solved in 1D: although the user can introduce geographical "bends" in a model, the equations are still solved as if the river is a straight line. Since D-Flow FM is set-up as a model-code for 1D-2D-3D, this is not the case for D-Flow FM. Also in 1D, the equations are solved in a vectorized way. This means that if there is a bend between computational nodes, the computed velocity can be very different from the velocity computed in SOBEK3. This test case is set-up to gain some insight in the effects of "bends" on water levels (backwater effects).

Linked claims

- "Bend effects" are treated differently in D-Flow FM and SOBEK3.
- For one single 90^o bend, the results are identical in 1D and 2D.

Approach

We start from an earlier test cases with straight channels in 1D and 2D: 'c10_straight_channel_1Dvs2D_zero_bedslope' (REF). In that test case we used a zero bed slope and bed level of 0 in the entire domain, which is convenient for modelling the channels with bends. In this test case we add various channels containing "bend lay-outs", and compare the water levels with those computed for straight channels of the same length. We consider two bedlevtypes: 1 (faces) and 3 (zk). For one bend lay-out, we compare 1D and 2D results.

Model description

The figure below shows the computational domain, containing both the straight 1D and 2D channels (bottom two) and the channels with bends (top three).

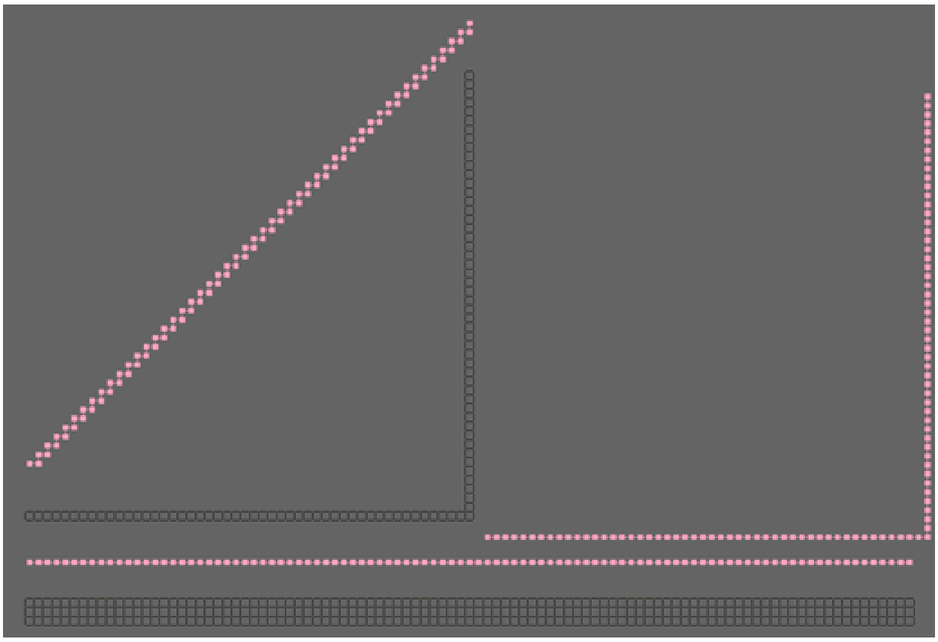

Figure 2.18: *Figure of the layout of the model.*

The 2D channel (3 cells wide, cell edges 0.1 m long, aspect ratio = 1) and 1D channel (0.3 m wide) are of equal length (30 m). Pressure points are at identical locations for the centerlines of the models. The bed level is 0 for the entire domain.

The model is forced with a constant discharge at the upstream boundary, and a constant water level at the downstream boundary. The discharge is 0.08 m^3/s for the 1D channel and 0.24 m^3/s for the 2D channel (since it is three cells wide). The water level at the downstream boundary (and because of the 0 bed level also the water depth) is 0.35 m.

For this test case we add the following grids to test the backwater effects due to bends:

- ◇ Two channels with a single 90^o bend, both in 1D and 2D (1 cell wide). The length of these channels is identical to the straight channels.
- ◇ One 1D channel with a 90^o bend between each node ("zigzag" per node, so each channel segment is 0.3 m long). Also for this case the total length of the channel is equal to the straight channel.

We use Bedlevtype = 1 and 3, which should be identical because of the uniform bed level in the computational domain. For the straight channel, the water levels are compared to a semi-analytical approximation of the surface profile.

Results

The results are shown in the figures below.

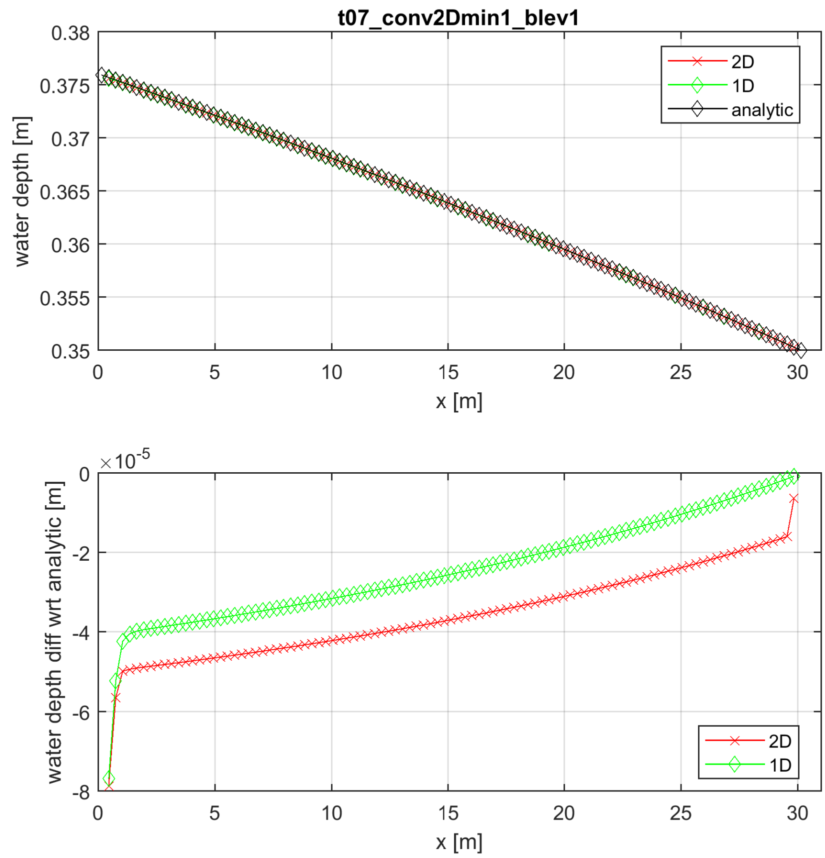

Figure 2.19: *Comparison water levels in the straight channels for 1D and 2D with semi-analytical solution, bedlevtype=1.*

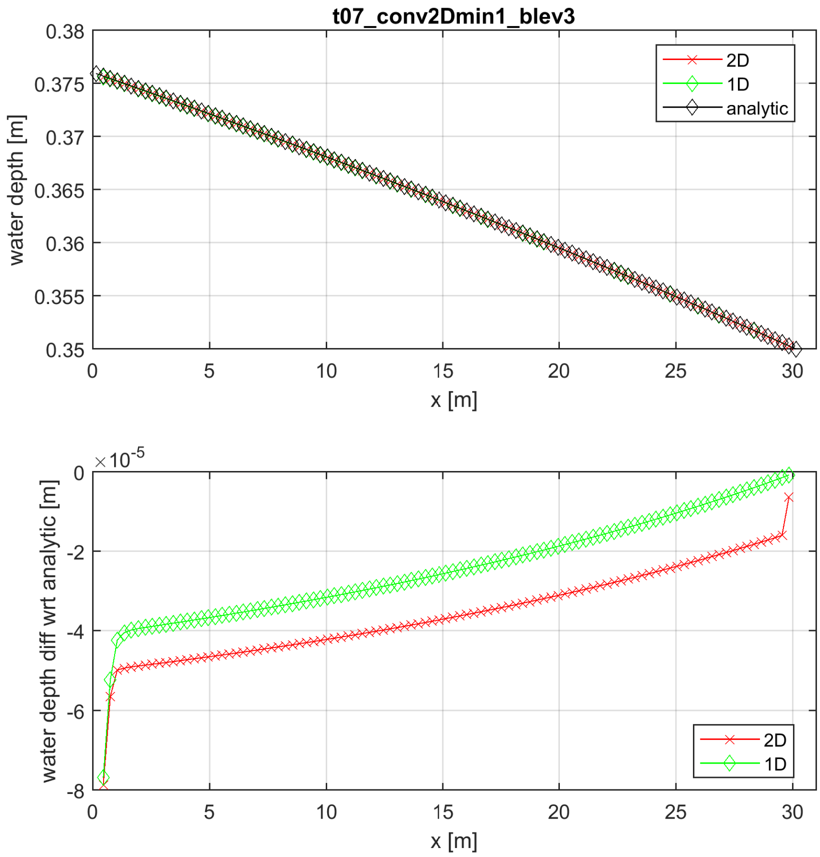

Figure 2.20: *Comparison water levels in the straight channels for 1D and 2D with semi-analytical solution, bedlevtype=3.*

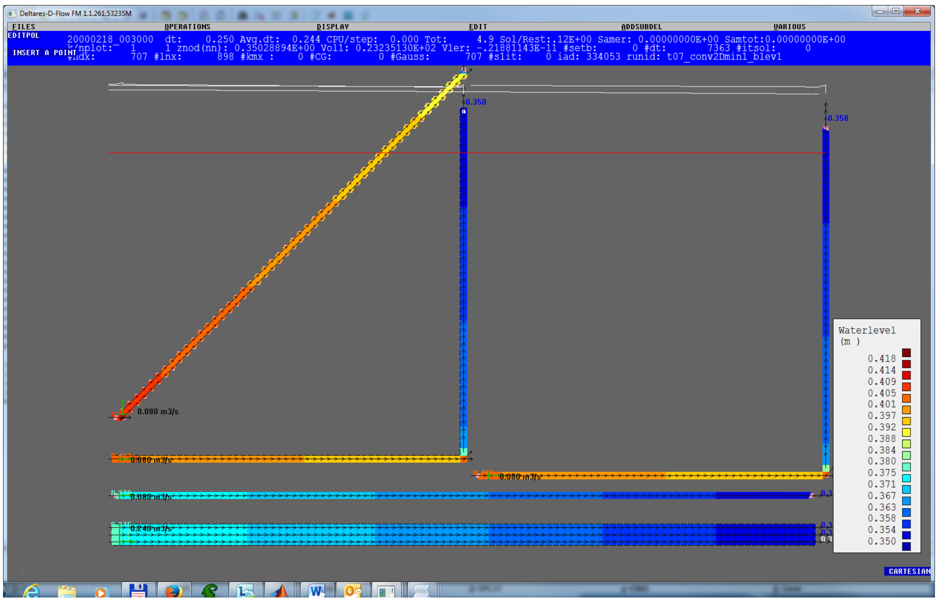

Figure 2.21: *Impression of water levels including bends, bedlevtype=1.*

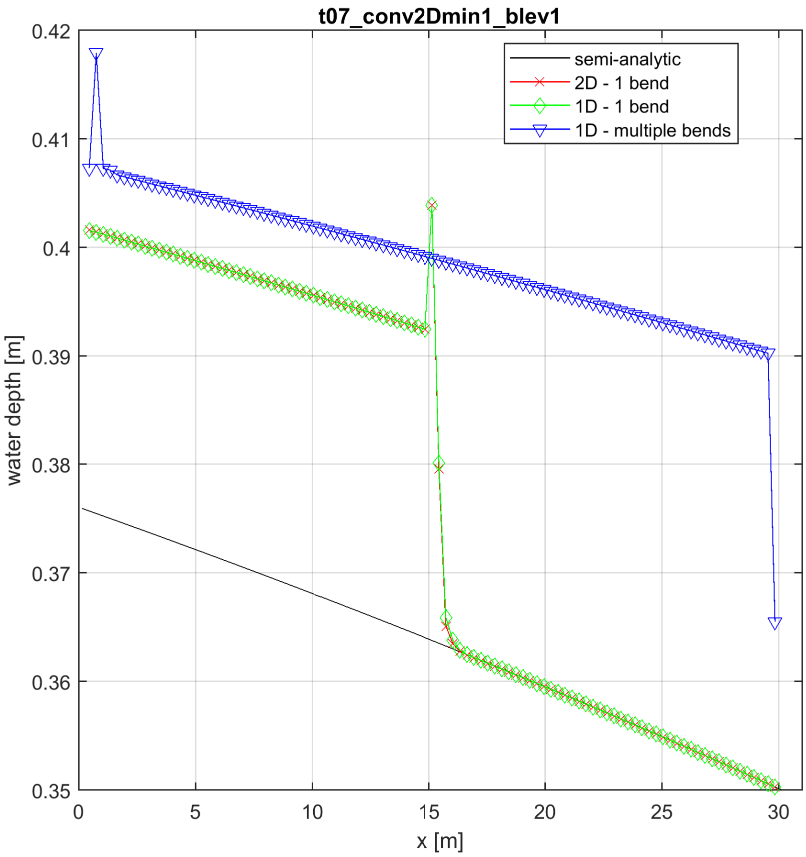

Figure 2.22: *Comparison of water levels in channels with bends compared to semi-analytical solution of surface profile for straight channel, bedlevtype=1.*

Analysis of results

From the figures above we can conclude:

- ◇ For straight channels: see previous test cases.
- ◇ Results independent of bedlevtype, so bend effects only analyzed for bedlevtype=1.
- ◇ Effect of one single 90^o bend is equal for 1D and 2D. For the considered geometry, the backwater effect is approximately 2.5 cm, which remains equal towards the upstream boundary of each model.
- ◇ For the case with multiple bends, the backwater effect originates at the downstream boundary. The effect is larger than considering one bend halfway a channel of equal length. In upstream direction, there appears to be no effect. Perhaps this is because we have schematized a 90^o bend at *each* node, making the channel virtually straight? At the upstream node, a backwater effect is visible due to the first downstream bend in the geometry.

Conclusion

"Bend-effects" are significant. It should be investigated how to treat this in D-Flow FM when considering 1D-models.
Another recommendation is to consider a “real world“ example for future test cases. Flow velocities in the channels with bends likely also deviate from those in the straight channel.

2.5 Straight channels in 1D and 2D: including 90 degree bend and effect of resolution

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Arthur van Dam		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

There is an important difference between SOBEK3 and D-Flow FM. In SOBEK3, the flow equations are solved in 1D: although the user can introduce geographical "bends" in a model, the equations are still solved as if the river is a straight line. Since D-Flow FM is set-up as a model-code for 1D-2D-3D, this is not the case. Also in 1D, the equations are solved in a vectorized way. This means that if there is a bend between computational nodes, the computed velocity can be very different from that computed in SOBEK3. The previous case gave insight in the effect of bends on water levels: backwater effects (opstuwing) at each bend. The question has risen whether this is physical or numerical. Therefore, in this test case we study whether the results from the previous case depend on the resolution of the grid.

Linked claims

◇ Bend effect independent of grid resolution.

Approach

In this case we compare a 1D straight channel with channels with a single 90^o bend with different horizontal resulotion (different dx).

Model description

See the figure below for the used grids in this case.

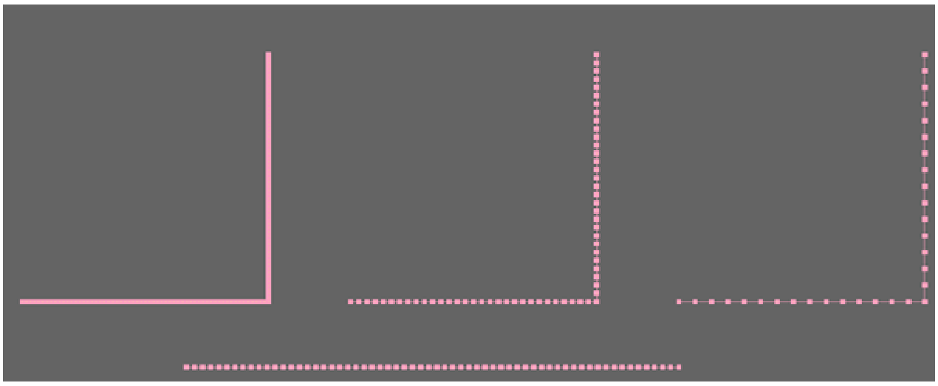

Figure 2.23: *Figure of the layout of the model.*

Properties of the considered cases:

- ◇ All channels are 30 m in length. Width of channel is 0.3 m.
- ◇ Straight 1D-channel: dx=0.5 m.
- ◇ 1D-channels with a single 90^o bend: from left to right dx=0.25 m, 0.50m, 1.00 m.
- ◇ Water depth downstream boundary: 0.35 m.
- ◇ Discharge at upstream boundary: 0.08 m^3/s.

Results

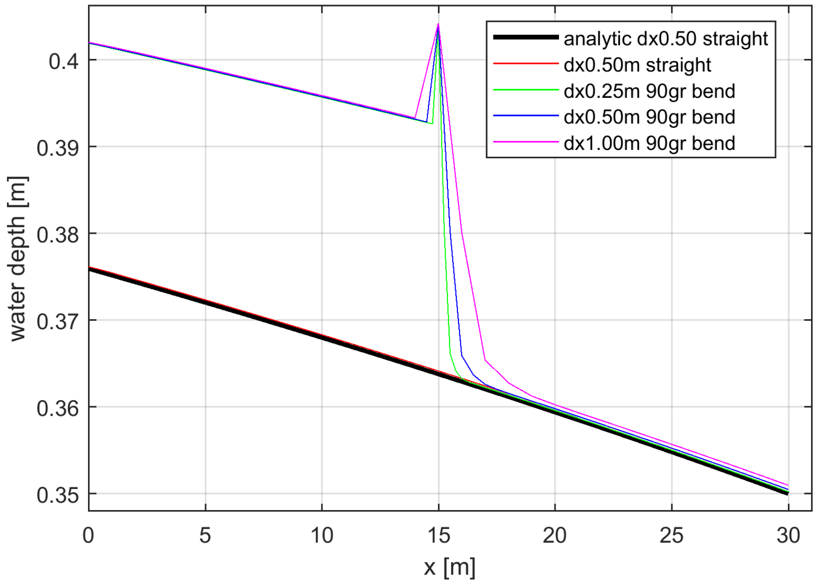

Figure 2.24: *Comparison of water depth for straight channels and channels with a single bend with various grid resolution.*

The backwater effect is independent of grid resolution (the apparent differences are only due to the relatively coarse grids). On hindsight, this result is probably logical. Two opposing effects "cancel out": the effect of a coarser grid and related numerical diffusion.

Conclusion

"Bend-effects" are independent of grid resolution. This gives reason to form a conceptual framework how to treat "bends" in 1D D-Flow FM applications.

3 Morphology 1D & 2D

3.1 1D uniform sediment

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
05 Dec 2017	Stef Boersen		Andries Paarlberg		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

The purpose of this validation case is to examine the performance of the Engelund-Hansen sediment transport formation in a 1D, also called, line model. The performance of the 1D model is compared with a validated 2D model. Furthermore, the 1D hydrodynamics have been tested in the previous chapter, see Chapter 2. Here, a schematised straight channel is modelled. The test case reference number is C01 till C04.

Linked claims

Claims that are related to the current test case are:

- The Engelund-Hansen sediment transport formulation in a 1D model is correctly programmed, according to a comparison with a 2D model.
- The differences in the sediment transport result from small differences in hydrodynamics between 1D and 2D grids.
- The differences in equilibrium bed slope are sufficiently small from a physical point of view.

Approach

Three different grids are designed and combined with two bathymetries. Each of the grids models a straight channel but the first grid has a width of 5 cells, the second a width of 1 cell and the third is a 1D grid, see Figure 3.1. The bathymetries are a flat channel and a channel with a trench, see Figure 3.2. These schematisations are combined to verify the claims.

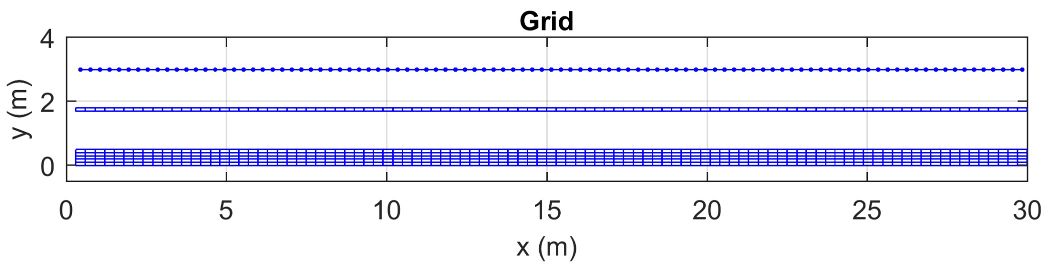

Figure 3.1: *Figure of the different grids. The top grid shows the 1D grid, the middle a quasi-2D grid and the bottom the full 2D grid.*

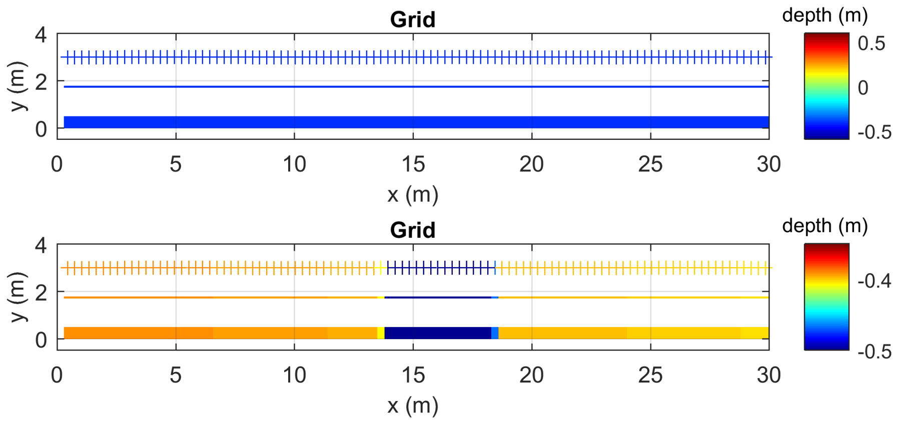

Figure 3.2: *The two bathymetries used for these cases. The top bathymetry represents the flat channel and the bottom bathymetry shows the trench. The plotmarks indicate the 1D bathymetry and the patches the 2D grids.*

Conclusion

The results show that the sediment transport in 1D gives equal results as in the 2D case. Tiny differences can be related to the accepted differences in the hydraulics between a 1D and 2D schematisation. The induced morphological changes show a larger difference between the 1D and 2D case. The inequality is in the order of 1% for the bottom slope. From a physical point of view this difference is acceptable but from a numerical point of view improvements are most likely possible.

Model description

In this test case we use a network composed of 3 straight channels in a single schematisation. The schematisation consists of 3 flat channels or 3 channels with each a trench. For the flat channel the bottom is kept at a constant depth of -0.4 m. For the trench a longitudinal bottom slope i_b is prescribed to be $4 \cdot 10^{-4}$ and the channel starts at a depth of -0.39 m. Each channel has a length of 30 m. The width of the 2D channel is set to 0.5 m. The line model and the quasi-2D model have a width of 0.1 m. In the 2D model a discharge Q of 0.09945 m^3/s is prescribed as an upstream boundary condition. In the 1D and quasi-2D the discharge is reduced according to the width to 0.0199 m^3/s. The Nikuradse roughness height is set to 0.025 m and evaluated using the White-Colebrook formula. For the downstream boundary condition a water level is set to 0 m.

In this test-case a uniform sediment grain size $D_{50} = 1.4 \cdot 10^{-4}$ is used.

The default parameters in the morphological setup are mainly used. Nevertheless, in the following section important related setup of morphology and sediment files used are described as follows:

◇ Sediment file $< *.sed >$:

```
[Sediment]
Name              = #Sediment_sand#                   Name of sediment fraction
SedTyp            = sand                              Must be "sand", "mud" or "bedload"
RhoSol            =  2.6500000e+003       [kg/m3]  Specific density
SedDia            =  1.4000000e-004       [m]      Median sediment diameter (D50)
CDryB             =  1.6000000e+003       [kg/m3]  Dry bed density
IniSedThick       =  5.0000000e-001       [m]      Initial sediment thickness layer-bed
FacDSS            =  1.0000000e+000       [-]      FacDss * SedDia = Initial SS dia
```

```
TraFrm          = 1
ACAL            = 1.0
```

Sediment transport equation is the transport relation by Engelund, F. and E. Hansen (1967).

The morphological update $MorUpd$ and bed composition update $CmpUpd$ are switched off to check the total transport. Then it is switched on to check the bed level change. Consequently, it results in 4 scenarios with each 3 channels, see Table 3.1. $MorFac$ is equal to 18 and the spin-up interval from the start time until the start of morphological changes $MorStt$ is 5.0 minutes.

Scenarios	Bathymetry	Morphological changes
1	Flat Channel	Unable
2	Flat Channel	Able
3	Trench	Unable
4	Trench	Able

Table 3.1: *Overview of the different scenarios.*

Results

The results for scenarios 1 are visualized in Figure 3.3 and Figure 3.4. The velocity differences between the different grids are of the order 10^{-4} m/s between the two 2D grids and of the order 10^{-5} m/s between the 1D and quasi-2D grid. Similar results were found in Chapter 2 and were excepted. The inequality between the 1D and quasi-2D grid in total sediment transport is in the order of 0.1 % of the total transport. Similar as for the velocity, the difference between the 1D and quasi-2D case is one order of magnitude smaller than between the 2D grids. The disparity can be related to the difference in flow velocity between the different grids and is therefore excepted.

The effects of the morphological developments are shown in Figure 3.5, Figure 3.6, Figure 3.7 and Figure 3.8. Here, the results for Scenario 2 after 300 min are used. The morphological changes have become zero and the bed has reached a slope of $-3.6 \cdot 10^{-4}$. A minor difference between the 1D and quasi-2D grid can be observed and is in the order of 1% of the slope. The difference in slope also explains the difference in flow velocity and consequently in total sediment transport.

In Scenario 3 and 4 a constant bedslope combined with a trench is simulated. The steady state flow conditions and total sediment transport are visualised in Figure 3.9 and Figure 3.10 for Scenario 3. The difference in flow velocity between the 1D and quasi-2D grid is of the order 10^{-5} m/s. This is one order of magnitude smaller than the inequality between the quasi-2D and full 2D grid and therefore acceptable. For the total sediment transport similar differences are found.

The morphology changes due to the spatial variation in total sediment transport, see Figure 3.11. At t=30 minutes the system has not reached a morphological steady state and the trench is still migrating in the current direction. The differences between the different grids are of similar order of magnitude as found in Scenario 2. Hence the same conclusions can be made: still a small inequality exist between the 1D and 2D grid. This difference results in a 1% inequality in bedlevel. It is acceptable from a physical point of view but from a numerical perspective improvements can me made. The difference in morphology also effects the current velocity and thereby the total sediment transport, see Figure 3.12 and Figure 3.13.

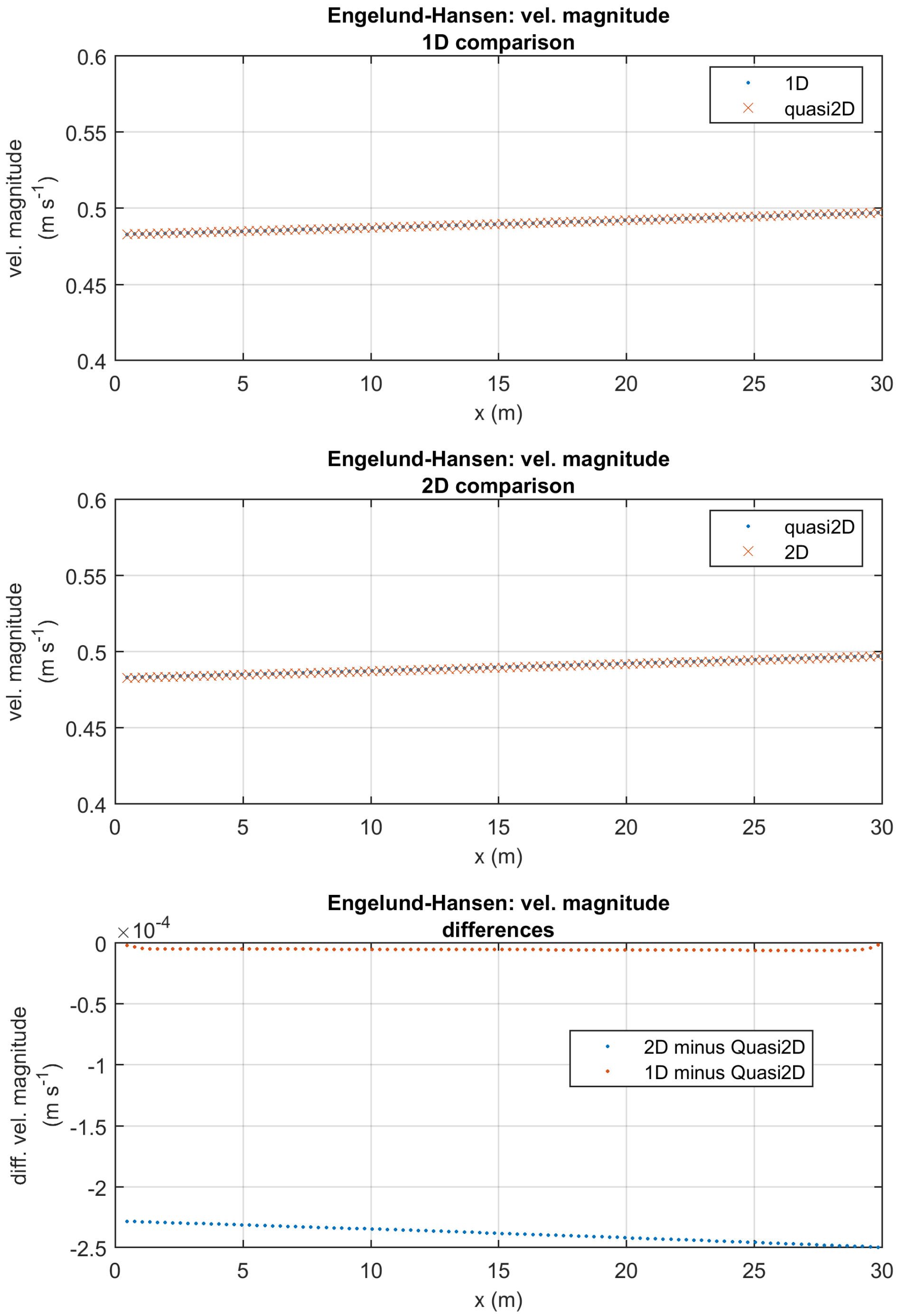

Figure 3.3: *The velocity magnitude for Scenario 1.*

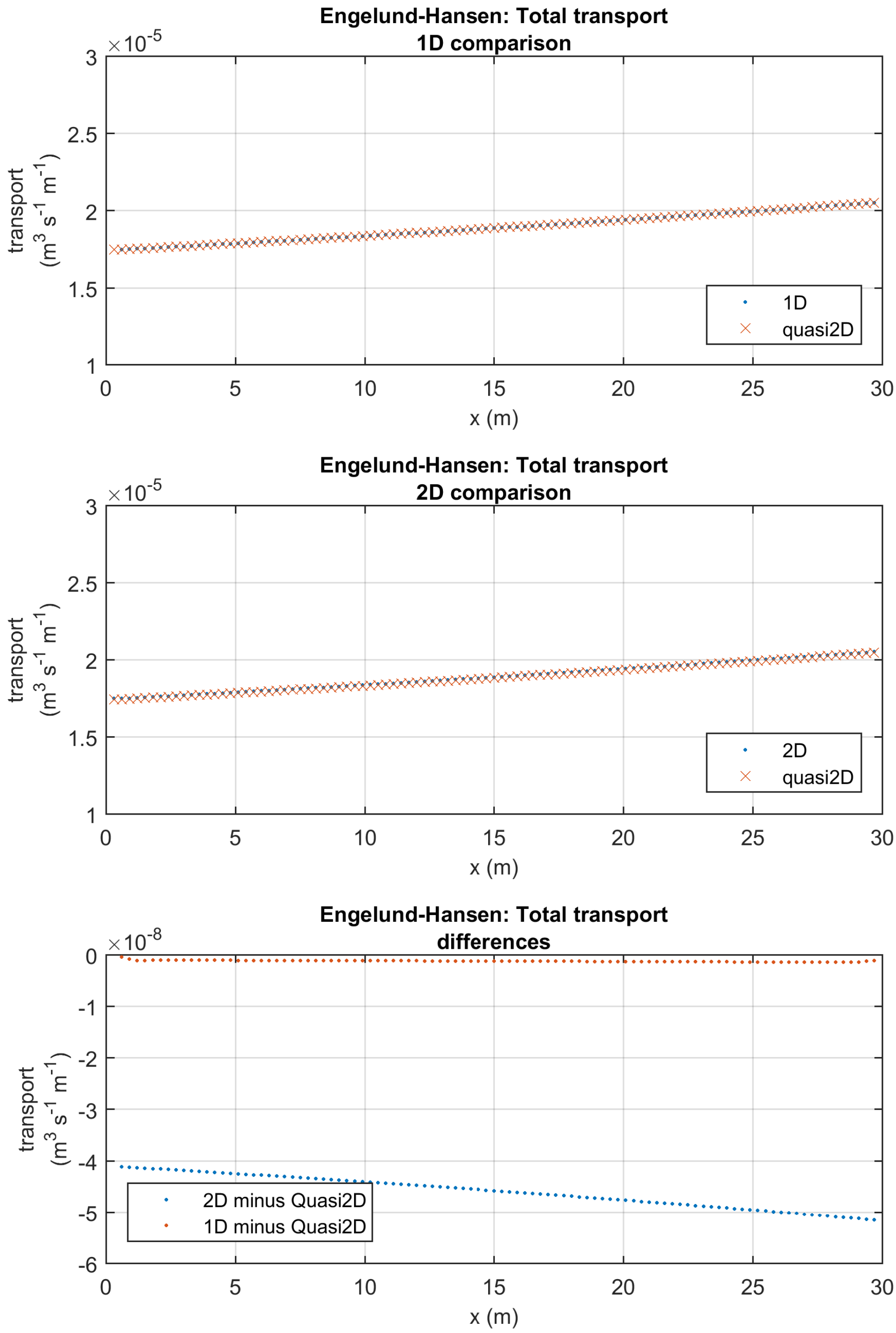

Figure 3.4: *The total sediment transport for Scenario 1.*

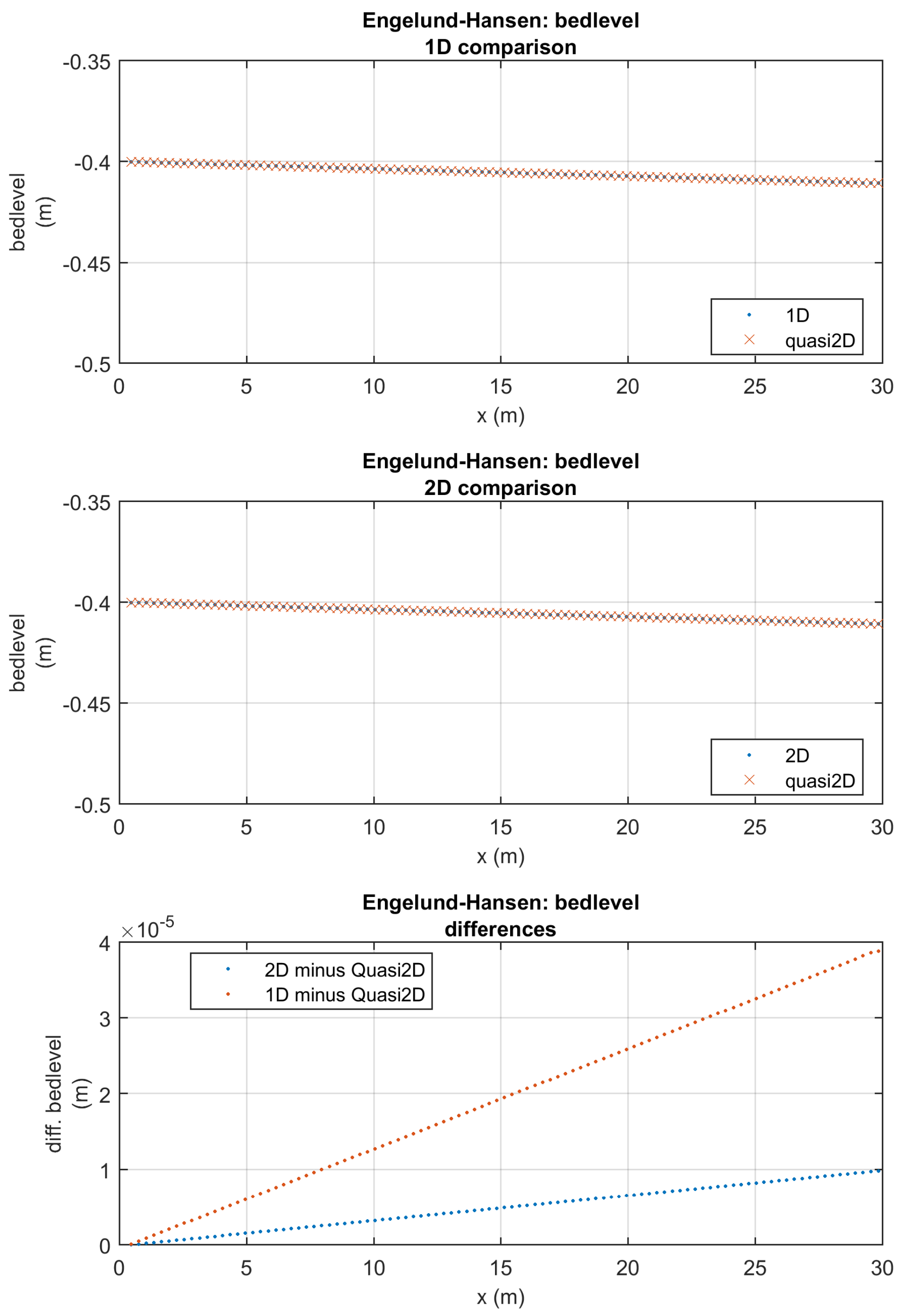

Figure 3.5: *The bathymetry for Scenario 2 after 300 min. The bathymetry is no longer changing.*

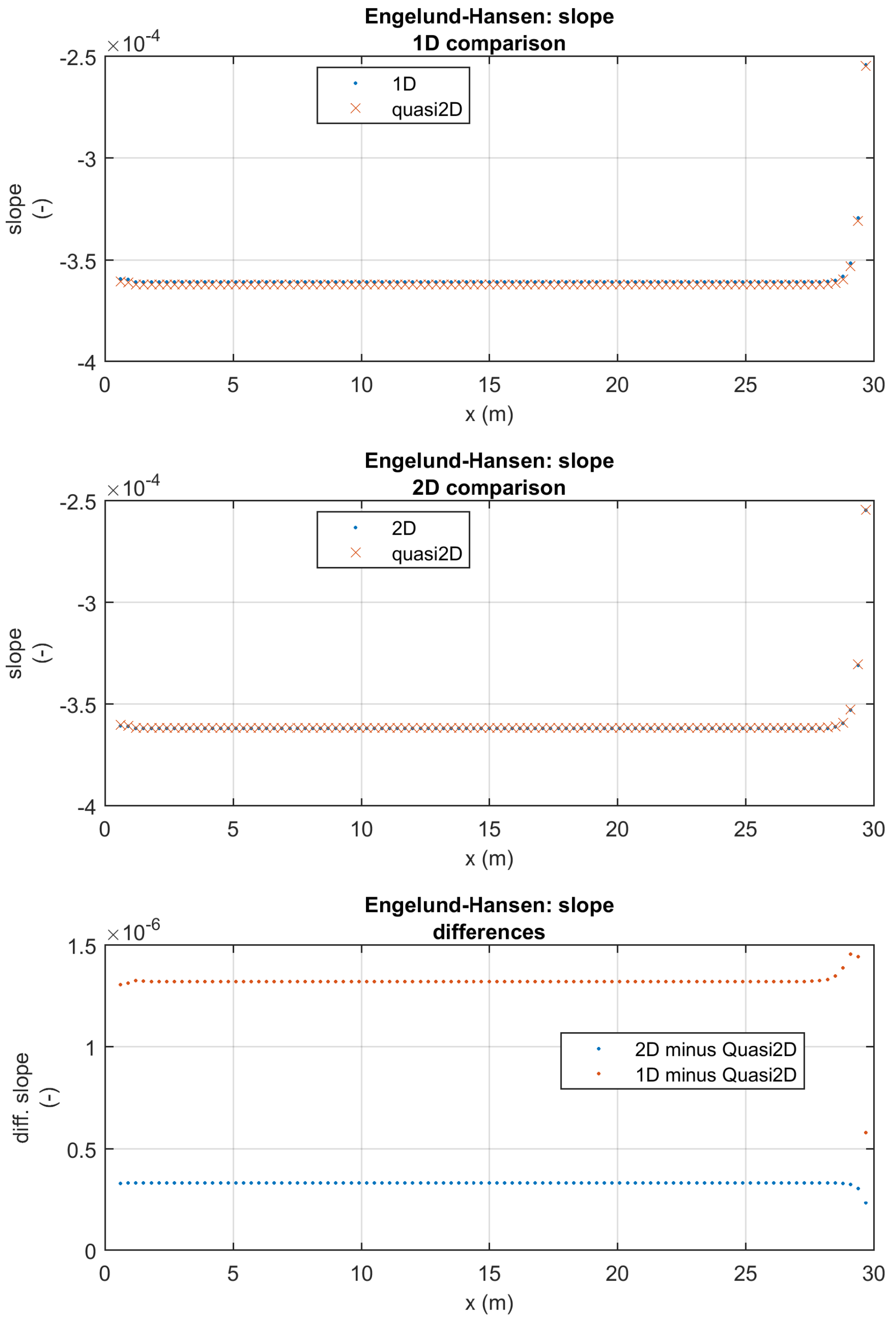

Figure 3.6: *The slope of the bed for Scenario 2 after 300 min. The bathymetry is no longer changing in time.*

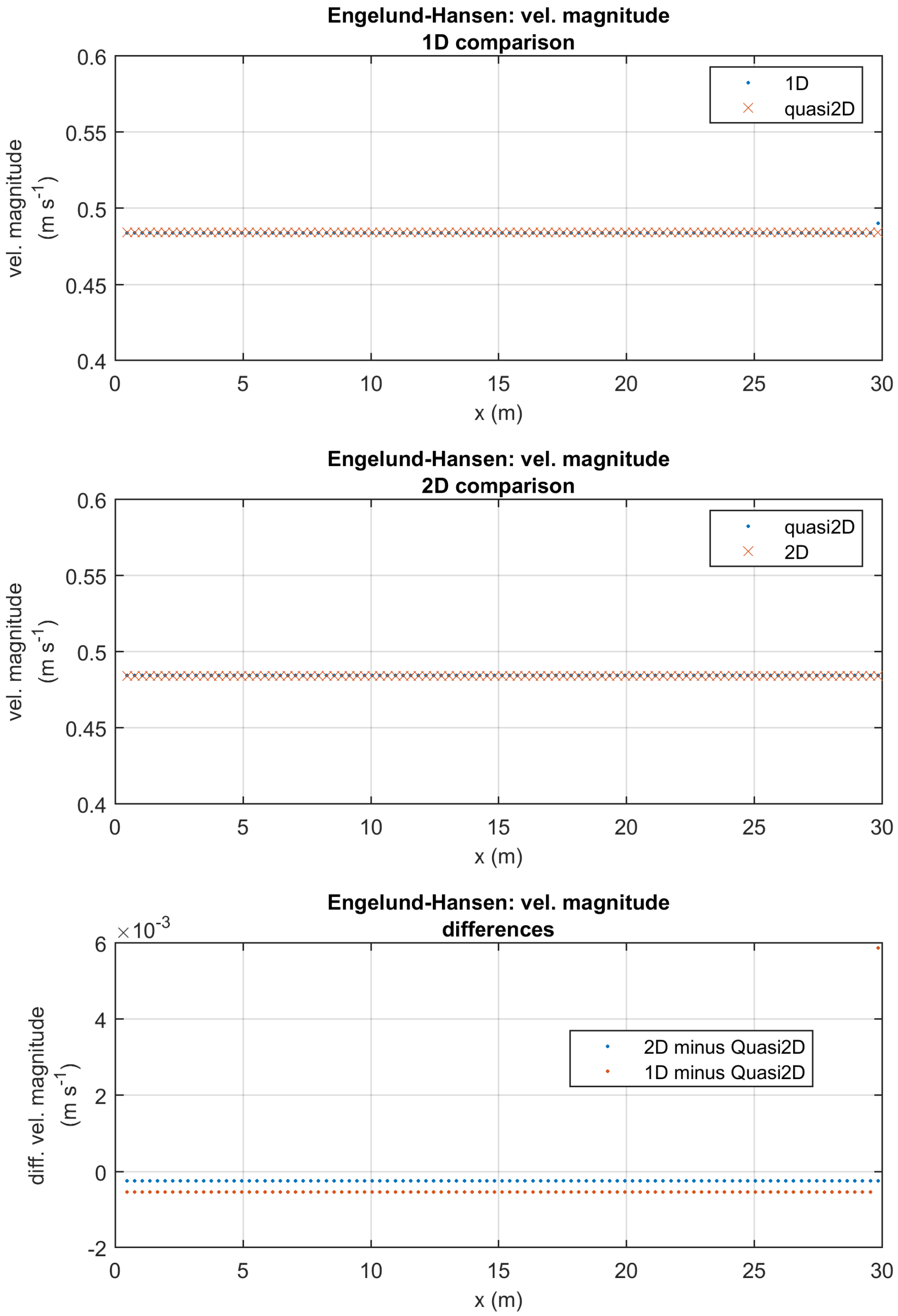

Figure 3.7: *The velocity after 300 min for Scenario 2. The velocity is no longer changing in time.*

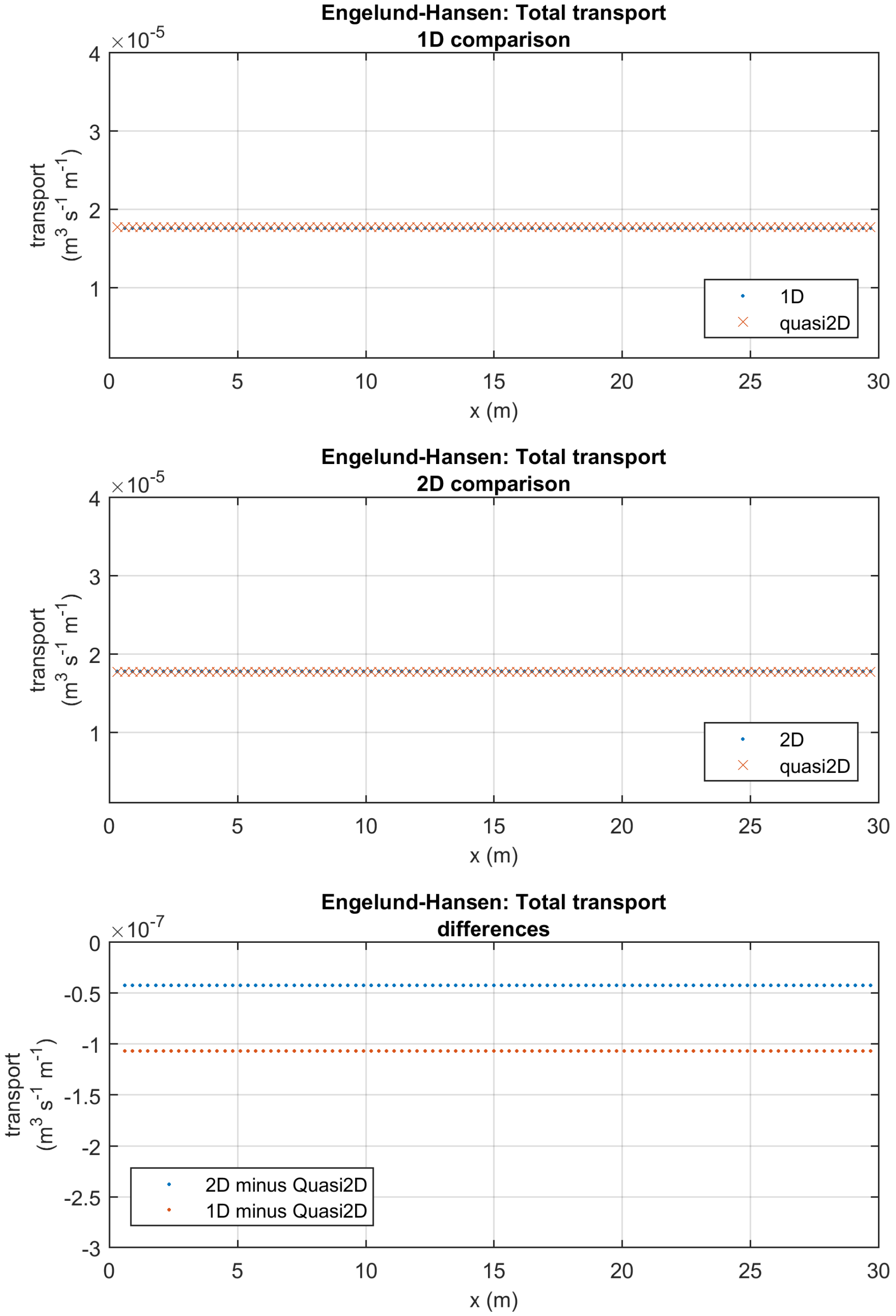

Figure 3.8: *The total sediment transport after 300 min for Scenario 2. The total sediment transport is no longer changing in time.*

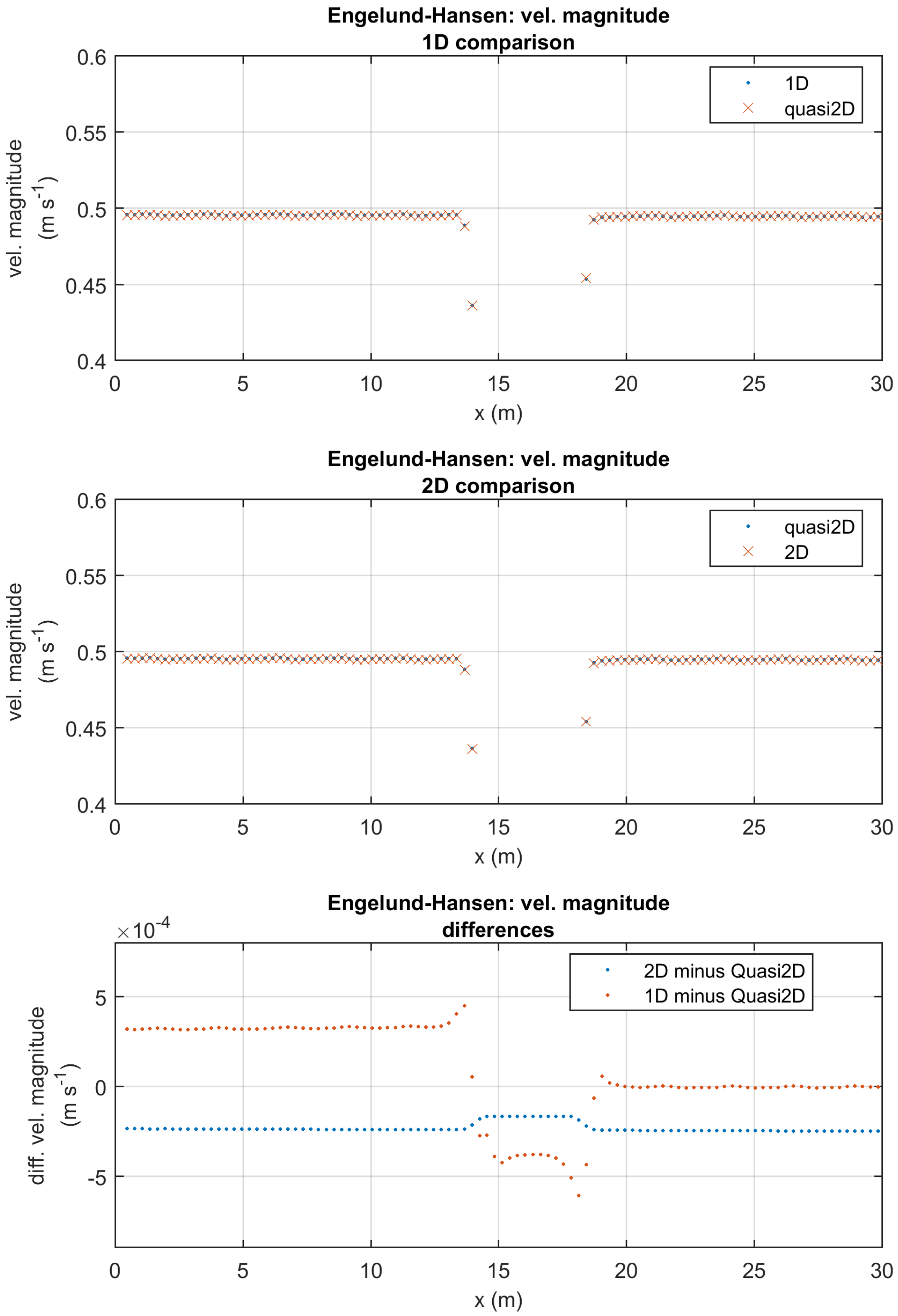

Figure 3.9: *The steady state flow velocity for Scenario 3.*

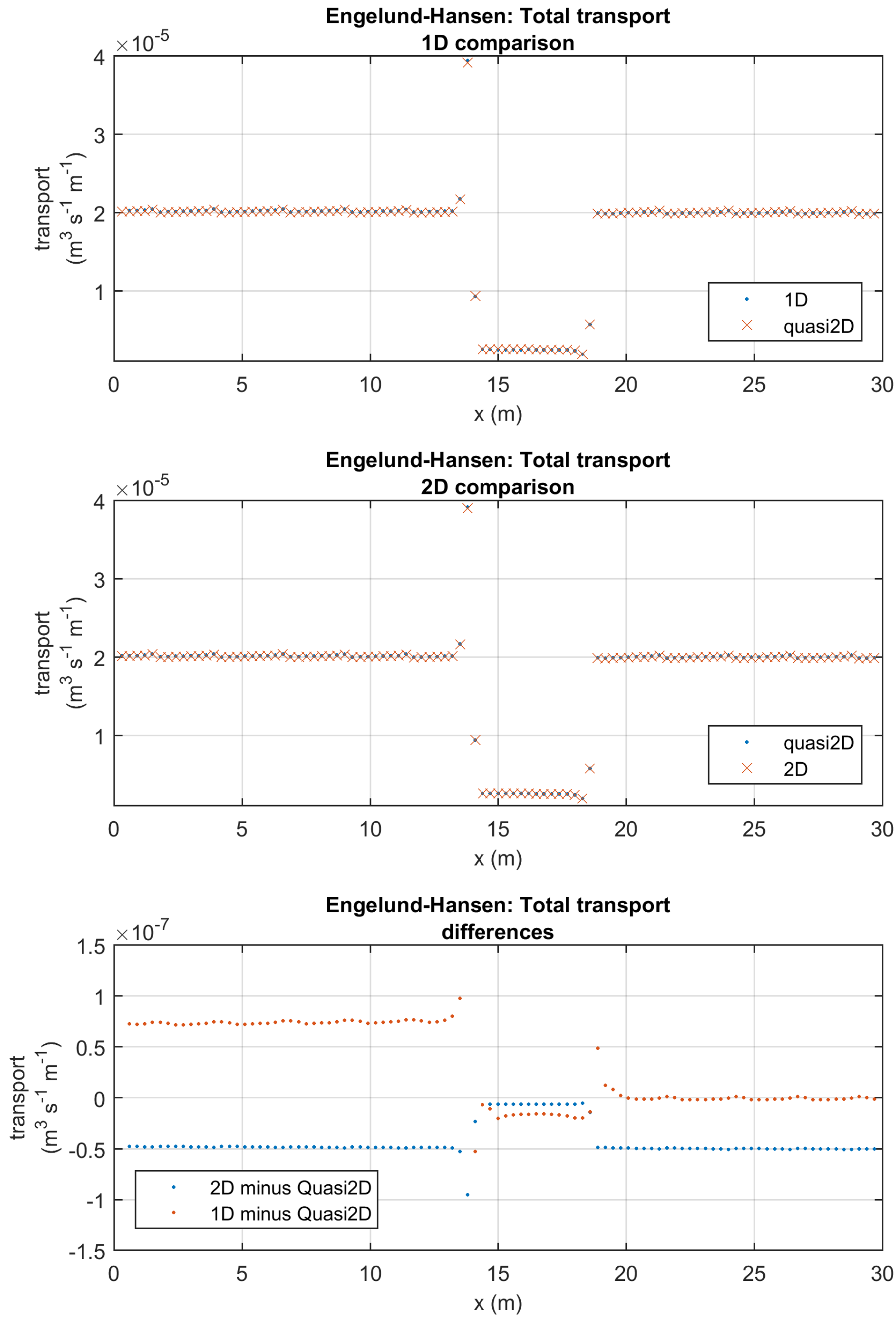

Figure 3.10: *The steady state total sediment transport for Scenario 3.*

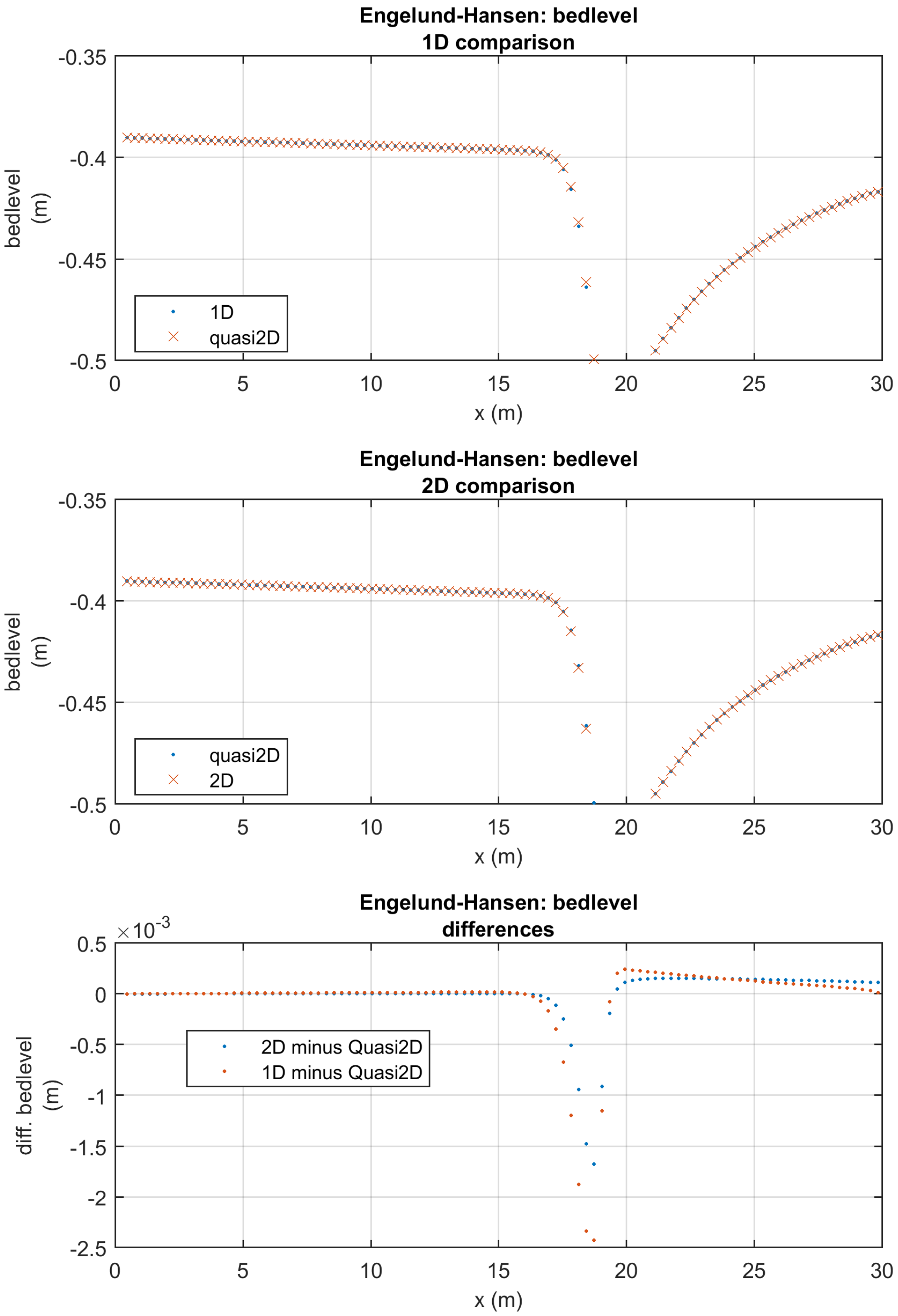

Figure 3.11: *The bathymetry for Scenario 4 after 30 min. The trench is still migrating in the current direction.*

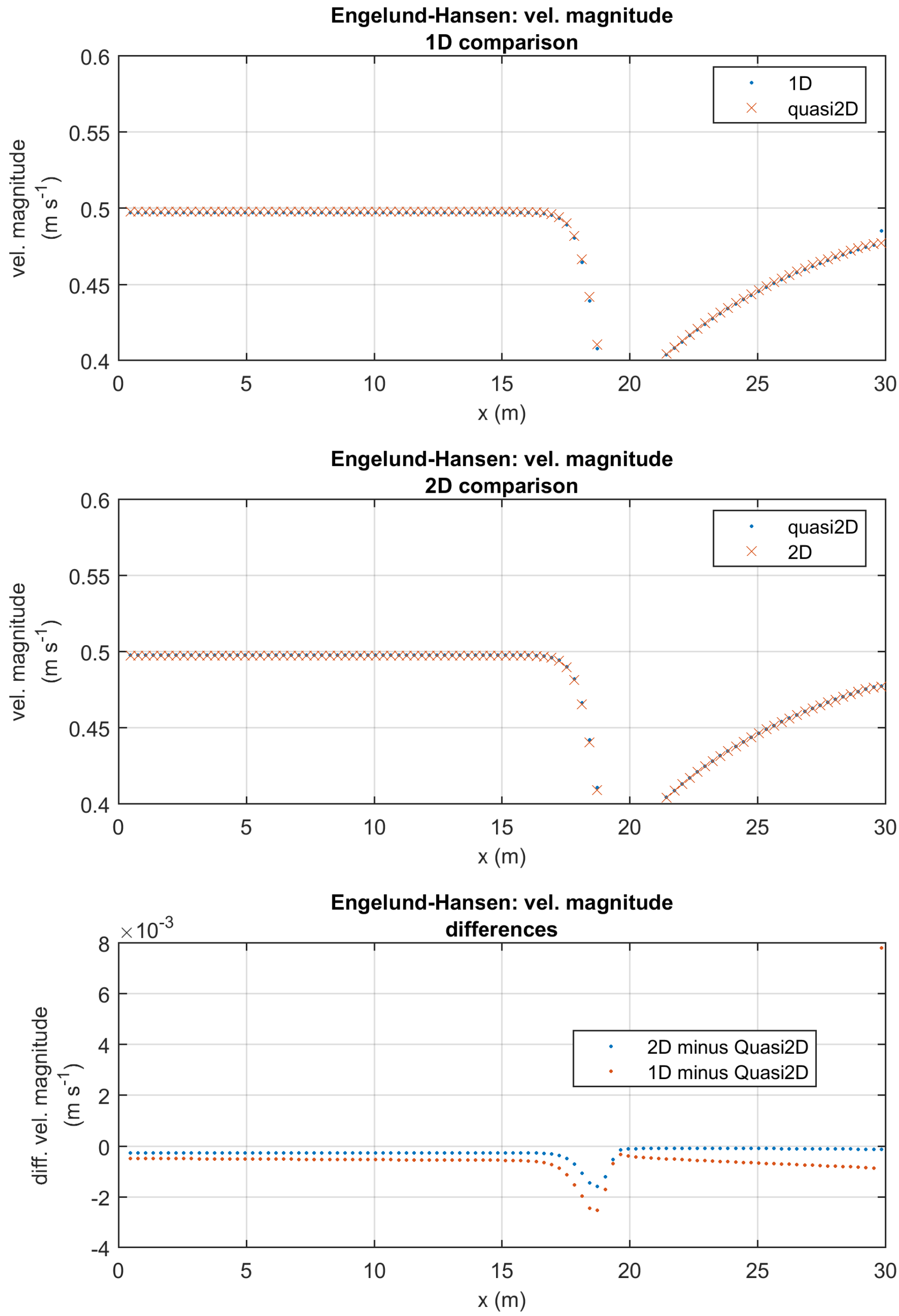

Figure 3.12: *The flow velocity for Scenario 4 after 30 min. The trench is still migrating in the current direction.*

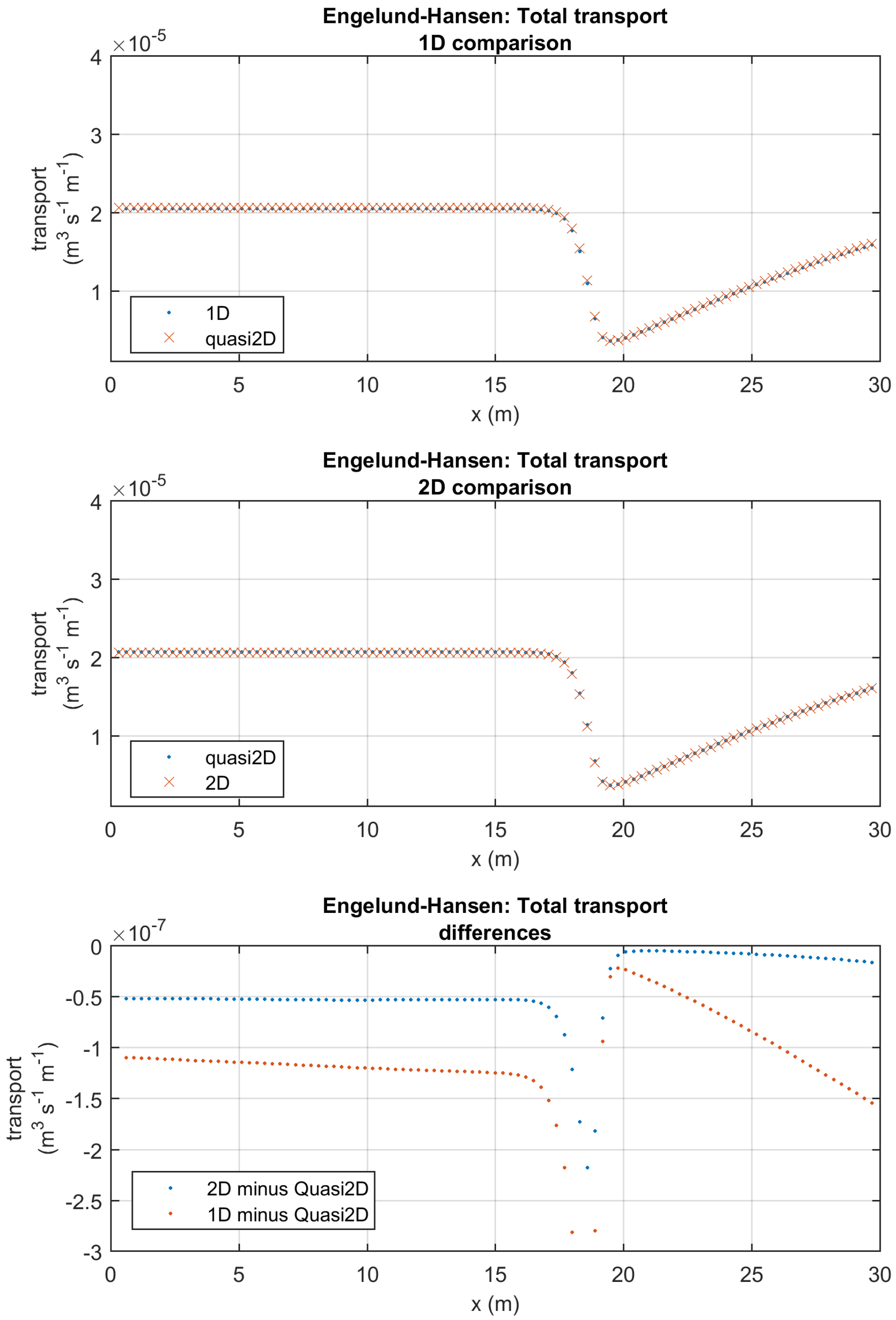

Figure 3.13: *The total sediment transport for Scenario 4 after 30 min. The trench is still migrating in the current direction.*

Conclusion

The results show that the sediment transport in 1D gives equal results as in the 2D case. Tiny differences can be related to the accepted differences in the hydraulics between a 1D and 2D schematisation. The induced morphological changes show a larger difference between the 1D and 2D case. The inequality is in the order of 1% for the bottom slope. From a physical point of view this difference is acceptable but from a numerical point of view improvements are most likely possible.

References

Engelund, F. and E. Hansen (1967). *A monograph on Sediment Transport in Alluvial Streams*. Teknisk Forlag, Copenhagen.

3.2 1D Upstream bedload sediment boundary condition (bcm)

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
12 Dec 2017	Amgad Omer		Stef Boersen		Aukje Spruyt	

Version information

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SVN revision : -

Purpose

The purpose of these tests are to assess model behaviour for different options of upstream sediment boundary conditions that are available in Delft3D-FM 1D. The options for boundary conditions, which can be imposed at upstream open boundary are:

(i) 'bed level fixed', default or can be specified in morphological input file (no need to have a boundary condition file)

(ii) 'depth', which implies specifying constant or varying bed level change in *.bcm file

(iii) 'depth change', which implies constant or time varying rate of bed level change (i.e. bed level acceleration) in $*.bcm$ file, and

(iv) 'transport including pores', which implies sediment transport rate including pores in *.bcm file.

From (ii) to (iv) are tested and documented here.The test cases numbers are e02-f29- c05,c06,c07,c08 and c09.

Linked claims

Claims that are related to the test cases are:

- ◇ The imposed upstream sediment transport conditions work in a proper way.
- ◇ The results are consistent and comparable.

Approach

Three different grids are designed and combined with similar bathymetry. Each of the grids models are a straight channel.The first grid has 20 cells along the width, the second has 1 cell along the width and the third is a 1D grid, see Figure 3.14. The bathymetries are a flat channel with bed level of $-5m$. These schematisations are combined to verify the claims.

The grids use a downstream water level boundary of $0.17m$ and upstream discharge boundary condition as follows:

- Discharge, of the 2D grid with 20 cells and total width of 1.6 m and a length of 16 m, is $Q = 1.6$ m^3/s . This grid will be called in this document "full 2D model or grid".
- Discharge, of the 2D model with 1 cell and total width of 0.08 m and length of 16 m, is $Q = 0.08$ m^3/s . This grid will be called in this document "quasi 2D model or grid".
- Discharge, of the 1D model and total width of 0.08 m and length of 15.68 m, is $Q = 0.08$ m^3/s. This grid will be called in this document "1D model or grid".

The model with three grids is used to test different options of upstream boundary condition of 1D-FM compared to 2D-FM. Four options are considered as mentioned above. Firstly, basic model behaviour is checked by imposing the conditions for 'Depth' and 'Depth change' at the boundary, and also 'transport incl pores' option. The simulations are made by imposing certain values for these options to assess whether the changes at the boundary are consistent. Some tests are made with multiple sediment fractions (two in current tests) under similar condition as for single fraction.

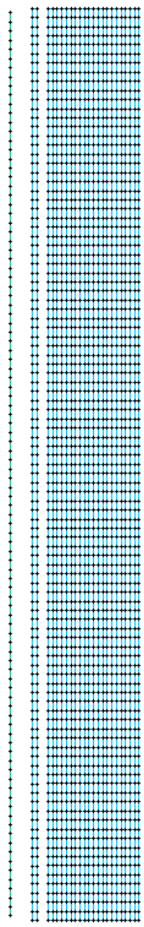


Figure 3.14: *Figure of the different grids. The figure (from left to right) shows the 1D grid,the 2D grid with 1 cell (a quasi-2D grid) in the width and 2D grid with 20 cells in the width.*

Model description

A simple model of 16 m long, 1.6 m wide with a flat bed at a constant level of -0.5 is used. A discharge of 2000 l/s is imposed. At the downstream boundary a water level of 0.17 m is imposed. A Chézy coefficient of 60 m$^{0.5}$/s is used for the channel roughness.

In these test cases, we use a network composed of 3 straight channels in a single schematisation. The schematisation consists of 3 flat channels. Each channel as a length of 16 m except the 1D channel is a bit less. Because the sediment transport results are interpolated in the cell center, while the 1D results are interpolated at the notes. Therefore, the first note of the 1D model has to be parallel to the first cell center of of the 2D model.

In these test cases the sediment grain size $D_{50} = 5.0 \cdot 10^{-4}$ m is used.

The default parameters in the morphological setup are mainly used. Nevertheless, in the following section important related setup of morphology and sediment files used are described as follows:

◇ Sediment file $< *.sed >$:

```
[Sediment]
Name             = #Sediment_sand#               Name of sediment fraction
```

```
SedTyp            = sand                          Must be "sand", "mud" or "bedload"
RhoSol            =  2.6500000e+003      [kg/m3]  Specific density
SedDia            =  5.0000000e-004      [m]      Median sediment diameter (D50)
CDryB             =  1.6000000e+003      [kg/m3]  Dry bed density
IniSedThick       =  5.0000000e-001      [m]      Initial sediment thickness layer-bed
FacDSS            =  1.0000000e+000      [-]      FacDss * SedDia = Initial SS dia
TraFrm            = 1
ACAL              = 1.0
```

Sediment transport equation is the transport relation by Engelund, F. and E. Hansen (1967).

◇ Morphology file $< *.mor >$:

```
IopKCW           = 1     Flag for determining Rc and Rw
RDC              = 0.01  [m] Current related roughness (IopKCW = 2)
RDW              = 0.02  [m] Wave related roughness (IopKCW = 2)
MorFac           = 1     [-] Morphological scale factor
MorStt           = 300   [TUnits] Spin-up interval
BedUpd           = true  Update bathymetry during flow run
CmpUpd           = true
EqmBc            = false     Equilibrium concentration at inflow boundaries
BcFil            = str2.bcm
[Boundary]
Name       = #up2dmulti#
IBedCond = 2     0 no bed level constraint
                 1 bed level fixed
                 2 depth specified as function of time
                 3 depth change specified as function of time
                 4 bedload transport rate prescribed (volume rate of bed material)
                 5 bedload transport rate prescribed (volume rate of stone)

ICmpCond = 2     0 no bed composition constraint
                 1 composition constant
                 2 mass fractions specified as function of time
                 3 volume fractions specified as function of time.
[Boundary]
Name       = #downstream#
IBedCond = 0
ICmpCond = 0
[Boundary]
Name       = #up2dsingle#
IBedCond = 2
ICmpCond = 2
[Boundary]
Name       = #uponedimen#
IBedCond = 2
ICmpCond = 2
```

The morphological update $MorUpd$ and bed composition update $CmpUpd$ are switched on to check the bed level change. The bedload upstream boundary condition is checked as follows for every test case:

◇ c05 with iBedcond = 2 and icmpcond = 2, using uniform sediment.
◇ c06 with iBedcond = 3 and icmpcond = 2, using uniform sediment.
◇ c07 with iBedcond = 4 and icmpcond = 2, using uniform sediment.
◇ c08 with iBedcond = 4 and icmpcond = 0, using graded sediment.
◇ c09 with iBedcond = 2 and icmpcond = 2, using graded sediment.

An example of the 'bcm' File used in c05 is shown below. In the bcm file we can specify the conditions of the boundary selected for the bedload.

◇ Morphology file $< *.mor >$:

```
table-name          'Boundary Section : 1'
contents            'Uniform'
location            'up2dmulti'
time-function       'non-equidistant'
reference-time      20151101
time-unit           'minutes'
interpolation       'linear'
parameter           'time' unit '[min]'
parameter           'depth'  unit  '[m]'
parameter           'mass fraction Sediment_sand'  unit  '[-]'
records-in-table     3
0.00000000          0.5   1
0.00000000          0.5   1
20                  1.0   1
 Note: Similar set up has beed imposed for the other 3 boundaries.
 Deltails can be found in the bcm file of the test case "c21".
 However, the bcm file parameters and parameters values are changed
 based on the requirement of every test case.
```

Results

The results will be discussed for every test case separately as follows:

c05 iBedcond2 and icmpcond2 (Uniform sediment)

In this test case , the model is setup to change the upstream bed level from -0.5 to -1 m. The comparison between water level and bed level simulated by 2D-model and 1D-model of FM after 20 minutes is shown in Figure 3.15 and Figure 3.16 respectively. These figures shows the change in a typical longitudinal section along both models.

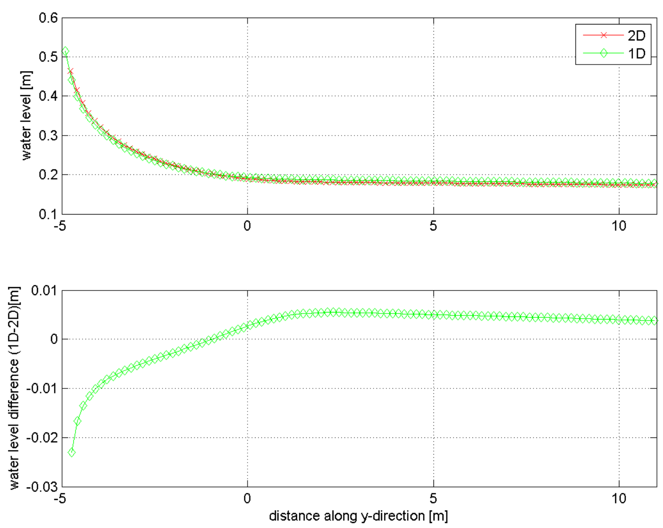


Figure 3.15: *c05:Comparison of water levels (iBedcond2).*

To investigate the imposed boundary at the upstream (at the ghost cell), we plotted the bed level change at the zero time and after 10 minutes and after 20 mintutes in Figure 3.17. A more clear view of the longitudinal section and the ghost cell bed level can be seen in Figure 3.18.

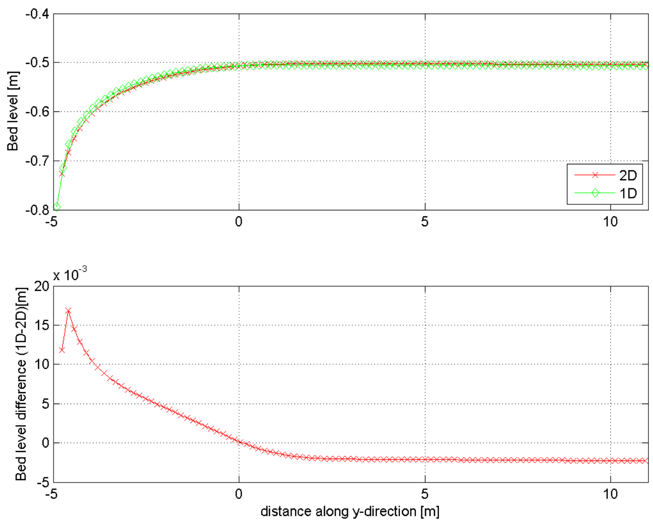


Figure 3.16: *c05:Comparison of bed levels (iBedcond2).*

c06 iBedcond3 and icmpcond2 (Uniform sediment)

Similar comparisons for other imposed conditions, namely 'Depth change' (from 0 to -0.5 m in 20 min of simulation time) are depicted in Figure 3.19 for water level and Figure 3.20 for the bed level. The result shows a difference between the results of 1D and 2D bed level. This also can be seen in the velocity comparison plot in Figure 3.21. This might need to be investigated further. The change rate of the depth creates a bed level at the upstream boundary of -300 m, which means the models read the imposed bed load boundary at the ghost cell correctly as shown in Figure 3.22.

c07 iBedcond4 and icmpcond2 (Uniform sediment)

In c07 test case, we impose bedload sediment fluxes at the upstream boundary 'transport incl pores' of (0.0002 m^2/s). The model results are depicted in Figure 3.23 for water level, and Figure 3.25 for the velocity and Figure 3.24 for the bed level. The result shows a small difference between the results of 1D and 2D bed level. In order to investigate the change of bed level and sediment transport at the boundary Figure 3.26 and 3.27 are plotted. In Figure 3.26, the bed level at the ghost cell goes down from -0.5 to 0.56 in the first 10 minutes and then from -0.56 to -0.57 in the last 10 minutes. Figure 3.27 indicates that there is sediment transport fluxes during the spin-up time of 300 second (Morstt). This has to be investigated whether the sediment transport has to be on during the spin-up time or not. However, after the spin-up time sediment transport recorded in the cross-sections shows that the model reads the correct amount of bed load fluxes imposed by the bcm file to the models.

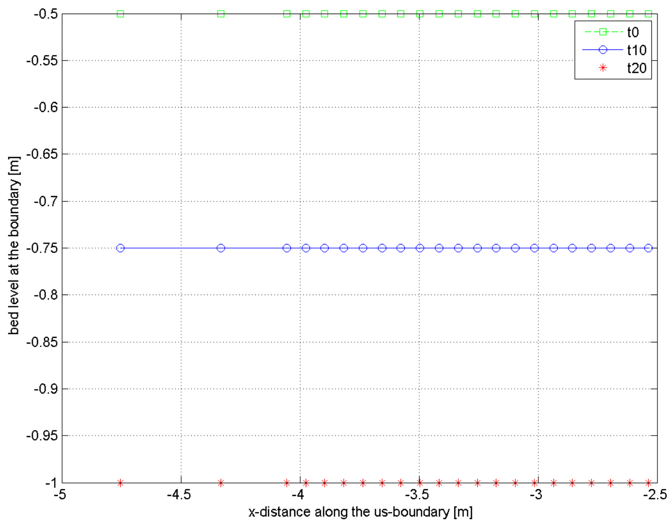


Figure 3.17: *c05:The bed level change at the upstream ghost cell(iBedcond2).*

08 iBedcond4 and icmpcond0 (graded sediment)

For computations with multiple fractions, two similar fractions are used for simplicity. The boundary condition 'transport incl pores' is tested to ensure correctness based on output results, namely imposing same amount (0.0002 m^2/s) for both fractions, but the initial layer of the model contains only one fraction to see if the second fraction gets into the model composition. Under layer approach ('IUnderLyr=2' and 'ThTrLyr = 0.5') has been used in this test case in the mor file. However, it is not yet clear how that could be seen from the model results. Results of this test are shown in Figure 3.28 for water level comparison, Figure 3.29 for bed level and Figure 3.30 for velocity magnitude comparison. The results shows that there a different of 1.5 cm in the water level at the upstream boundary. This difference start to decrease after 2.5 m far from the boundary. A difference can also be seen in the velocity plot and the bed level.

By looking to the bed level at the upstream ghost cell in Figure 3.31, it can be seen that the bed is going up which is logical as we are imposing sediment. However, Figure 3.32 shows that there is bed load sediment transport recorded during the spin-up time (the first 5 minutes) after that the amount of sediment transport recorded is similar to the sediment input fluxes.

c09 iBedcond2 and icmpcond2 (graded sediment)

For computations with multiple fractions, we change c05 to test the graded sediment. Two similar fractions are used for simplicity. The boundary condition 'depth' and 'mass fractions specified as function of time' are tested to ensure correctness based on output results. The parameters setup used in the bcm file is shown below. Under layer approach ('IUnderLyr=2' and 'ThTrLyr = 0.5') has been also used in this test case in the mor file.

◇ bed load boundary file $< *.bcm >$ for c09:

```
parameter            'time' unit '[min]'
parameter            'depth'  unit  '[m]'
parameter            'mass fraction Sediment_sand'  unit  '[-]'
parameter            'mass fraction Sediment_tracer'  unit  '[-]'
records-in-table      2
```

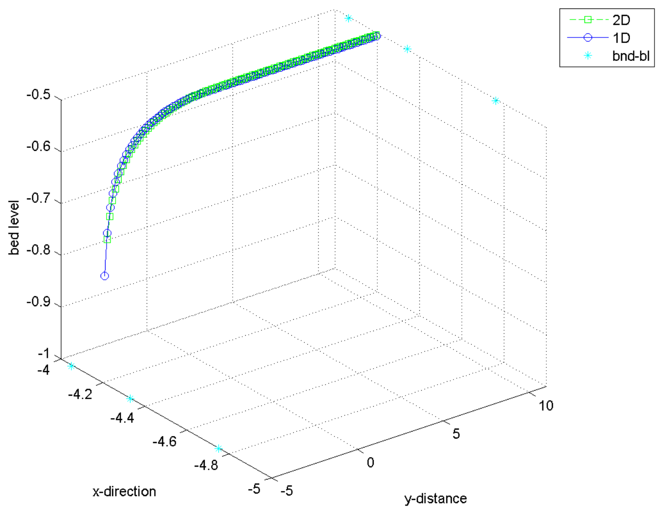


Figure 3.18: *c05:3D-view of the longitudinal section and the bed level at the ghost cell (iBedcond2).*

```
0.00000000          0.5    1    0
20.0000000          1.0    0    1
```

The results show that the water level and bed-level comparisons have some differences as shown in Figure 3.33 and Figure 3.34. The model read the depth imposed at the upstream boundary correctly as shown in Figure 3.36. However, the change in bed composition at the boundary (ghost or dummy cell) can not be seen. No change is recorded inside the model. This might be because the computation time is not enough to propagate the bed composition change.

Analysis of results

The results show that the 1D model is able to read the boundary condition correctly. However, the following are some comment based on every test case.

- ◇ c05 with iBedcond = 2 and icmpcond = 2, using uniform sediment: The result is quite acceptable as 1D-model read the imposed condition correctly. The propagation of the bed lowering is slow inside the model. This could be due to the low discharge and limited computation time used.
- ◇ c06 with iBedcond = 3 and icmpcond = 2, using uniform sediment: The model also reads the change in depth at the boundary correctly.
- ◇ c07 with iBedcond = 4 and icmpcond = 2, using uniform sediment: The model reads sediment inflow fluxes correctly. However, there is quite a difference in sediment transport magnitude during the spin-up time. This may need to be investigated further. Moreover, the bed level close to the upstream boundary is expected to be subjected to deposition (due to the sediment inflow). This is not the case as bed-level goes down there.This might be due to the high capacity of water to transport sediment.
- ◇ c08 with iBedcond = 4 and icmpcond = 0, using graded sediment: The 1D model is able to read the inflow fluxes of the both sediment fractions. However, the morphological changes are quite different between both 1D and 2D results. This might not be only because of the sediment bedload boundary condition.
- ◇ c09 with iBedcond = 2 and icmpcond = 2: Using graded sediment: The combination

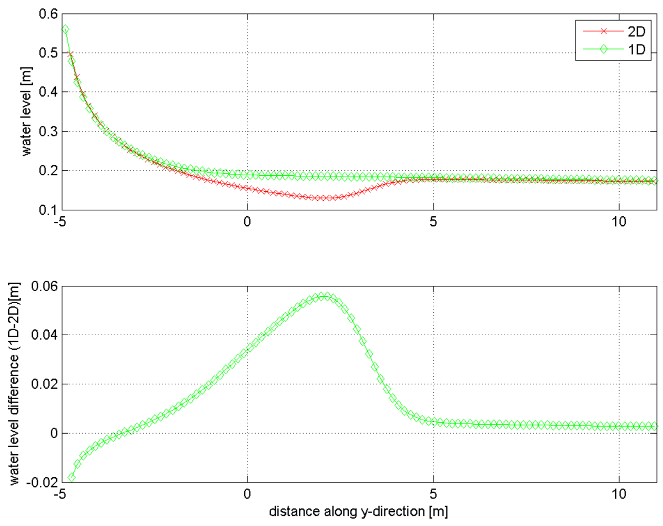


Figure 3.19: *c06:Comparison of water levels (iBedcond3).*

of depth change and bed composition change at the boundary is tested in 1D-model. The result shows that it is working well. However, the change of bed composition at the boundary may need to be investigated further.

Conclusion

The results show that the bed load upstream boundary conditions in 1D gives similar results as in the 2D case of depth (iBedcond2), depth change (iBedcond3) and bed-load transport rate (iBedcond4). However, the different change in morphology and bed level between 1D and 2D models leads to some discrepancies and issues. These discrepancies and issues cannot be fully attributed to the morphological boundary condition only. It is recommended to be investigated further. The following has to be considered for improving the testing in future:

- ◇ Investigate why during the Spin-up time (MorStt), the model is calculating the sediment transport and whether this has influence in the bed update directly after the spin-up time. It seems that the spin-up time is not well recognized by the 1D model.
- ◇ Investigate why the observation points do not record data at the ghost or the dummy cell at the boundary.
- ◇ Find a method to record the bed composition change at the ghost cell in order to verify that the model is reading the imposed boundaries correctly.

References

Engelund, F. and E. Hansen (1967). *A monograph on Sediment Transport in Alluvial Streams*. Teknisk Forlag, Copenhagen.

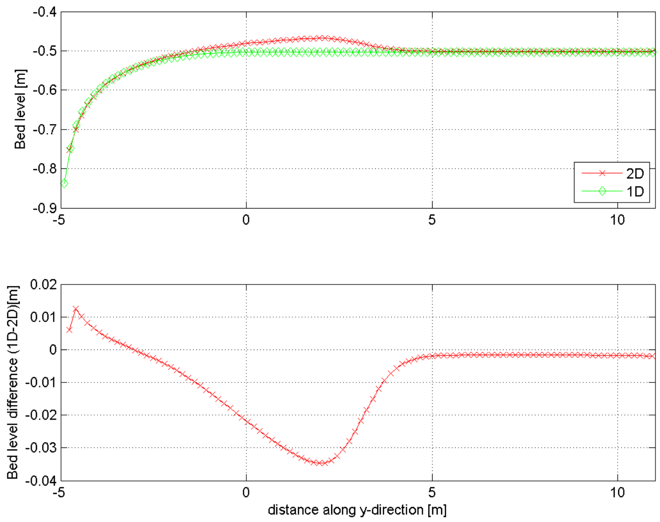


Figure 3.20: *c06:Comparison of bed levels (iBedcond3).*

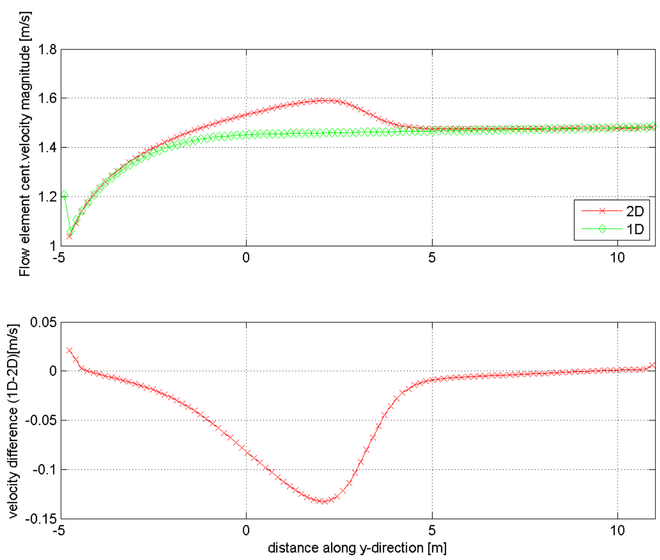


Figure 3.21: *c06:Averaged velocity magnitude along the 1D and 2D models (iBedcond3).*

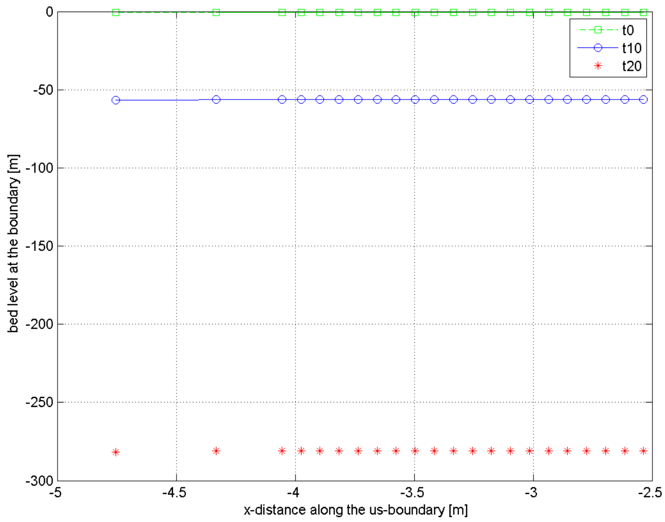


Figure 3.22: *c06:The bed level change at the upstream ghost cell (iBedcond3).*

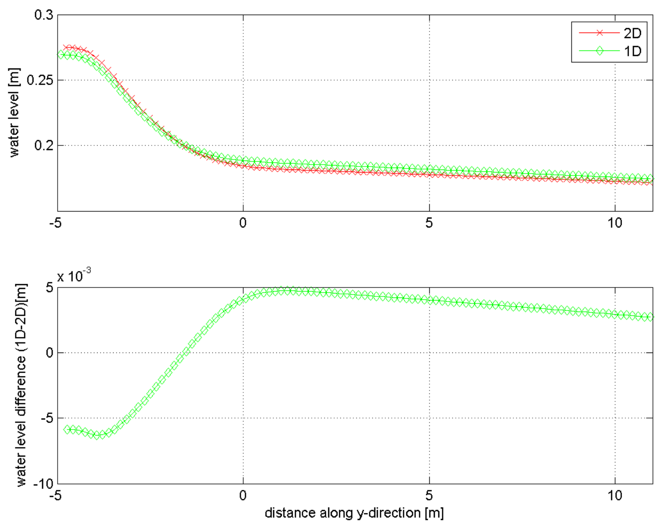


Figure 3.23: *c07:Comparison of water levels (iBedcond4).*

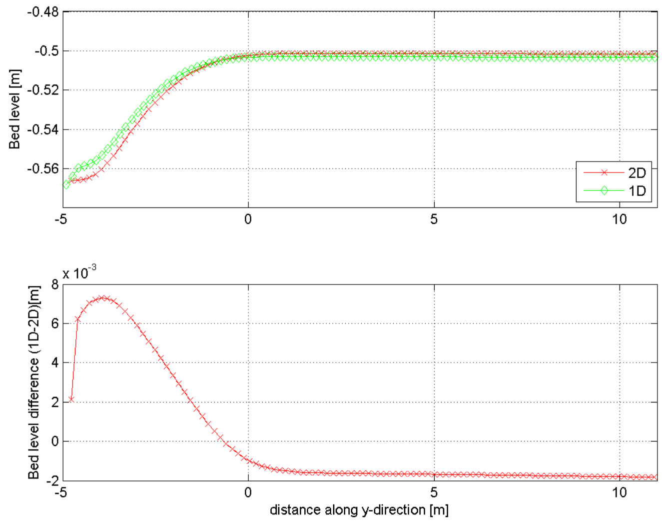


Figure 3.24: *c07:Comparison of bed levels (iBedcond4).*

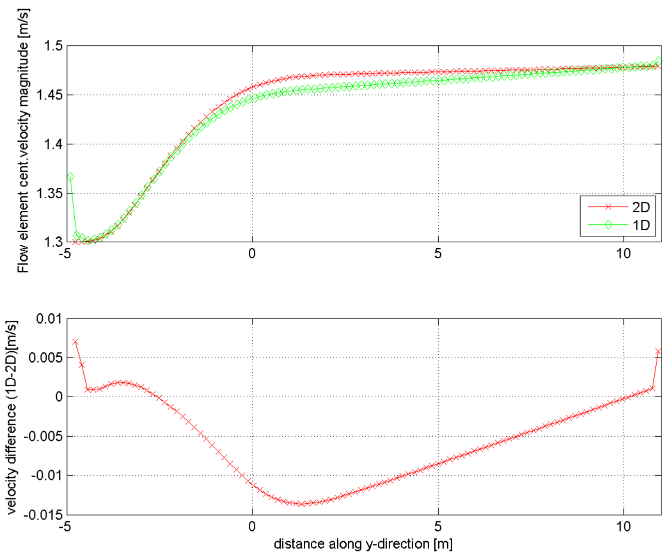


Figure 3.25: *c07:Averaged velocity magnitude a long the 1D and 2D models (iBedcond4).*

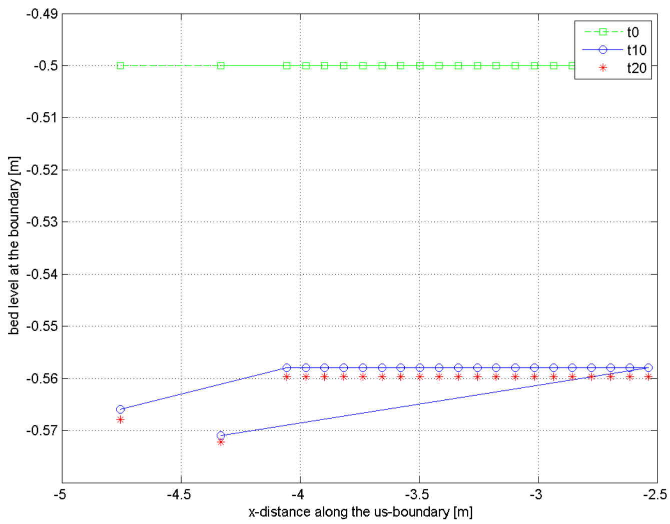


Figure 3.26: *c07:The bed level change at the upstream ghost cell (iBedcond4).*

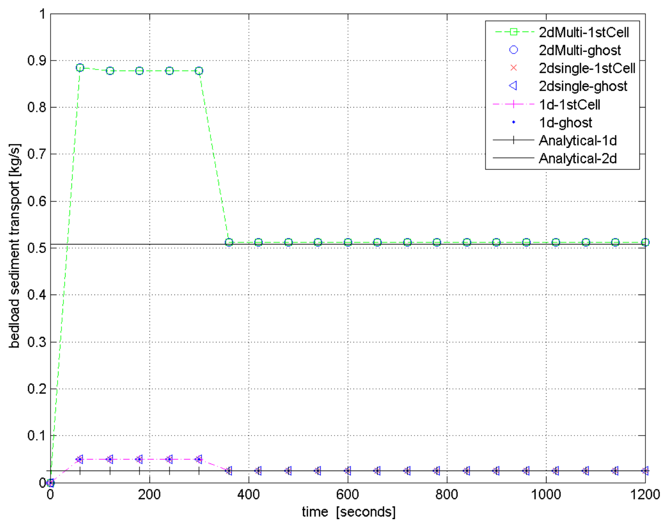


Figure 3.27: *c07:bed load sediment transport flues recorded at the ghost cell and the 1st cell of every model(iBedcond4).*

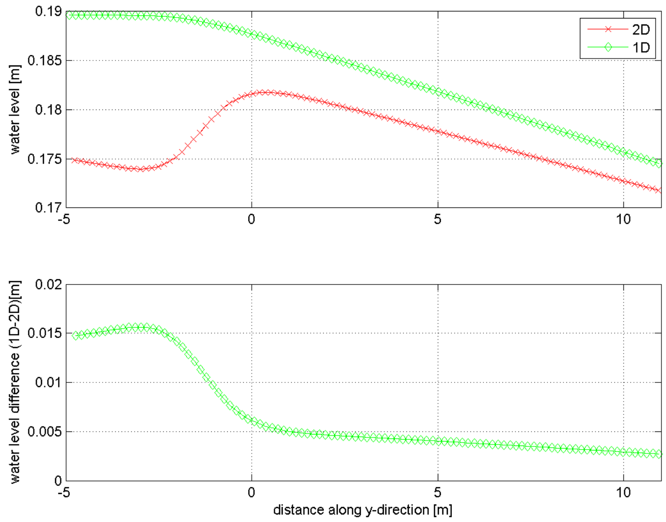


Figure 3.28: *c08:Comparison of water levels (iBedcond4).*

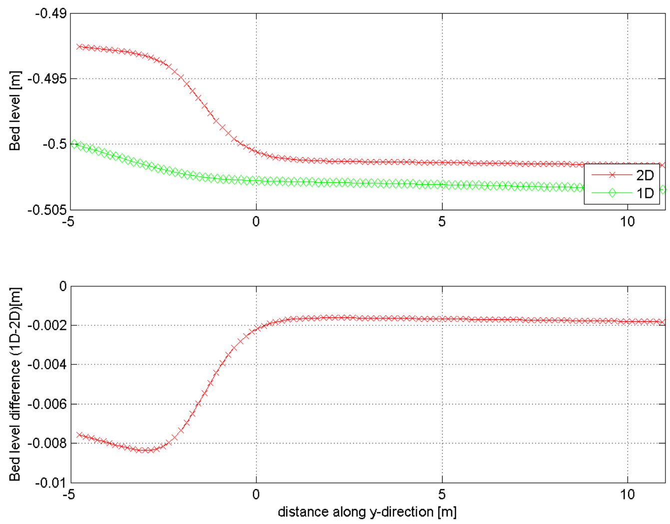


Figure 3.29: *c08:Comparison of bed levels (iBedcond4).*

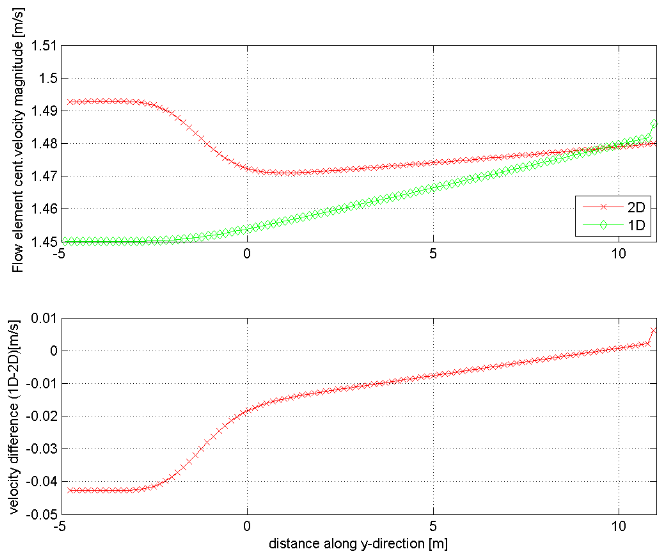


Figure 3.30: *c08:Averaged velocity magnitude a long the 1D and 2D models (iBedcond4).*

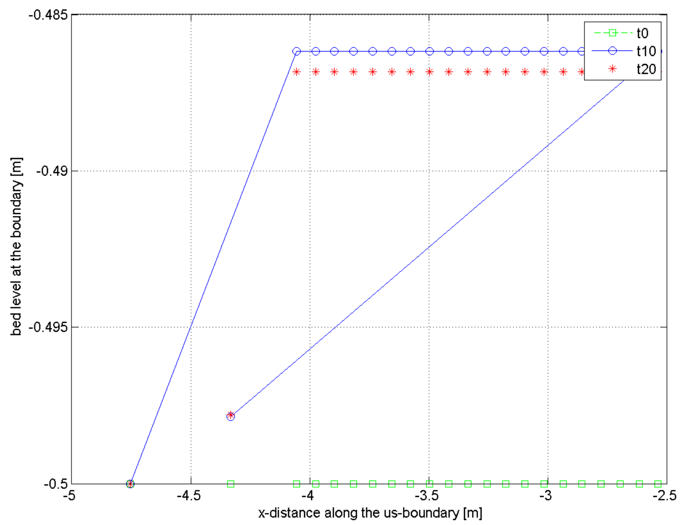


Figure 3.31: *c08:The bed level change at the upstream ghost cell (iBedcond4).*

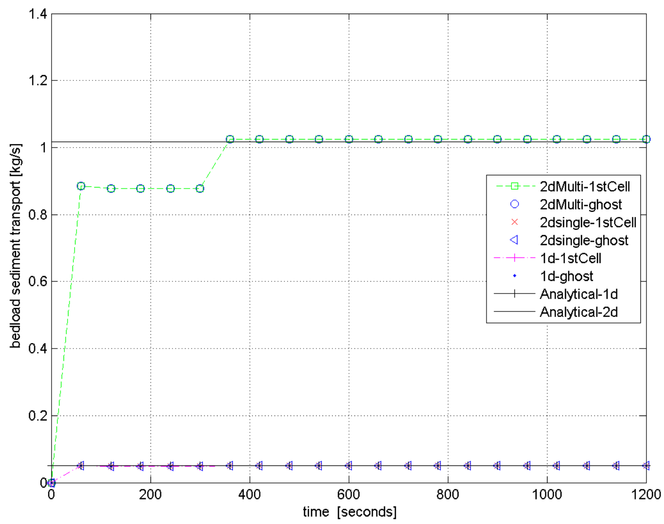


Figure 3.32: *c08:bed load sediment transport flues recorded at the ghost cell and the 1st cell of every model(iBedcond4).*

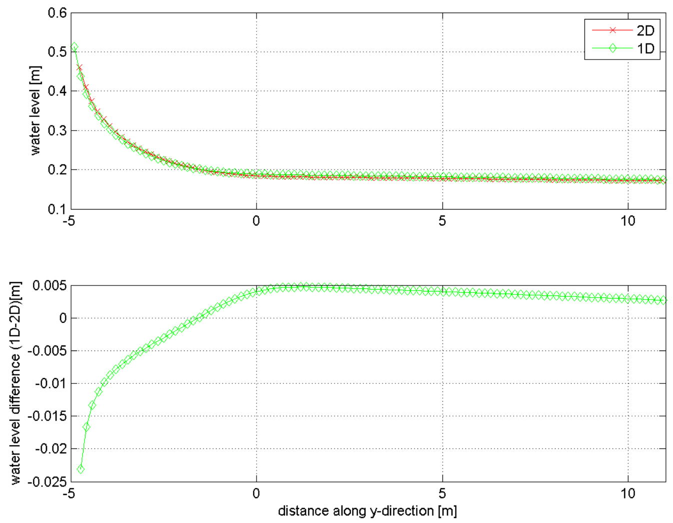


Figure 3.33: *c28: Comparison of water levels (iBedcond2).*

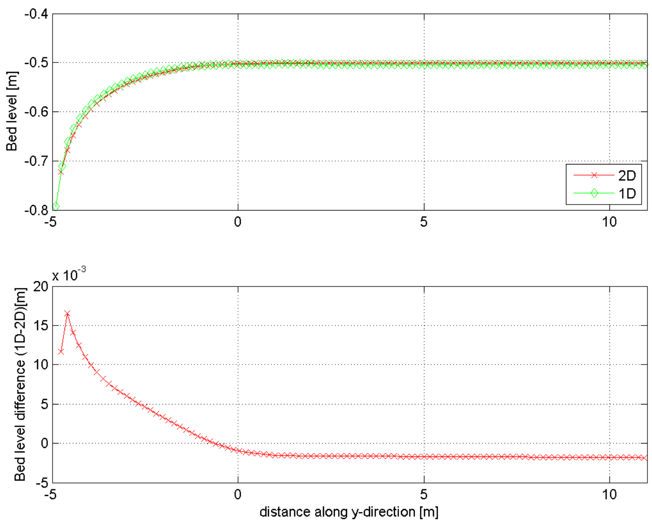


Figure 3.34: *c28: Comparison of bed levels (iBedcond2).*

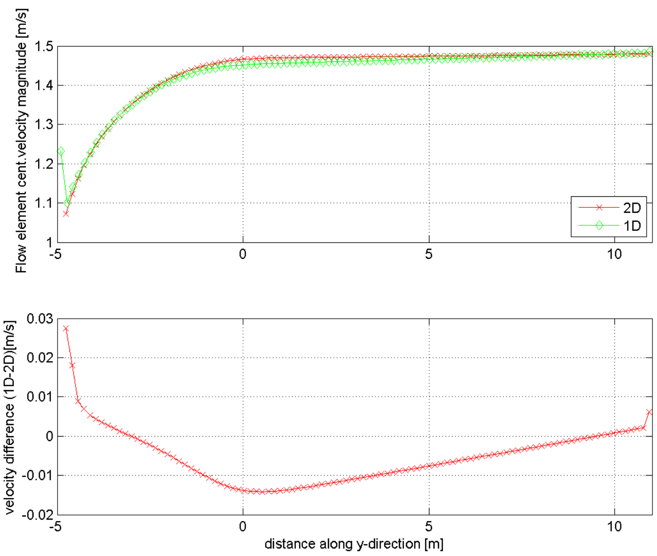


Figure 3.35: *c28: Averaged velocity magnitude a long the 1D and 2D models (iBedcond4).*

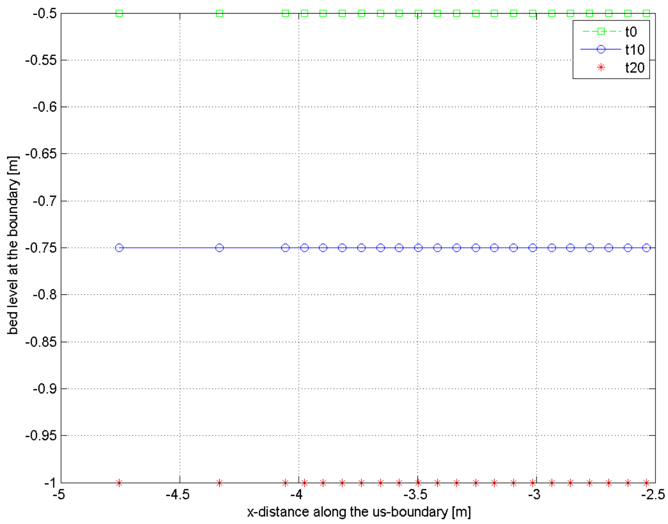


Figure 3.36: *c26: The bed level change at the upstream ghost cell (iBedcond2).*

4 Tabulated profiles from SOBEK3 schematizations

4.1 Engelund-Hansen transport formula for total transport

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 22 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : `https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c01_mc_sediment_transport_Engelund_Hansen`
SVN revision : -

Purpose

D-Flow FM-1D-mor can use so-called tabulated cross-sections (from SOBEK3), where the flow width is specified as a function of the water level. The bed level is updated in the main channel only.
The purpose of this validation case is to prove that the calculated sediment transport with the Engelund, F. and E. Hansen (1967) formula is correct in D-Flow FM-1D, with tabulated cross sections. The formula is tested using several different parameter values, as outlined below.

Linked claims

- ◇ Water levels computed with D-Flow FM are comparable to water levels computed with SOBEK3.
- ◇ D-Flow FM accurately calculates sediment transport according to the formula of Engelund-Hansen.

Approach

We start from an existing SOBEK3-test model (`/DSCTestbench/cases/e106_dflow1d/f13_morphology/c01_sediment_transport_Engelund_Hansen`). That model consists of four (non-connected) branches, each with the same length, but different properties. The values of the Chézy roughness, and the bed slope i_b are varied. The test is carried out for several different discharge values (and downstream water levels). In this test case, we assume that the velocities as calculated by the flow module are correct; simulated water levels are compared with SOBEK3.

The total sediment transport S [kg/s] calculated by the Engelund-Hansen formula is given by:

$$S = B\rho_s s = B\rho_s(0.05\frac{\alpha u^5}{\sqrt{g}C^3\Delta^2 D_{50}}) \tag{4.1}$$

where

u	the magnitude of the flow velocity [m/s],
Δ	the relative density given by $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$ [-],
C	the Chézy friction coefficient [m$^{1/2}$/s],

D_{50}	the median diameter of sediment [m],
α	the user-defined calibration coefficient [-],
B	the width of the main channel [m] and
ρ_s	the sediment density [kg/m^3].

In this test, the sediment transport is calculated analytically based on the calculated velocity by the flow module. The analytically computed sediment transport is then compared to the sediment transport as calculated by D-Flow FM-1D.

Model description

The model domain, consisting of four (non-connected) straight branches, each with the same length of 10 km, but different properties is shown in Figure 4.1.

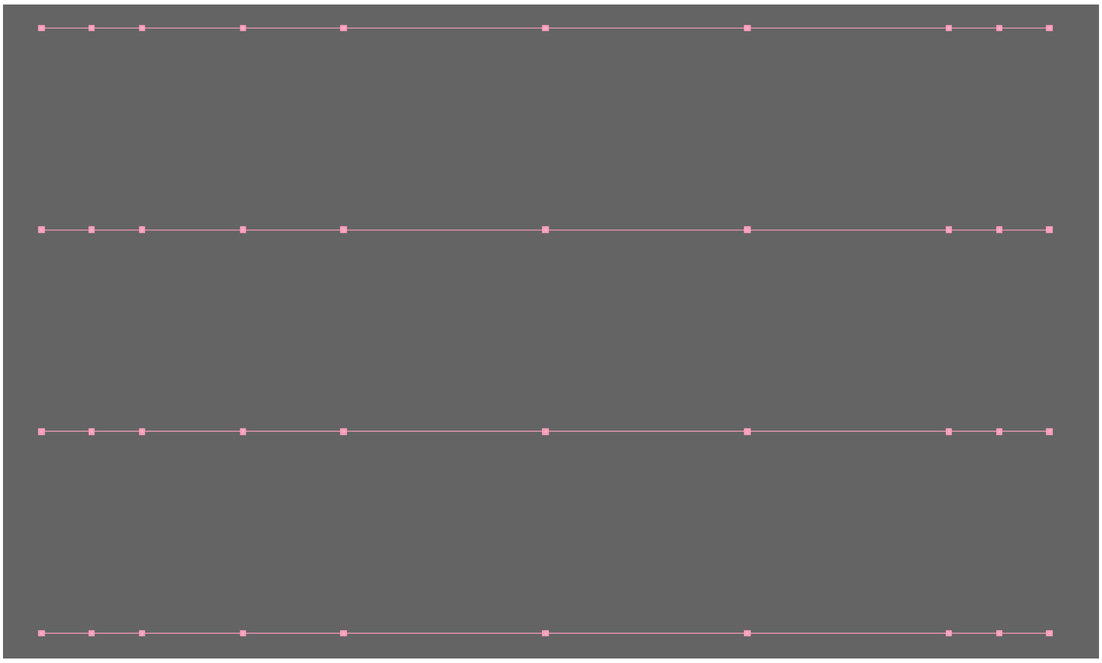


Figure 4.1: *Four (non-connected) branches, channels with equal length, but different properties.*

For this test case, each of the channels is straight with homogeneous cross-sections. The flow is stationary but non-homogeneous. The flow direction in the channel is oriented in the same direction as the computational grid. Upstream a discharge boundary is imposed (Figure 4.2), downstream a water level boundary (Figure 4.3). No further connection nodes are added. The channel contains rectangular cross-sections of 200 m in width throughout. See Figure 4.4. Computational nodes are placed at non-uniform distances. Calculations are done for four different testcases in which several parameter values are varied. An overview of these varied parameter values is shown in Table 4.1. Note that T1 and T3, two independent branches, have identical settings and should produce identical results. Other model settings for all cases are given in Table 4.2.

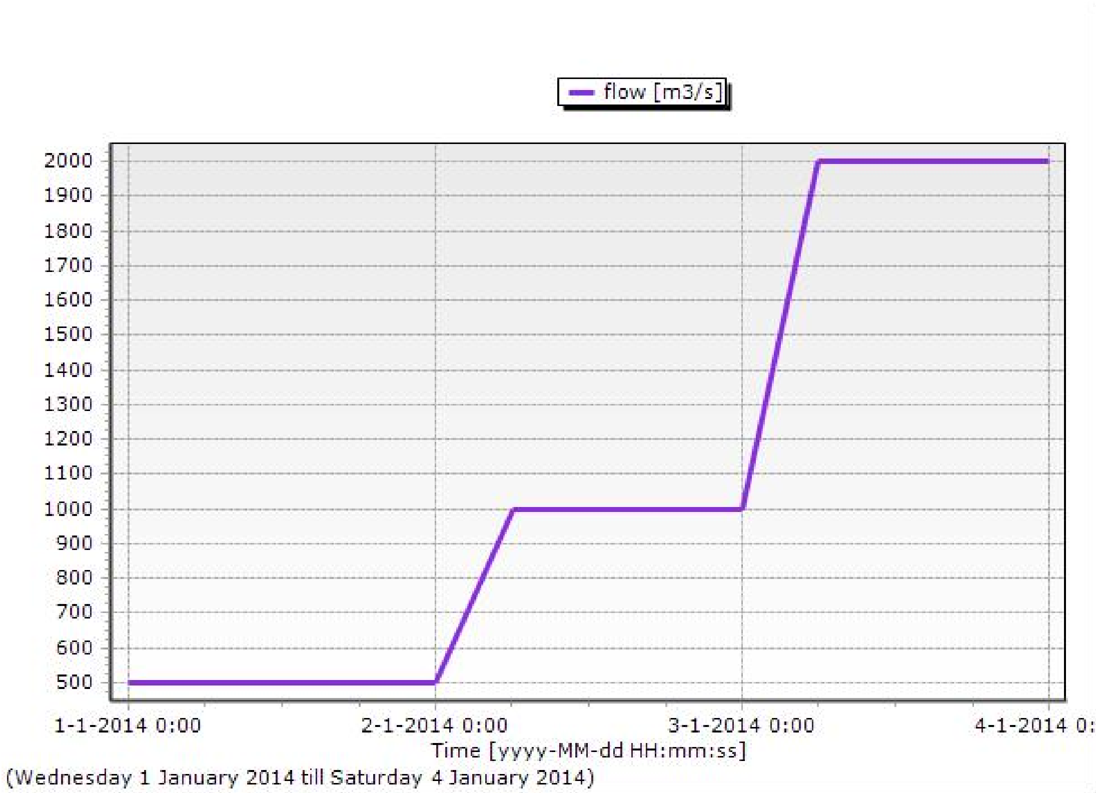


Figure 4.2: *Upstream discharge boundary condition.*

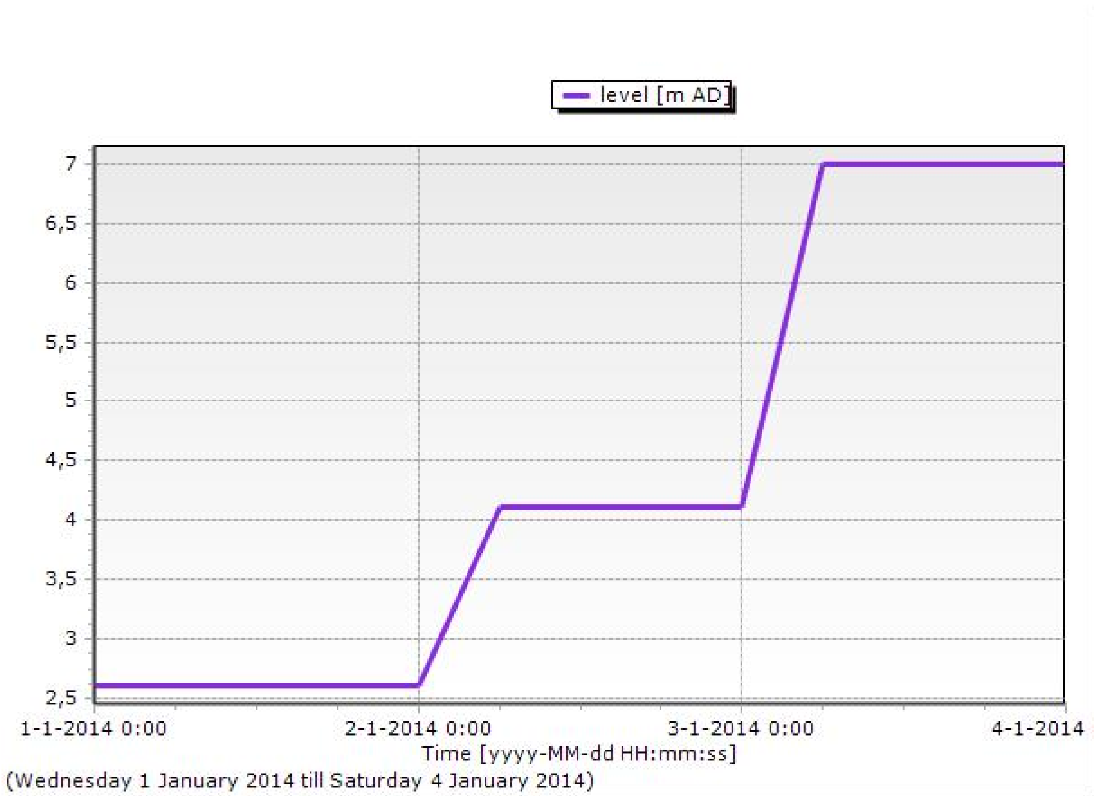


Figure 4.3: *Downstream water level boundary condition.*

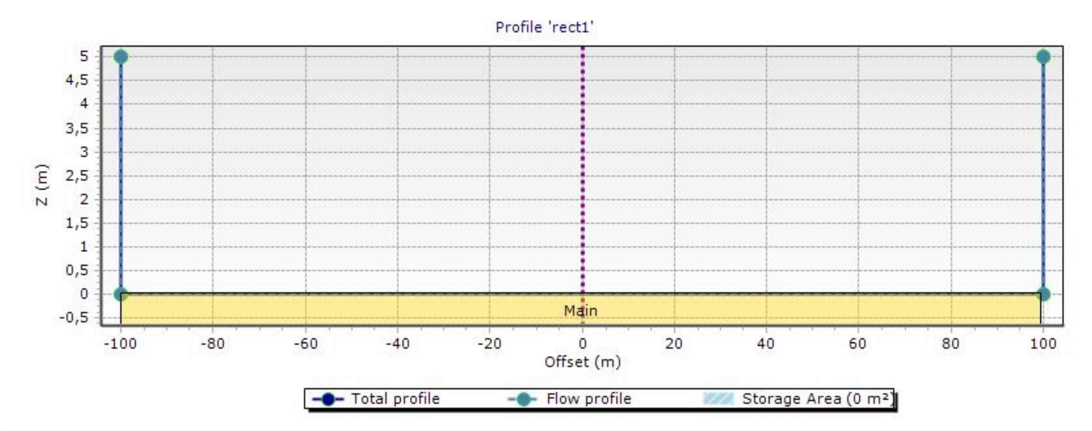


Figure 4.4: *Cross-section of test case.*

The basis model we use is set-up in SOBEK3. The geometry (tabulated cross-sections, roughness and some other properties), are directly imported into D-Flow FM using a specific keyword in the MDU-file:

```
OneDNetworkFile = dflow1d\water flow 1d.md1d
```

Some settings have to be set manually though:

- ◇ A SOBEK3 import only works if a (dummy) Network file is present. We advise to use a 2D network, to ensure that it doesn't conflict with the 1D network (as imported from SOBEK3).
- ◇ Timings such as refdate, start/end time and map-output intervals need to be converted manually to the MDU-file.
- ◇ The boundary conditions (locations and values) are not yet imported from SOBEK3. They have to be manually created. We defined 4 polylines at the upstream boundary for imposing the discharge, and 4 polylines at the downstream boundary to impose the water levels. Note that the boundary lines must be just *outside* the model. Also note that for the boundary definition when using morphology, each branch must have *its own* polyline, otherwise the morphological boundary condition is invalid.
- ◇ Recall that in SOBEK3 the water level at the downstream boundary holds at the last pressure point in the grid, while in D-Flow FM it gets mirrored half a grid cell outside the control volume around each grid point. Effectively, this means that the water level has to be specified as if it is Δx further downstream, considering the bed slope. For this case, at the downstream boundary, $\Delta x = 500m$. For a bed level slope of 1×10^{-4} this implies a 5 cm lower water level compared to SOBEK3.
- ◇ In the MOR input file, the boundaries need to be imposed at the polylines specified in one of the steps above.
- ◇ For the upstream (us) and downstream (ds) bed boundary condition we specify
  ```
  IBedCond_us=1
  IBedCond_ds=0
  ```
  Note that, since morphological updating is switched off, this is not relevant for this case though.

Results - hydraulics, comparison SOBEK3 vs D-Flow FM

Remember that for this case, we have 3 distinct discharges, all run for 1 day (to a stationairy condition).
The figures below compare some hydraulic output between SOBEK3 and D-Flow FM.

Table 4.1: *Parameter values for the different test cases.*

	T1	T2	T3	T4
Sediment size D_{50} (mm)	0.6	0.6	0.6	0.6
Chézy roughness C (m$^{1/2}$/s)	50	70	50	50
Bed slope i_b (m/m)	0.0001	0.0001	0.0001	0.0002

Table 4.2: *Model Settings*

Input description	Symbol	Value	Unit
flow			
gravitational acceleration	g	9.81	ms^{-2}
branch length	s_{tot}	10000	m
height upstream crosssection	z_{offset}	1	m
bed level slope	i	0.0001 / 0.0002	m/m
cross section width	B	200	m
upstream discharge boundary	Q	Q(t)	m^{3}s^{-1}
downstream water level boundary	h	Q-h	m
Chezy roughness coefficient	C	50 / 70	m$^{1/2}$s^{-1}
initial water depth	h_{ini}	4.71	m
water density	ρ_w	1000	kg m^{-3}
morphology parameters			
sediment diameter	D_{50}	0.0006	m
sediment density	ρ_s	2650	kg m^{-3}
relative density	Δ	1.65	
porosity	ϵ_p	0.4	
engelund-hansen calibration parameter	α	1	
model parameters			
computational grid size	Δx	500-2000	m
computational time step	Δt	60	s
output time step		24	h

- Figure 4.5: Apart from some "initial condition effects" the upstream water level for branch T1 compares very well between SOBEK3 and D-Flow FM.
- Figure 4.6: Differences in water level just a couple of cm.
- Figure 4.7: Also along the channels only small differences in water level.
- Figure 4.8: Differences in water level small.
- Figure 4.9: Some strange differences near the boundaries of the model.

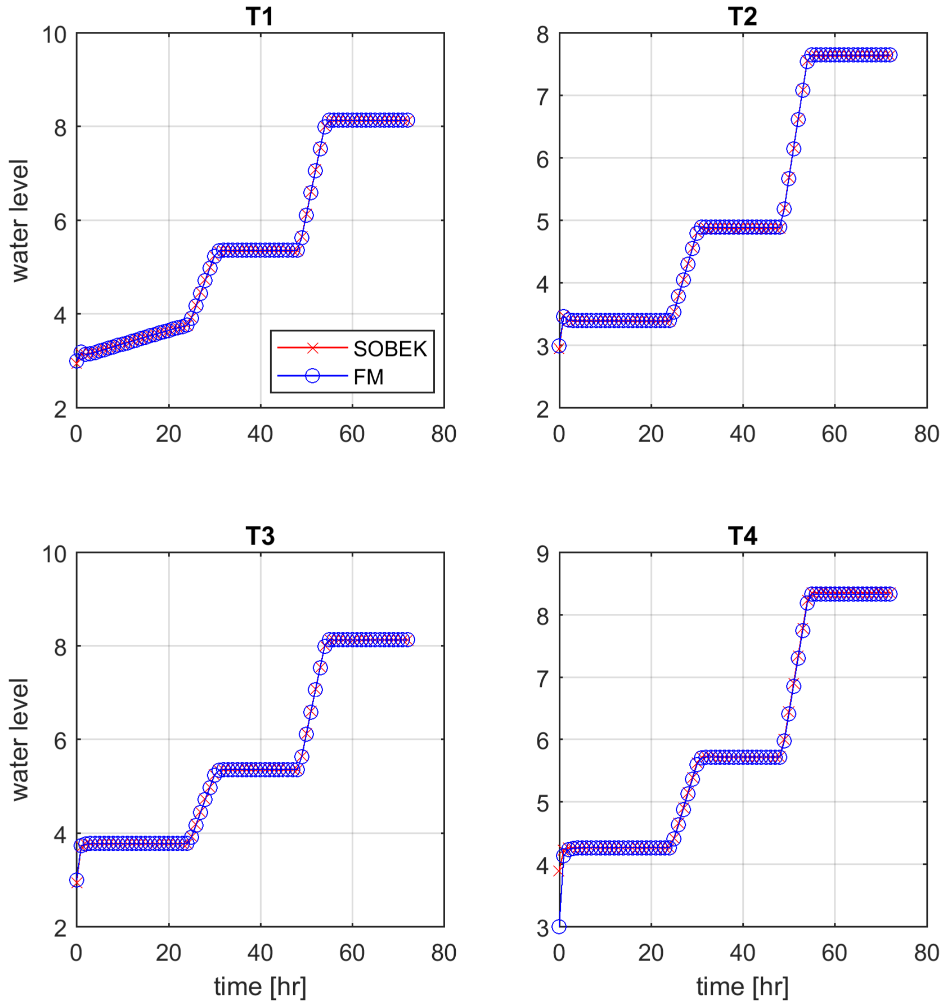


Figure 4.5: *Time series of water level at the second computational node at branch T1 (lowest).*

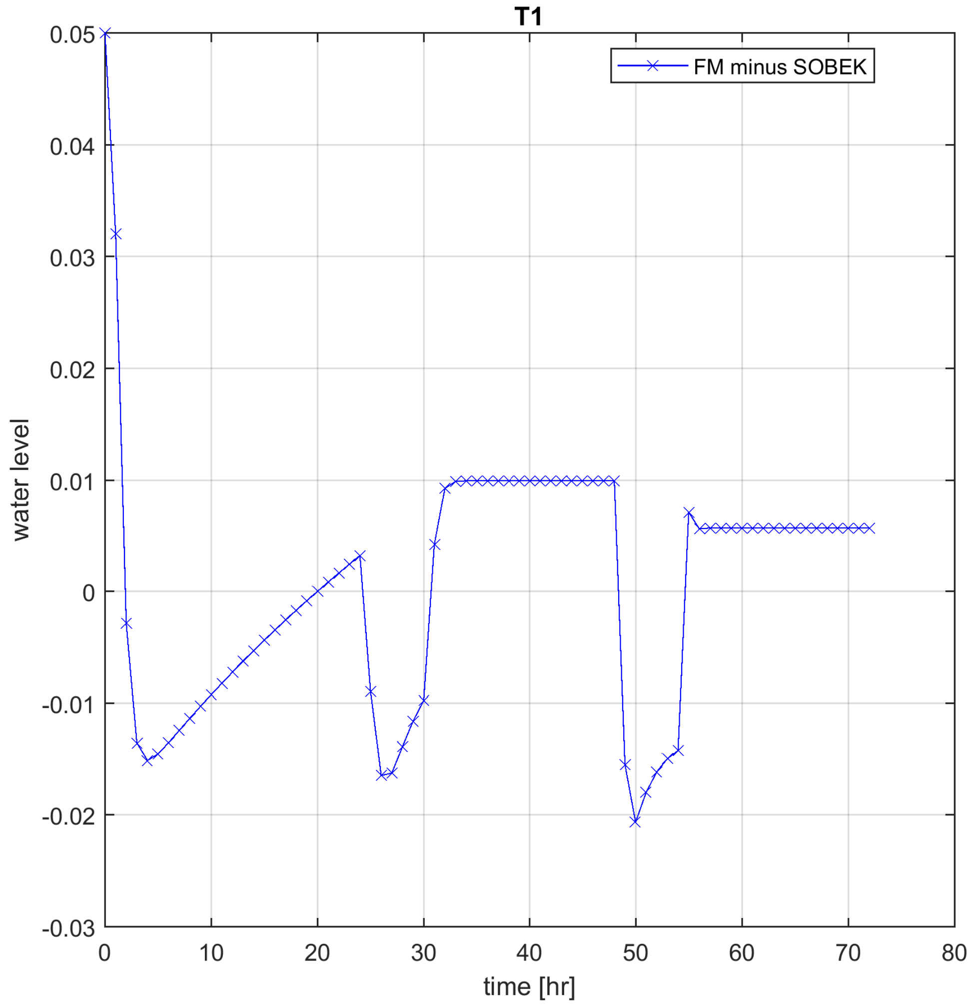


Figure 4.6: *Time series of difference in water level at the second computational node at branch T1 (lowest).*

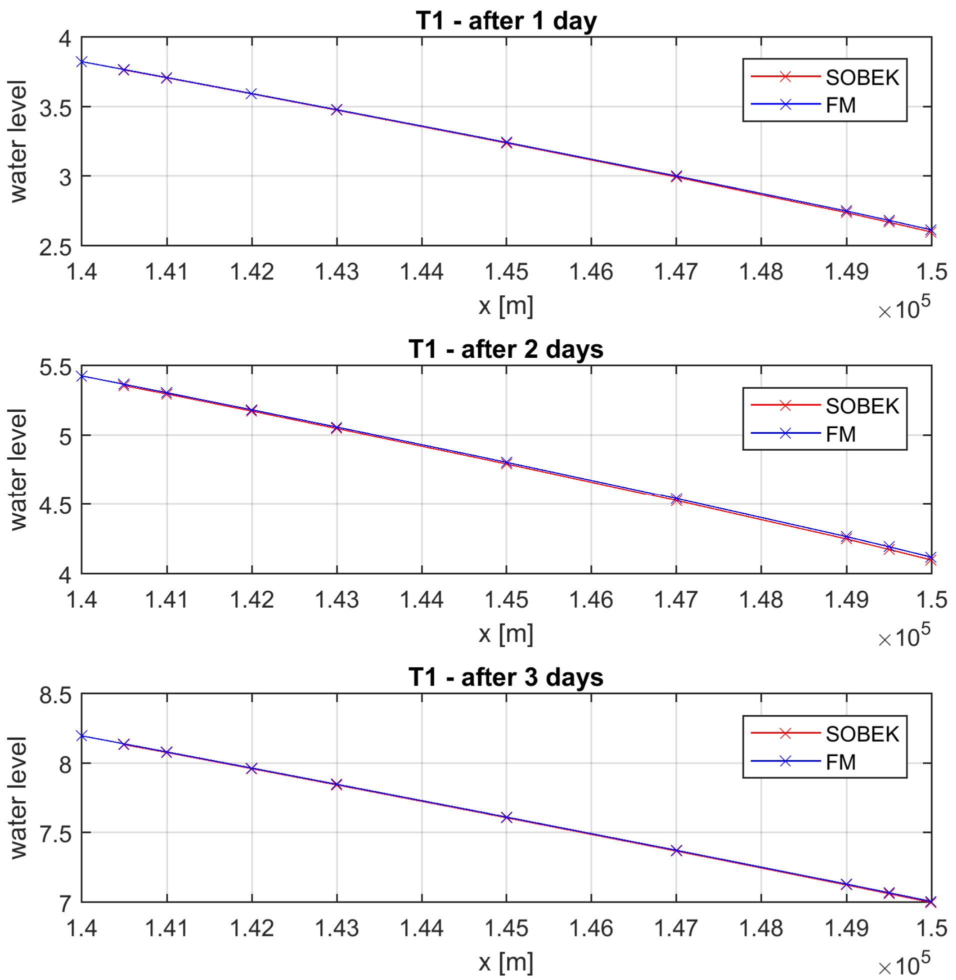


Figure 4.7: *Water level along the channel for branch T1 (top: Q1, center: Q2, bottom: Q3).*

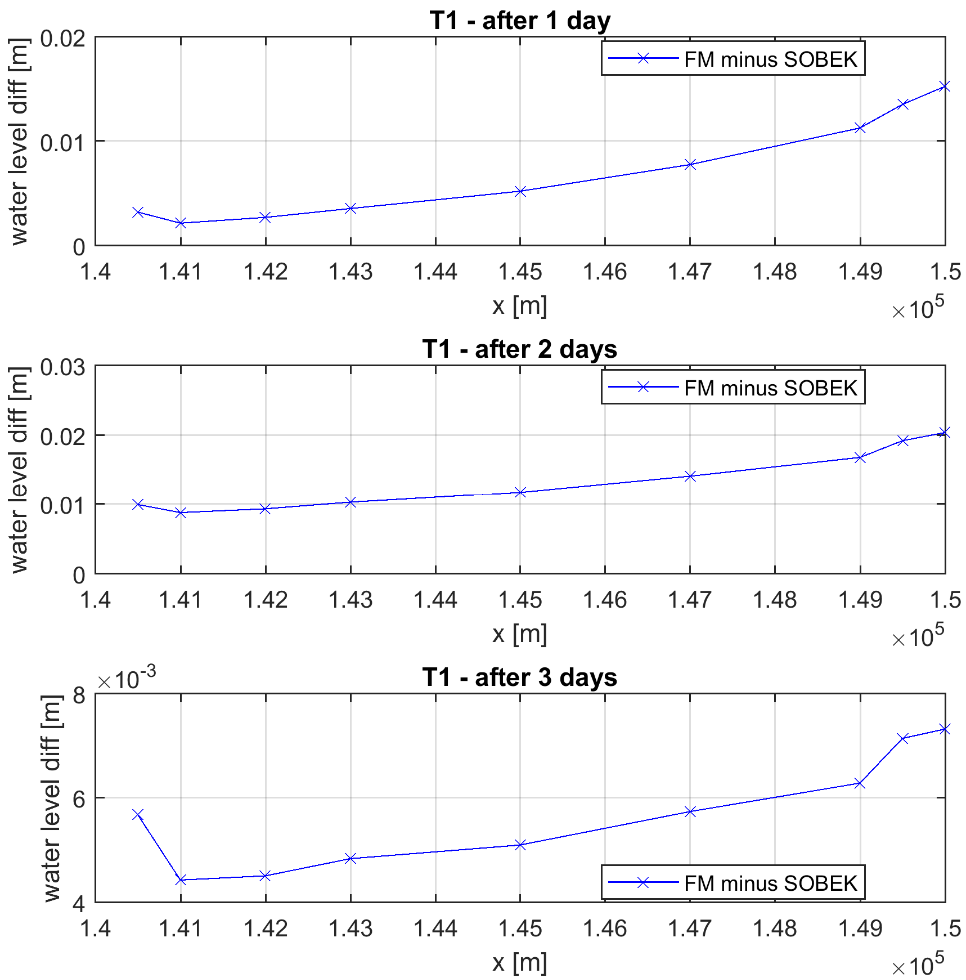


Figure 4.8: *Water level difference along the channel for branch T1 (top: Q1, center: Q2, bottom: Q3).*

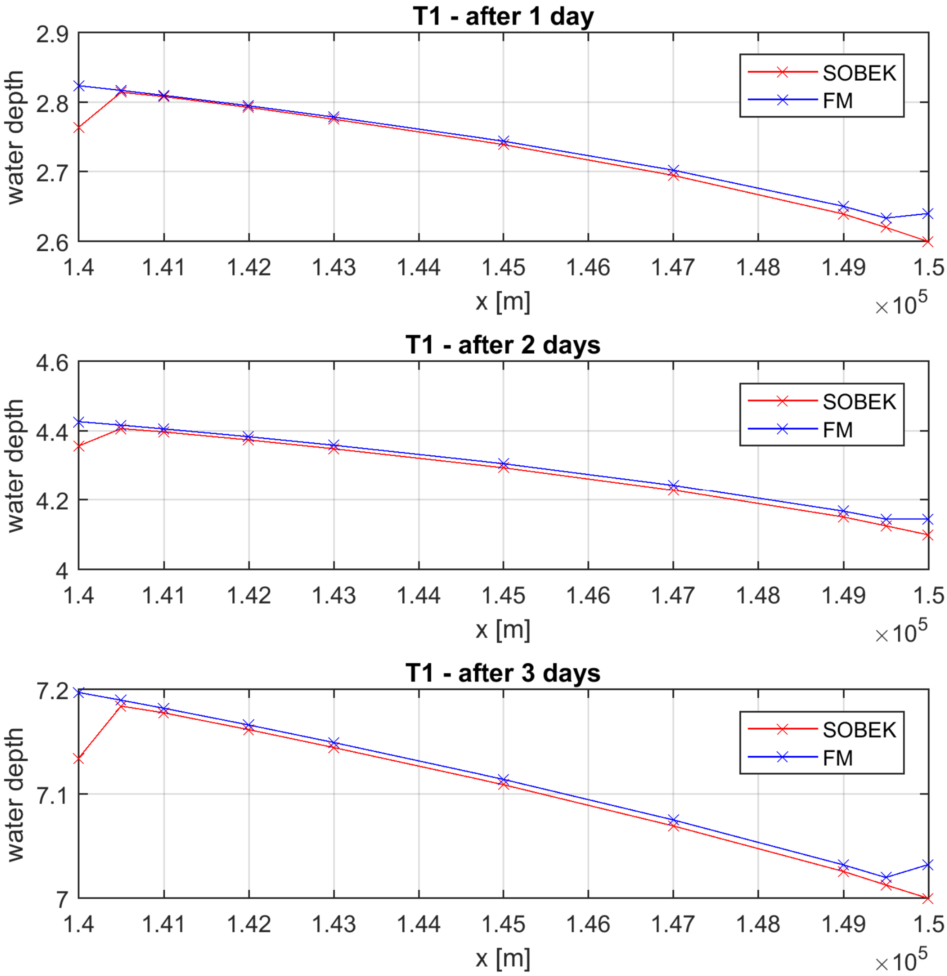


Figure 4.9: *Water depth along the channel for branch T1 (top: Q1, center: Q2, bottom: Q3).*

	Q1	Sed.tr. FM				[kg/s]				
x	140000	140500	141000	142000	143000	145000	147000	149000	149500	150000
T1	22.43	22.33	22.23	22.23	22.32	22.43	22.97	23.76	26.33	27.99
T2	46.37	46.11	45.48	44.75	43.41	41.77	39.15	37.15	34.29	32.65
T3	21.92	21.90	22.04	22.22	22.69	23.14	24.15	25.29	28.61	30.84
T4	54.58	54.35	53.78	53.11	51.79	49.94	46.54	43.60	38.79	35.44
	Q1	Sed.tr. Analytic				[kg/s]				
T1	22.44	22.27	22.29	22.33	22.47	22.73	23.74	25.39	27.82	28.33
T2	16.91	16.72	16.52	16.12	15.69	14.78	13.77	12.66	12.35	11.46
T3	21.93	21.93	22.17	22.42	22.99	23.65	25.22	27.38	30.49	31.39
T4	54.62	54.16	53.65	52.64	51.42	48.52	44.62	39.63	38.00	32.94
	Q1	DIFF, FM minus analytic				[kg/s]				
T1	-0.01	0.05	-0.06	-0.10	-0.16	-0.30	-0.76	-1.63	-1.48	-0.34
T2	29.46	29.39	28.96	28.63	27.72	26.99	25.38	24.49	21.94	21.18
T3	-0.01	-0.03	-0.13	-0.20	-0.30	-0.51	-1.07	-2.09	-1.88	-0.55
T4	-0.04	0.19	0.13	0.47	0.37	1.41	1.92	3.97	0.79	2.51
	Q1	DIFF relative, FM minus analytic				[-]				
T1	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.03	-0.06	-0.05	-0.01
T2	1.74	1.76	1.75	1.78	1.77	1.83	1.84	1.93	1.78	1.85
T3	0.00	0.00	-0.01	-0.01	-0.01	-0.02	-0.04	-0.08	-0.06	-0.02
T4	0.00	0.00	0.00	0.01	0.01	0.03	0.04	0.10	0.02	0.08

Figure 4.10: *Sediment transport from D-Flow FM and analytical values in kg/s for Q1.*

	Q2	Sed.tr. FM				[kg/s]				
x	140000	140500	141000	142000	143000	145000	147000	149000	149500	150000
T1	76.11	76.05	76.56	77.23	78.94	80.52	83.94	87.70	97.60	104.06
T2	136.60	136.00	134.58	132.95	130.04	126.59	121.19	117.21	111.63	108.34
T3	76.11	76.05	76.56	77.23	78.94	80.52	83.94	87.70	97.60	104.06
T4	160.08	159.33	157.52	155.39	151.44	146.38	137.89	131.13	120.94	114.22
	Q2	Sed.tr. Analytic				[kg/s]				
T1	76.16	76.16	77.04	77.97	79.99	82.26	87.46	94.12	102.91	105.78
T2	49.81	49.38	48.93	48.04	47.11	45.21	43.18	41.01	40.41	38.61
T3	76.16	76.16	77.04	77.97	79.99	82.26	87.46	94.12	102.91	105.78
T4	160.19	158.69	157.09	153.90	150.35	142.60	133.36	122.63	119.41	109.18
	Q2	DIFF, FM minus analytic				[kg/s]				
T1	-0.05	-0.12	-0.48	-0.74	-1.05	-1.74	-3.52	-6.42	-5.31	-1.72
T2	86.79	86.62	85.65	84.91	82.93	81.38	78.01	76.20	71.22	69.73
T3	-0.05	-0.12	-0.48	-0.74	-1.05	-1.74	-3.52	-6.42	-5.31	-1.72
T4	-0.11	0.65	0.43	1.49	1.08	3.78	4.53	8.50	1.53	5.04
	Q2	DIFF relative, FM minus analytic				[-]				
T1	0.00	0.00	-0.01	-0.01	-0.01	-0.02	-0.04	-0.07	-0.05	-0.02
T2	1.74	1.75	1.75	1.77	1.76	1.80	1.81	1.86	1.76	1.81
T3	0.00	0.00	-0.01	-0.01	-0.01	-0.02	-0.04	-0.07	-0.05	-0.02
T4	0.00	0.00	0.00	0.01	0.01	0.03	0.03	0.07	0.01	0.05

Figure 4.11: *Sediment transport from D-Flow FM and analytical values in kg/s for Q2.*

	Q3	Sed.tr. FM				[kg/s]				
x	140000	140500	141000	142000	143000	145000	147000	149000	149500	150000
T1	214.43	214.34	214.99	215.84	217.92	219.80	223.59	227.55	236.49	240.63
T2	309.86	308.25	304.49	300.20	292.69	284.16	271.35	262.34	250.33	244.79
T3	214.43	214.34	214.99	215.84	217.92	219.80	223.59	227.55	236.49	240.63
T4	381.30	378.35	371.35	363.32	349.06	332.53	307.30	289.23	264.82	253.34
	Q3	Sed.tr. Analytic				[kg/s]				
T1	214.57	214.57	215.67	216.83	219.26	221.86	227.41	233.73	240.97	240.93
T2	113.00	111.83	110.64	108.30	105.95	101.30	96.61	91.90	90.68	87.86
T3	214.57	214.57	215.67	216.83	219.26	221.86	227.41	233.73	240.97	240.93
T4	381.55	375.65	369.57	357.54	345.16	320.35	294.66	268.48	261.50	245.51
	Q3	DIFF, FM minus analytic				[kg/s]				
T1	-0.14	-0.23	-0.68	-0.99	-1.34	-2.05	-3.82	-6.18	-4.48	-0.30
T2	196.86	196.43	193.84	191.89	186.74	182.86	174.74	170.44	159.66	156.93
T3	-0.14	-0.23	-0.68	-0.99	-1.34	-2.05	-3.82	-6.18	-4.48	-0.30
T4	-0.25	2.70	1.78	5.78	3.90	12.19	12.64	20.76	3.31	7.83
	Q3	DIFF relative, FM minus analytic				[-]				
T1	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.03	-0.02	0.00
T2	1.74	1.76	1.75	1.77	1.76	1.81	1.81	1.85	1.76	1.79
T3	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.03	-0.02	0.00
T4	0.00	0.01	0.00	0.02	0.01	0.04	0.04	0.08	0.01	0.03

Figure 4.12: *Sediment transport from D-Flow FM and analytical values in kg/s for Q3.*

Results - sediment transport D-Flow FM

The differences in the sediment transport between results of D-Flow FM and analytical values are shown in Figure 4.10 for Q1, in Figure 4.11 for Q2 and in Figure 4.12 (Q3). Each line represents a branch, T1 being the most southern branch, T4 the most northern branch. Both absolute differences [kg/s] as relative differences [[-]] are shown.

The differences are much larger than SOBEK3 (max difference 0.000023% for branch T2).
This is still under investigation; most probably it has to do with how the Chézy coefficient is used in D-Flow FM.
Note that especially the difference in branch 2 is larger. This is because in D-Flow FM, the global value as specified in the MDU-file is used for the sediment transport computation, which is 50 for this case. For the analytical computation, we use C=70, since that is the value for branch 2 (it is verified that for the flow it is taken into account correctly).

THIS NEEDS TO BE FIXED IN THE CODE, TO DO, note that this is also related to / linked to the division in C_{main} and $C_{\text{floodplain}}$ for the computation of the flow velocity in the main channel (see case 4.3)

Conclusion

Hydraulics almost equal between SOBEK3 and D-Flow FM with tabulated cross sections.
These tests show that D-Flow FM with tabulated cross sections is not yet able to accurately calculate sediment formulation according to Engelund-Hansen.

References

Engelund, F. and E. Hansen (1967). *A monograph on Sediment Transport in Alluvial Streams*. Teknisk Forlag, Copenhagen.

4.2 Meyer-Peter-Muller transport formula for total transport

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 22 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c02_mc_sediment_transport_MPM
SVN revision : -

Purpose

This test case is for 1D-morphology in D-Flow FM with tabulated cross sections. D-Flow FM-1D can use so-called tabulated cross-sections (from SOBEK3), where the flow width is specified as a function of the water level. The bed level is updated in the main channel only.
The purpose of this validation case is to prove that the calculated sediment transport with the Meyer-Peter, E. and R. Müller (1948) formula is correct in D-Flow FM-1D. The formula is tested using several different parameter values, as outlined below.

Linked claims

- ◇ Water levels computed with D-Flow FM are comparable to water levels computed with SOBEK3.
- ◇ D-Flow FM accurately calculates sediment transport according to the formula of Meyer-Peter-Muller.

Approach

We start from an existing SOBEK3-model (/DSCTestbench/cases/e106_dflow1d/f13_morphology/c02_sediment_transport_Meyer-Peter-Muller).

THIS TEST CASE NEEDS STILL TO BE FILLED.

References

Meyer-Peter, E. and R. Müller (1948). “Formulas for bed load transport”. In: *Proceedings of the 2nd Congress IAHR, Stockholm*. Vol. 2, pp. 39–64.

4.3 Cross-section with floodplain: Umain

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 22 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c07_fp_sediment_transport_Umain
SVN revision : -

Purpose

D-Flow FM-1D (mor) can use so-called tabulated cross-sections (from SOBEK3), where the flow width is specified as a function of the water level. The bed level is updated in the main channel only.
SOBEK3 (and thus D-Flow FM 1D-mor) allows the user to define compound channels by defining multiple sections ('Main', 'FloodPlain1' and 'FloodPlain2'). For Morphology and Sediment Transport, D-Flow FM uses only the 'Main' channel for the calculation of sediment transport and morphological updating. The purpose of this validation case is to analyze whether D-Flow FM and SOBEK3 compute comparable water levels and to prove that D-Flow FM uses the velocity of the main channel for the calculation of sediment transport.

Linked claims

- ◇ Water levels computed with D-Flow FM are comparable to water levels computed with SOBEK3.
- ◇ D-Flow FM accurately uses the flow velocity of the 'main' section in a compound cross-section.
- ◇ D-Flow FM accurately calculates sediment transport according to the formula of Engelund-Hansen.

Approach

We start from an existing SOBEK3-model (/DSCTestbench/cases/e106_dflow1d/f13_morphology/c07_sediment_transport_main_channel). That model is converted to D-Flow FM and run with the same properties. Then, we calculate, given the wet area of the compound channel, the velocity in the main channel:

$$u = \frac{Q_{main,sobek}}{d_{main} W_{main}} \tag{4.2}$$

where

$Q_{main,sobek}$	is the discharge in the main channel as calculated by D-Flow FM,
d_{main}	is the water depth in the main channel and
W_{main}	is the width of the main channel.

Subsequently, we calculate the sediment transport according to Engelund Hansen and compare with D-Flow FM results (see also case 4.1).

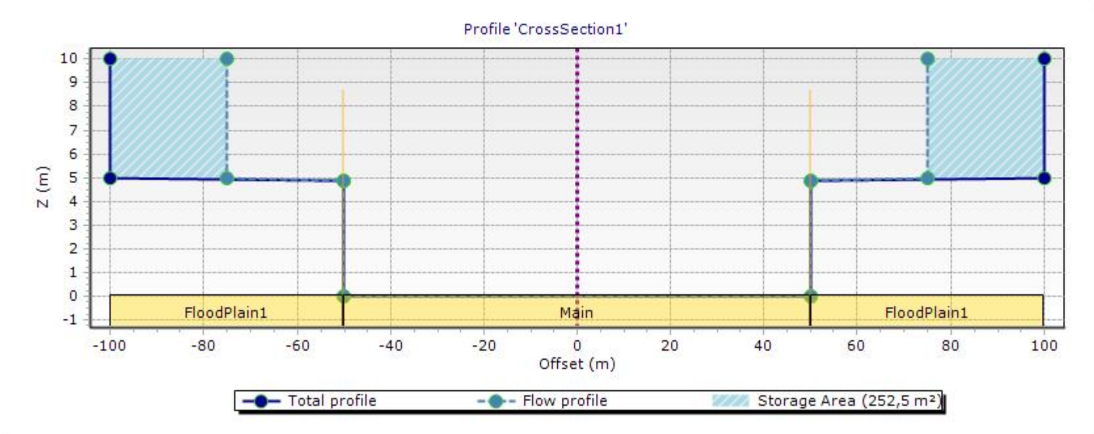


Figure 4.14: *Cross-section of test case*

Model description

The model consists of a single branch with an approximate length of 11 km, unevenly spaced computational points as shown in shown in Figure 4.13.

Figure 4.13: *One branch of 11 km.*

The single branch has one cross-section which consist of a main channel and a floodplain on either side, see Figure 4.14. Table 4.3 gives an overview of the model settings. The upstream boundary condition is given by a discharge timeseries: Q1=250, Q2=500, Q3=1000, Q4=2000; each discharge level has a duration of 1 days, before it steps to the next discharge in 6 hours time. The downstream boundary condition is given by a water level time series (2.0, 4.5, 7.0, 8.0 m w.r.t. a certain reference). Together the boundary conditions describe a quasi-stationary computation with four distinct stationary situations. For the first two discharge, the water remains in the main channel, for the third discharge the floodplains just start to flood and for the fourth discharge the floodplains convey quite some water.

The basis model we use is set-up in SOBEK3. The geometry (tabulated cross-sections, roughness and some other properties), are directly imported into D-Flow FM using a specific keyword in the MDU-file:

```
OneDNetworkFile = dflow1d\water flow 1d.md1d
```

Some settings have to be set manually though:

- ◇ A SOBEK3 import only works if a (dummy) Network file is present. We advise to use a 2D network, to ensure that it doesn't conflict with the 1D network (as imported from SOBEK3).
- ◇ Timings such as refdate, start/end time and map-output intervals need to be converted manually to the MDU-file.
- ◇ The boundary conditions (locations and values) are not yet imported from SOBEK3. They have to be manually created. We defined one polyline at the upstream boundary for imposing the discharge, and one polyline at the downstream boundary to impose the water level. Note that the boundary lines must be just *outside* the model.

Table 4.3: *Model settings*

Input description	Symbol	Value	unit
flow			
gravitational acceleration	g	9.81	ms^{-2}
branch length	s_{tot}	11000	m
height upstream crosssection	z_{offset}	1	m
bed level slope	i	0.0001	m/m
cross section width	B	100	m
upstream discharge boundary	Q at 2-1-2014	250	m^3s^{-1}
upstream discharge boundary	Q at 3-1-2014	500	m^3s^{-1}
upstream discharge boundary	Q at 4-1-2014	1000	m^3s^{-1}
upstream discharge boundary	Q at 5-1-2014	2000	m^3s^{-1}
downstream water level boundary	h	Q-h	m
Chézy roughness coefficient	C	50	$m^{1/2}s^{-1}$
initial water depth	h_ini	4.71	m
water density	ρ_w	1000	kg m^{-3}
morphology parameters			
sediment diameter	D_{50}	0.0002	m
sediment density	ρ_s	2650	kg/m3
relative density	Δ	1.65	
porosity	ϵ_p	0.4	
engelund-hansen calibration parameter	α	1	
model parameters			
computational grid size	Δx	500-2000	m
computational time step	Δt	60	s
output time step		24	h

- ◇ Recall that in SOBEK3 the water level at the downstream boundary holds at the last pressure point in the grid, while in D-Flow FM it gets mirrored half a grid cell outside the control volume around each grid point. Effectively, this means that the water level has to be specified as if it is Δx further downstream, considering the bed slope. For this case, at the downstream boundary, $\Delta x = 1000m$. For a bed level slope of 1×10^{-4} this implies a 10 cm lower water level compared to SOBEK3.
- ◇ No morphological boundary conditions are specified for this case (so default "free boundaries" are used). Since bed level updating is switched off, this is not relevant.
- ◇ For the sediment transport calculation, we use the Engelund, F. and E. Hansen (1967) formula, see case 4.1 for details.

Results - hydraulics, comparison SOBEK3 vs D-Flow FM

Remember: three discharges, all run for 1 day (to a stationairy condition).
The figures below compare some hydraulic output between SOBEK3 and D-Flow FM. For this case we have used:

```
NonLin1D = 1
```

(we are still investigating the exact effects of this settings, but it doesn't seem to have an effect for straight channels with uniform cross-sections).

- ◇ Figure 4.15: Water level ok when flow in main channel, too high when in floodplain (compared to SOBEK3).
- ◇ Figure 4.16: See above.
- ◇ Figure 4.17: See above.
- ◇ Figure 4.18: See above.
- ◇ Figure 4.19: See above.

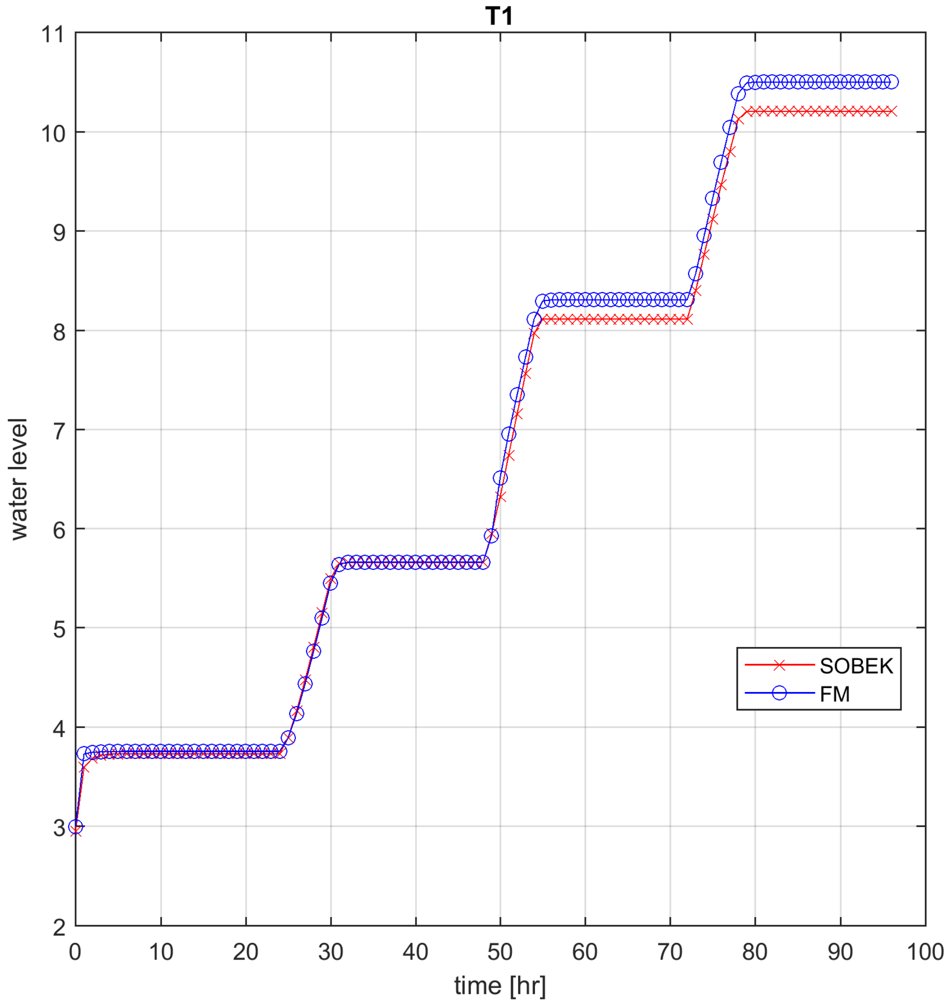


Figure 4.15: *Time series of water level at the second computational node of the channel.*

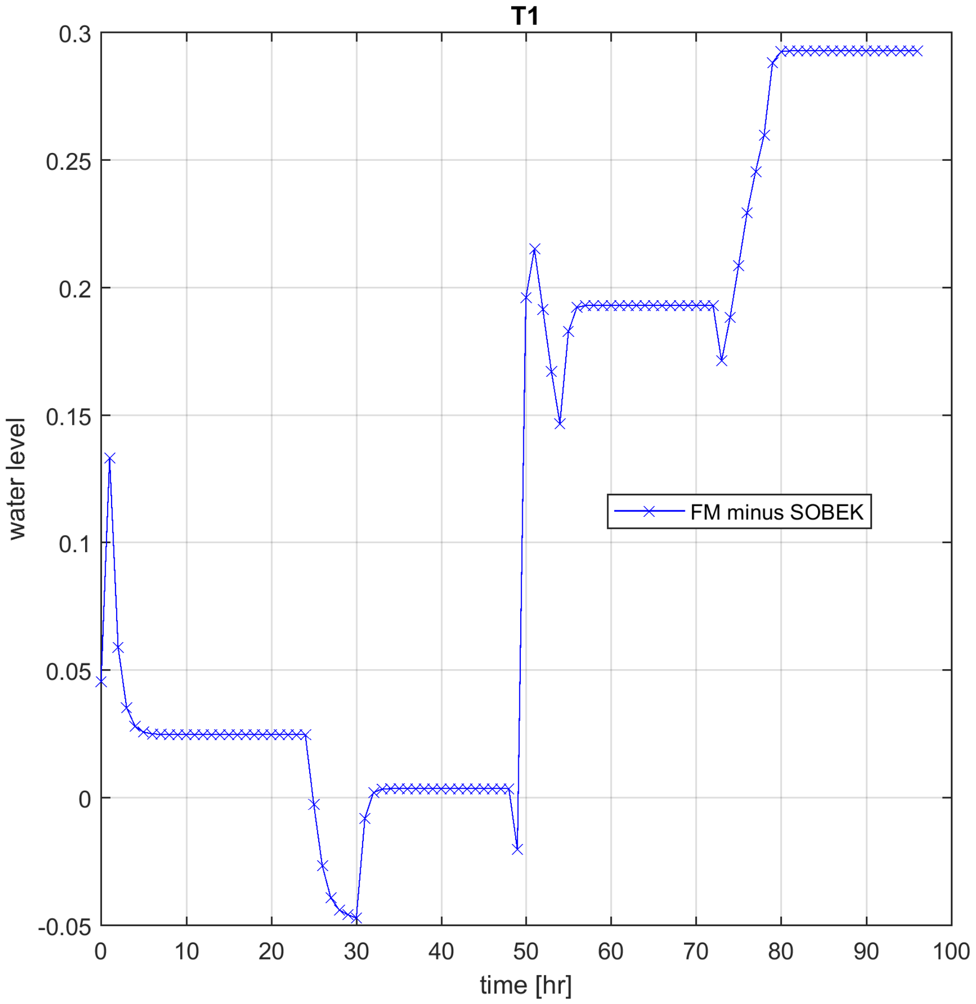


Figure 4.16: *Time series of difference in water level at the second computational node of the channel.*

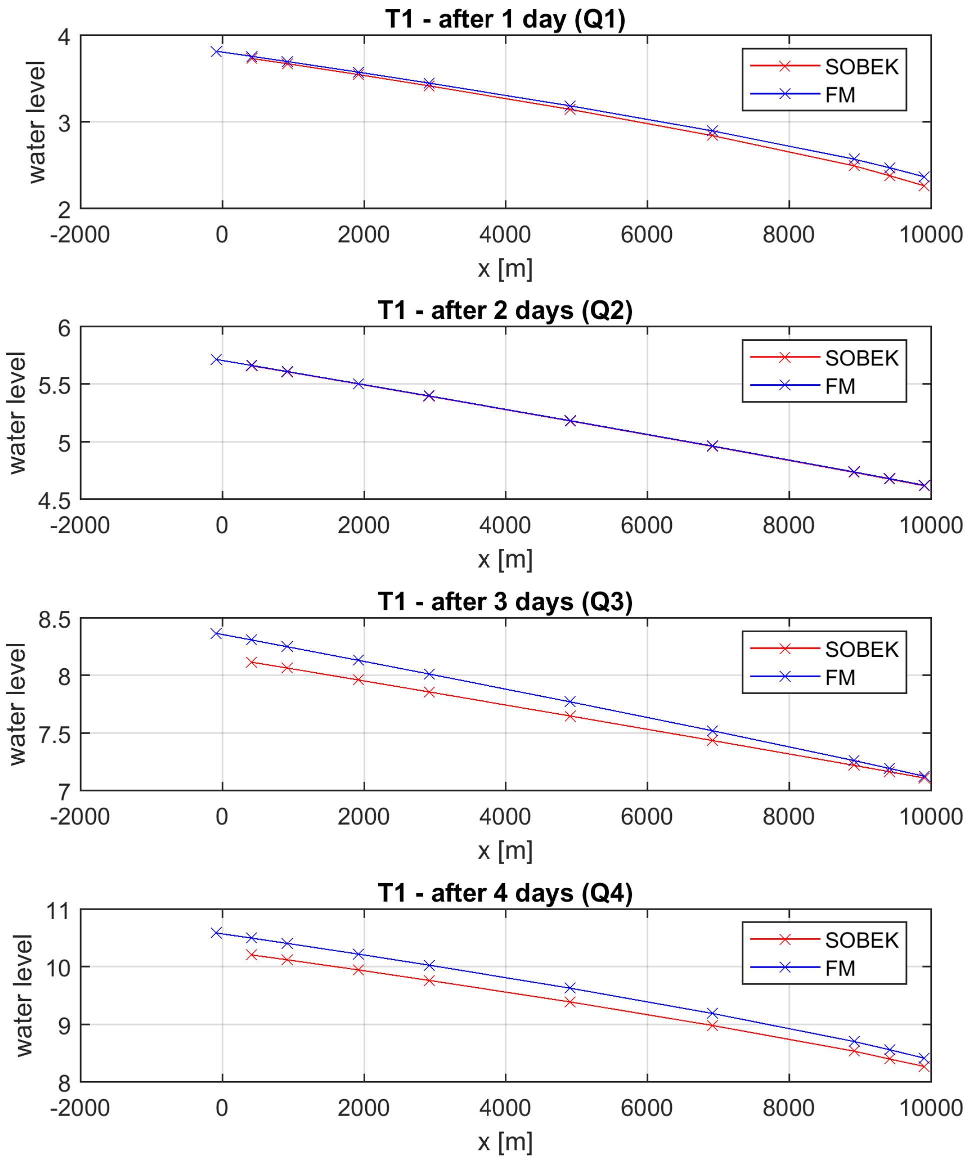


Figure 4.17: *Water level along the channel.*

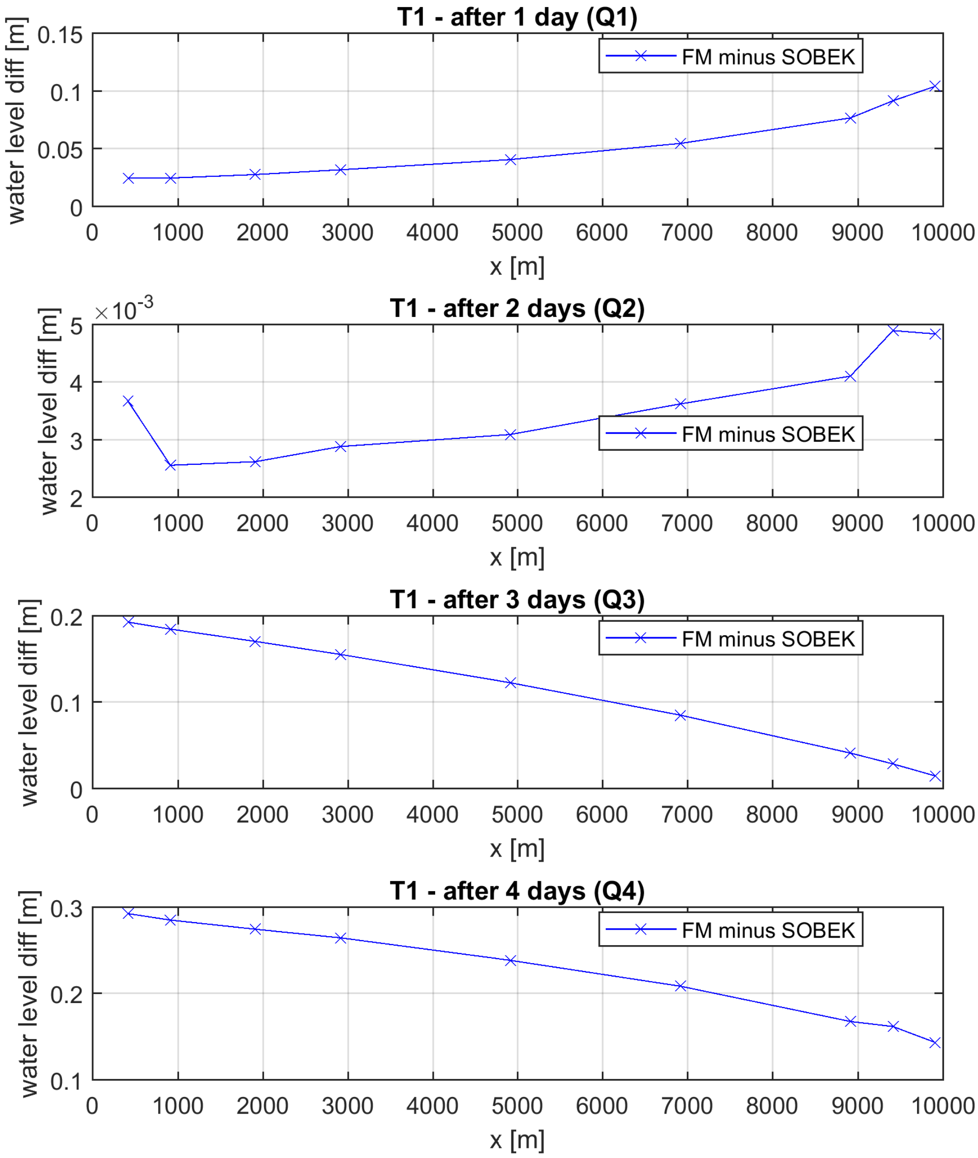


Figure 4.18: *Water level difference along the channel.*

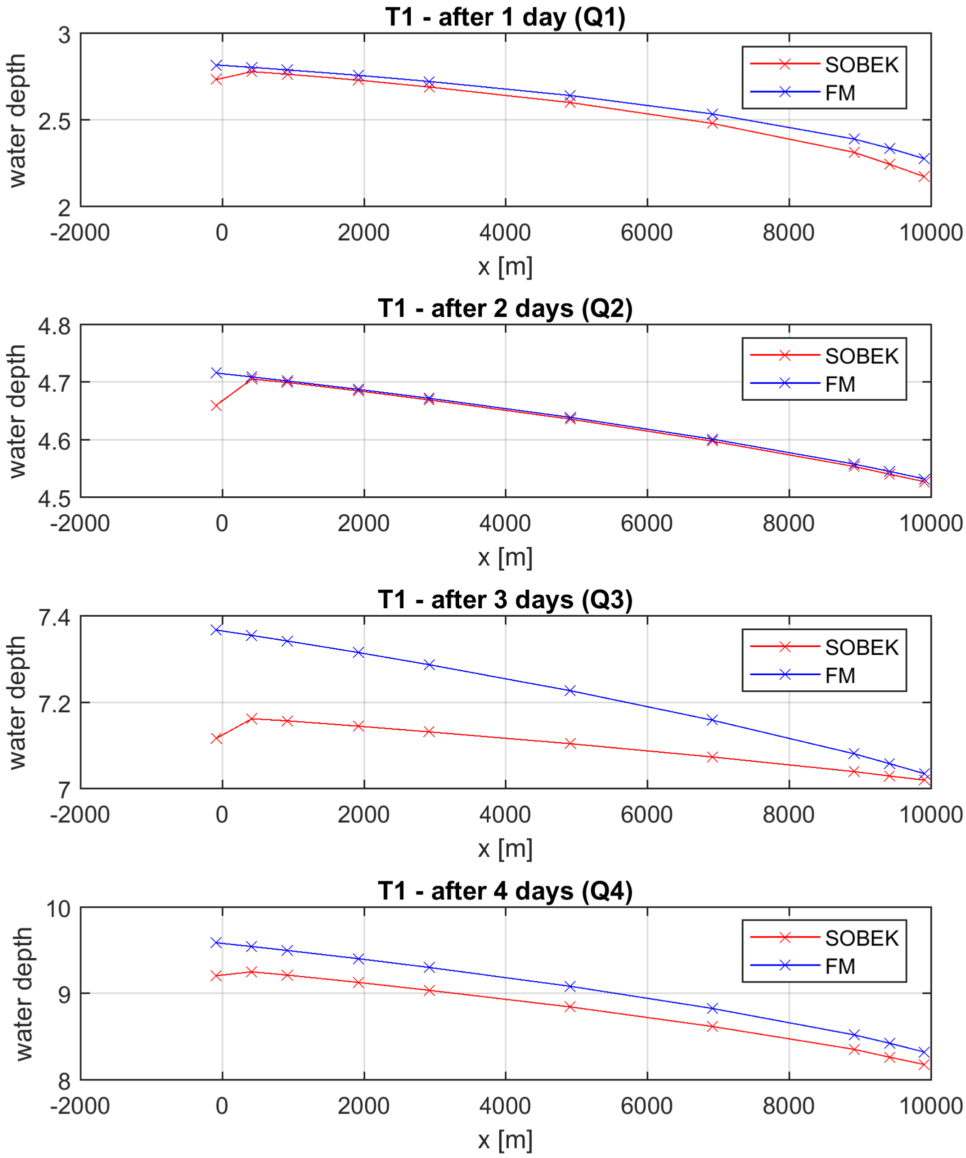


Figure 4.19: *Water depth along the channel.*

Results - sediment transport D-Flow FM

[TODO (Umain not yet implemented).]

NOTE: sediment transport not yet computed in D-Flow FM for this case (since first Umain needs to be available).

Conclusion

Hydraulics main channel OK, floodplain NOT OK, but for now acceptable.

TODO: implement Umain.

References

Engelund, F. and E. Hansen (1967). *A monograph on Sediment Transport in Alluvial Streams*. Teknisk Forlag, Copenhagen.

4.4 Equilibrium slope

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
22 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 21 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c21_equilibrium_slope_ds_IBedCond_us_IBedCond
SVN revision : -

Purpose

The purpose of this validation case is to prove that the computed morphological equilibrium in D-Flow FM-1D is correct and to prove that the different morphological boundary conditions are correct.

Linked claims

Claims that are related to the current test case are:

- Morphological factor works correctly.
- Morphological boundary conditions work correctly.
- Equilibrium slope is found.

Approach

The morphological equilibrium of a straight channel with homogenious cross-sections can be approximated by the following formulas for the equilibrium bed level slope (Equation 4.3) and the equilibrium water depth (Equation 4.4).

$$i_{bed} = \left(\frac{q^2}{C^2 h^3} \right) \tag{4.3}$$

$$h_e = \left(\frac{q}{C\sqrt{i_b}} \right)^{2/3} \tag{4.4}$$

To prove that the computed morphological equilibrium in is correct, the initial bed level of the test case is not in morphological equilibrium. At the end of the simulation, the water depth has to be equal to the equilibrium depth and the bed level slope has to be equal to the equilibrium bed level slope.

Model description

The model domain is a straight channel with a length of approximately 11 km. The initial bed level slope is 2×10^{-5}. The cross-section is a rectangular profile with a width of 200 m. For this case, the width of the main channel is equal to the total width of the cross-section.

The model is forced with a constant upstream total discharge of 1000 m^3/s. The downstream water level has a fixed value of 4.64 m AD. The hydraulic roughness of the channel (Chézy) is 50 $m^{1/2}/s$.

The median sediment diameter is 0.2 mm. The sediment transport is computed with the formula of Engelund-Hansen.

FOR FURTHER DOCUMENTATION FOR THIS TEST CASE, SEE APPENDIX A.

4.5 Shoal propagation

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 22 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : `https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c31_shoal_ds_IBedCond0_us_IBedCond1`
SVN revision : -

Purpose

D-Flow FM-1D (mor) can use so-called tabulated cross-sections (cf SOBEK3), where the flow width is specified as a function of the water level. The bed level is updated in the main channel only.
The purpose of this validation case is to prove that the propagation speed of bed disturbances in D-Flow FM-1D is correct.

Linked claims

- ◇ The propagation speed of bed disturbances in D-Flow FM-1D is identical to SOBEK3.
- ◇ The propagation speed of bed disturbances in D-Flow FM-1D is in line with an analytical approximation based on the method of characteristics.

Approach

We start from an existing SOBEK3-model (`/DSCTestbench/cases/e106_dflow1d/f13_morphology/c31_shoal_ds_IBedCond0_us_IBedCond0`), and set-up the equivalent model in D-Flow FM-1D. The propagation speed of bed disturbances c_{bed} [m/s] can be approximated by the following formula (Equation 4.5) which is based on the method of characteristics. The formula is valid for small Froude numbers (Fr $\ll$ 1).

$$c_{bed} = \left(\frac{u \bullet n \frac{S}{Q}}{1 - Fr^2} \right). \tag{4.5}$$

Table 4.4: *Symbol definitions*

Symbol	Definition	Unit
u	flow velocity in main channel	ms^{-1}
n	power in sediment transport equation, for Engelund-Hansen: n=5	$-$
S	sediment transport (volume rate of bed material)	m^3s^{-1}
Q	discharge in main channel	m^3s^{-1}
Fr	Froude number, $Fr = u/\sqrt{gh}$	$-$
h	water depth	m
g	gravitational acceleration	m^2s^{-1}

Figure 4.20: *Computational grid for T1 and T2.*

To prove that the computed propagation speed of bed disturbances in D-Flow FM is correct, the simulated propagation of a shoal is compared with the analytical approximation (and with SOBEK3). A local shoal is included in the initial bed level of the test case. This local shoal is on top of the equilibrium bed level.

Model description

The model domain, consists of a straight channel with a length of 10 km. The (equilibrium) bed level slope is 1×10^{-4}. The shoal is initially located halfway the channel. The initial maximum height of the shoal is 0.4 m above the equilibrium bed level. The cross-section is a rectangular profile with a width of 200 m. For this case, the width of the main channel is equal to the total width of the cross-section.

The model is forced with a constant upstream total discharge of 1000 m^3/s. The downstream water level has a fixed value of 4.64 m AD such that the water depth equal is to the equilibrium water depth. The hydraulic roughness of the channel (Chézy) is 50 $m^{1/2}$/s.

The median sediment diameter is 0.2 mm. The sediment transport is computed with the formula of Engelund-Hansen. As upstream boundary conditions, a fixed bed level is applied. At the downstream boundary, no bed level constraints are applied (i.e. Neumann boundary condition for sediment transport).

Simulations are done for three different test cases. An overview of the test cases is given in Table 4.5. In test case T2, a morphological acceleration factor (MorFac) of 10.0 is applied.

The model has a uniform computational grid size of 250 m. The computational grid of test cases T1 and T2 is visualized in Figure 4.20. In test case T3, the branch is split by a connection node (see Figure 4.21). The time step is the same for all test cases and has a value of 2 minutes.

Table 4.5: *Parameter values for the different testcases.*

test	branch split	MorFac
T1	no	1.0
T2	no	10.0
T3	yes	1.0

NOTE: TESTS T2 and T3 NOT YET PERFORMED.

The basis model we use is set-up in SOBEK3. The geometry (tabulated cross-sections, roughness and some other properties), are directly imported into D-Flow FM using a spe-

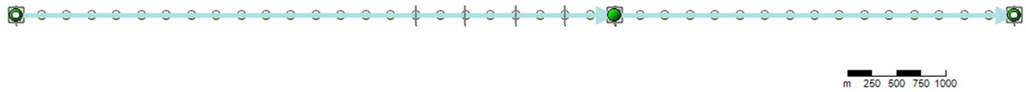


Figure 4.21: *Computational grid for T3 with the branch split by a connection node.*

cific keyword in the MDU-file:

```
OneDNetworkFile = dflow1d\water flow 1d.md1d
```

Some settings have to be set manually though:

- ◇ A SOBEK3 import only works if a (dummy) Network file is present. We advise to use a 2D network, to ensure that it doesn't conflict with the 1D network (as imported from SOBEK3.
- ◇ Timings such as refdate, start/end time and map-output intervals need to be converted manually to the MDU-file.
- ◇ The boundary conditions (locations and values) are not yet imported from SOBEK3. They have to be manually created. We defined one polyline at the upstream boundary for imposing the discharge, and one polyline at the downstream boundary to impose the water level. Note that the boundary lines must be just *outside* the model.
- ◇ Recall that in SOBEK3 the water level at the downstream boundary holds at the last pressure point in the grid, while in D-Flow FM it gets mirrored half a grid cell outside the control volume around each grid point. Effectively, this means that the water level has to be specified as if it is Δx further downstream, considering the bed slope. For this case, at the downstream boundary, $\Delta x = 250m$. For a bed level slope of 1 $\times$ 10^{-4} this implies a 2.5 cm lower water level compared to SOBEK3.
  NOTE: IT IS NOW SPECIFIED AS 1.25 cm, but will not make a big difference.
- ◇ In the MOR input file, the boundaries need to be imposed at the polylines specified in one of the steps above.
- ◇ For the upstream (us) and downstream (ds) bed boundary condition we specify
  `IBedCond_us=1`
  `IBedCond_ds=0`
  Note that in the SOBEK3 test case it was both 0.

Results

Figure 4.21 shows the initial bed level for this test case.

TODO: check bed level at downstream boundary, something wrong in D-Flow FM?

Figure 4.23 shows that the water level as a function at the upstream and downstream boundaries of the model compares very well between SOBEK3 and D-Flow FM.

Figure 4.24 to Figure 4.26 visualize the propagation of the shoal for test case T1 in different ways for a total period of 120 days. Figure 4.24 shows the longitudinal profile of the bed level with an interval of 10 days. Figure 4.25 compares SOBEK3 and D-Flow FM by plotting the bed level in one figure, with an interval of 20 days. Figure 4.26 just gives another representation, with an interval of 30 days.

The propagation speed (and evolution of bed level shape) of the shoal is equal in SOBEK3

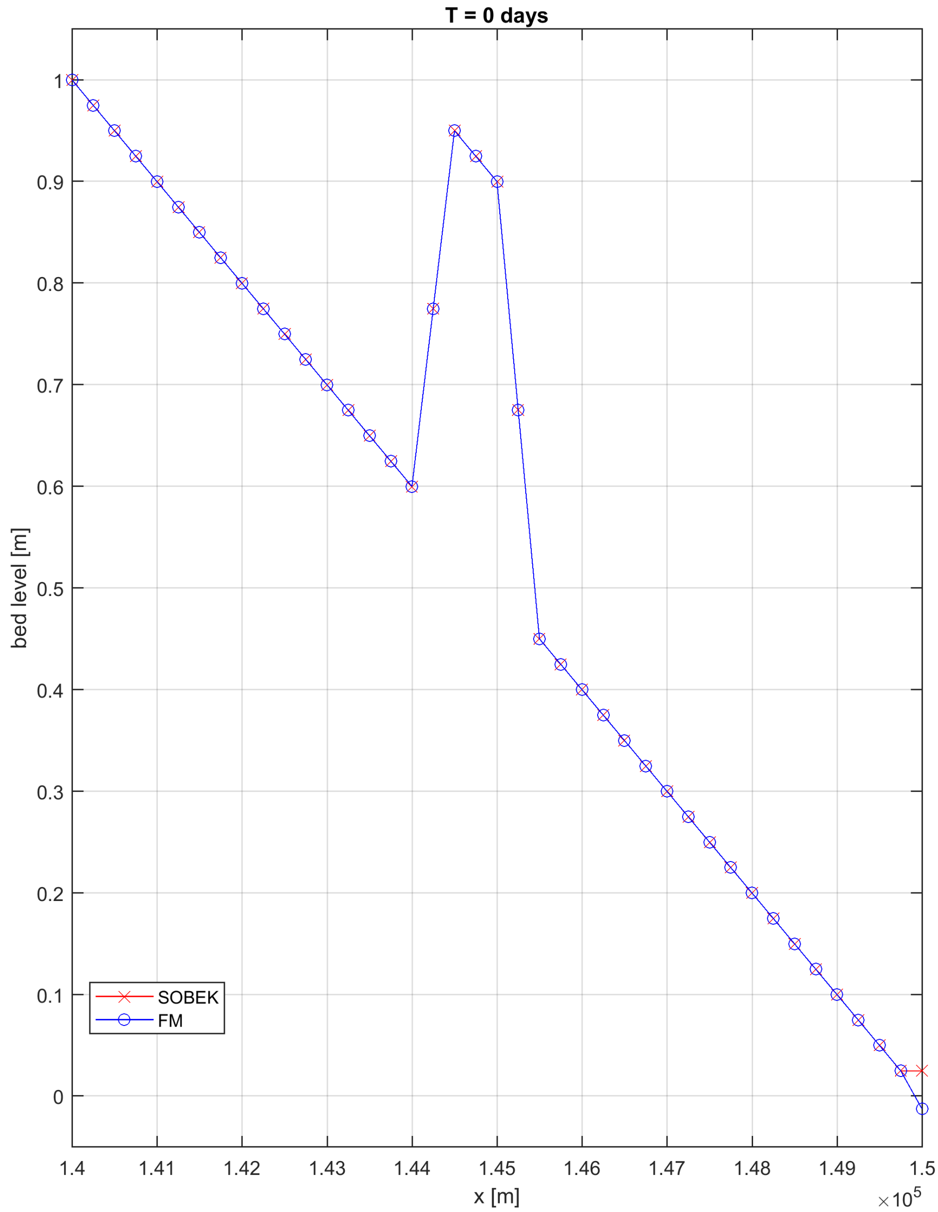


Figure 4.22: *Initial bed level.*

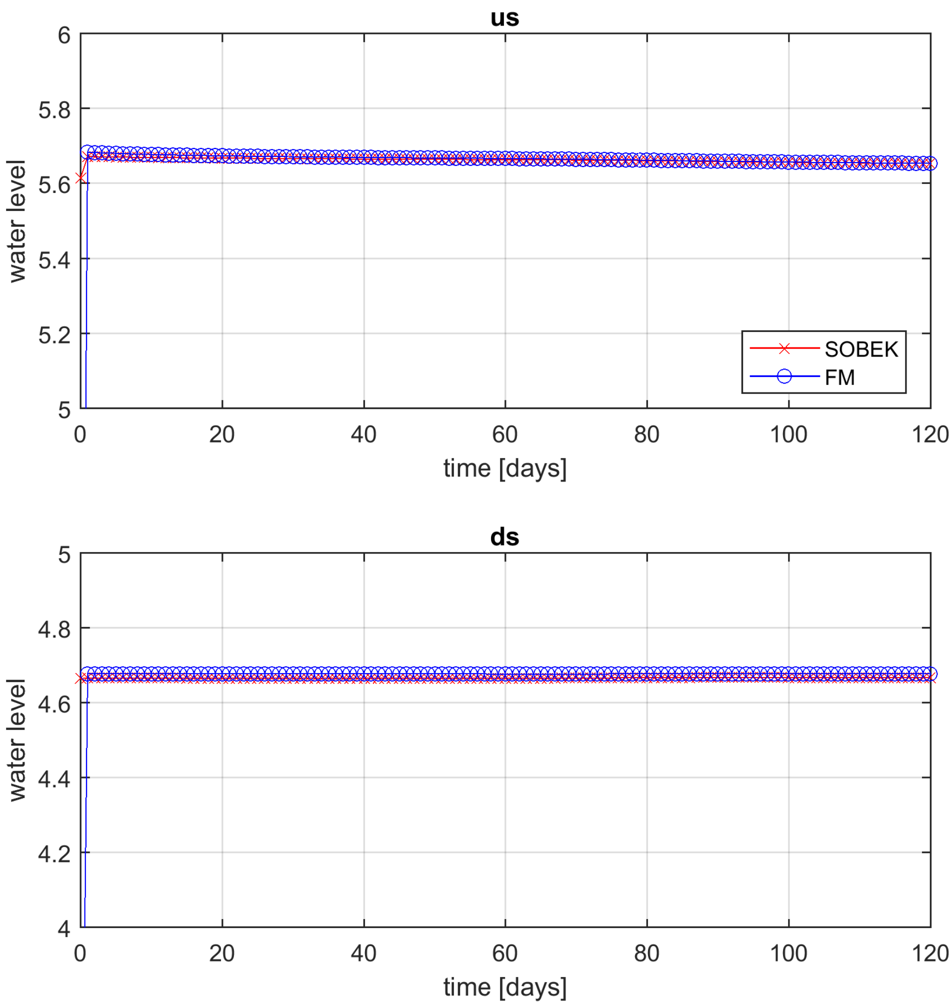


Figure 4.23: *Water level in SOBEK3 and D-Flow FM.*

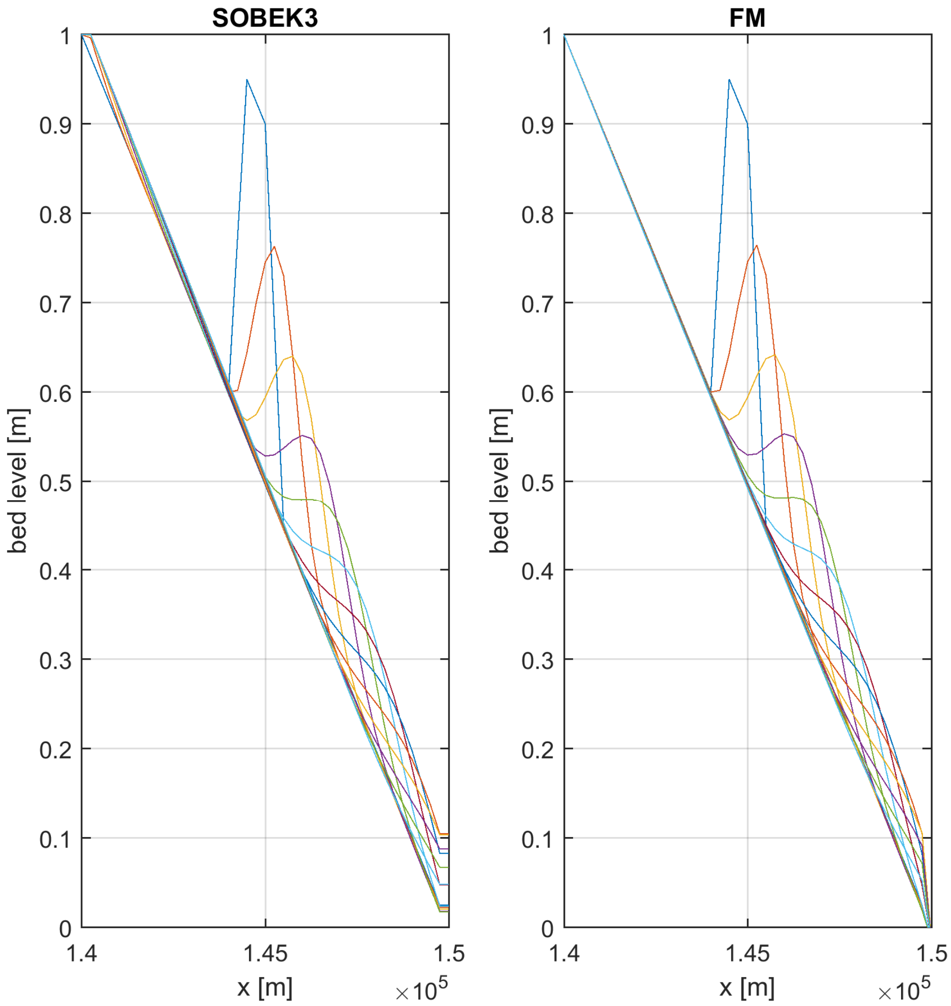


Figure 4.24: *Shoal propagation in SOBEK3 and D-Flow FM 1D.*

and D-Flow FM. These figures shows that the shoal leaves the model domain after about 3 months.

[INFO BELOW COPIED FROM SOBEK3 TEST CASE, SINCE SOBEK3 and D-Flow FM COMPARE WELL.]

NOTE THAT T2 and T3 ARE NOT YET PERFORMED FOR D-Flow FM!!

For SOBEK3 the propagation was calculated from the horizontal shift of the maximum of the shoal during time. Figure 4.27 shows the location of the maximum of the shoal with the symbol: $*$. In this figure, the bed level relative to equilibrium bed level is indicated with the color range.

A comparison of the simulated propagation speed of the shoal with the analytical approximation of the propagation speed is included in Table 4.6. Both absolute differences [m/s] as relative differences [%] are shown.

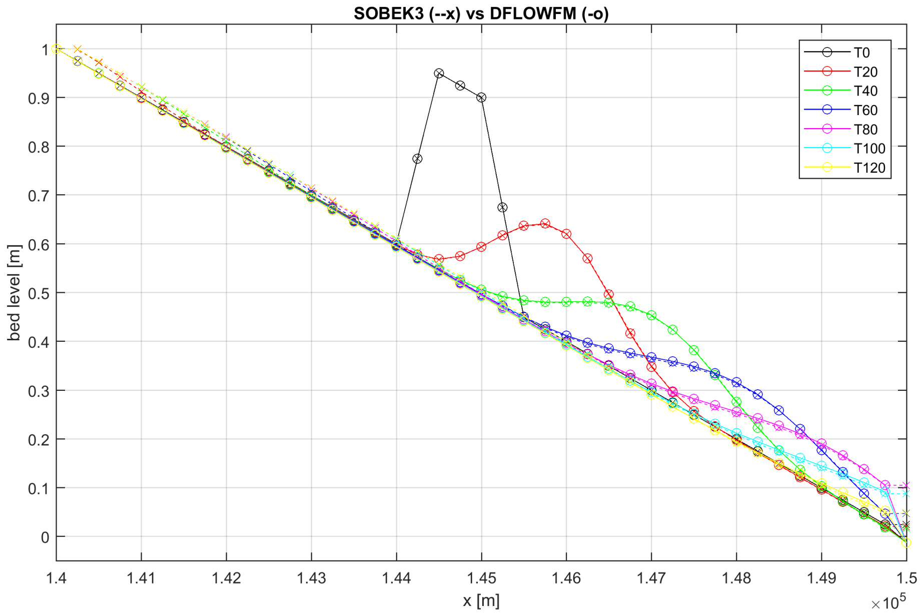


Figure 4.25: *Shoal propagation in SOBEK3 and D-Flow FM 1D.*

It turns out that the relative difference of the propagation speed is the same for test cases T1 and T2. This means that the simulated propagation speed is proportional to the morphological acceleration factor as expected.

The relative difference of the propagation speed of test case T3 is larger than for test case T1. This means that the propagation speed of is affected by splitting a branch with a connection node.

Table 4.6: *Comparison of simulated propagation speed of bed disturbance c_{bed} with analytical propagation speed for the different test cases.*

	T1	**T2**	**T3**
Difference [m/s]	0.000003	0.000033	0.000011
Relative difference [%]	0.89	0.89	3.64

Conclusion

Based on T1, the propagation of a shoal is simulated accurately in D-Flow FM-1D. It compares well to SOBEK3 and an analytical approximation.
T2 and T3 have to be performed (with connection node and different morphological acceleration factor.

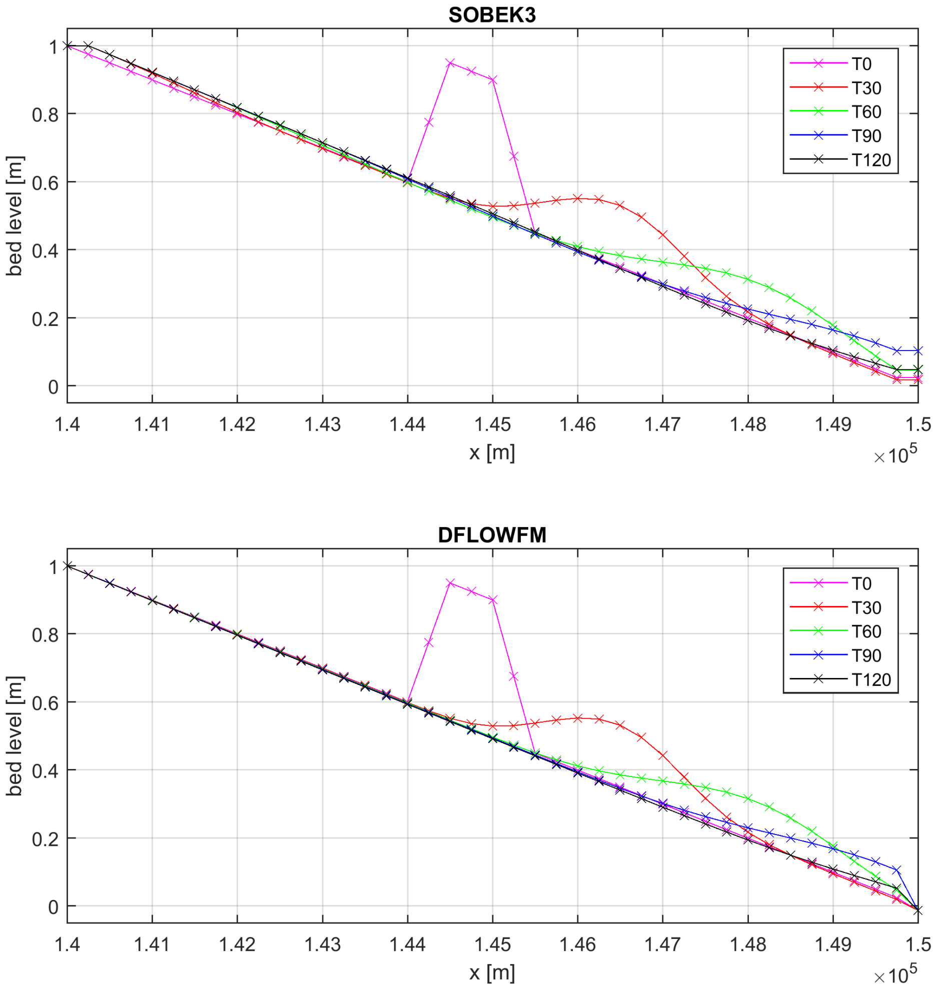


Figure 4.26: *Shoal propagation in SOBEK3 and D-Flow FM 1D.*

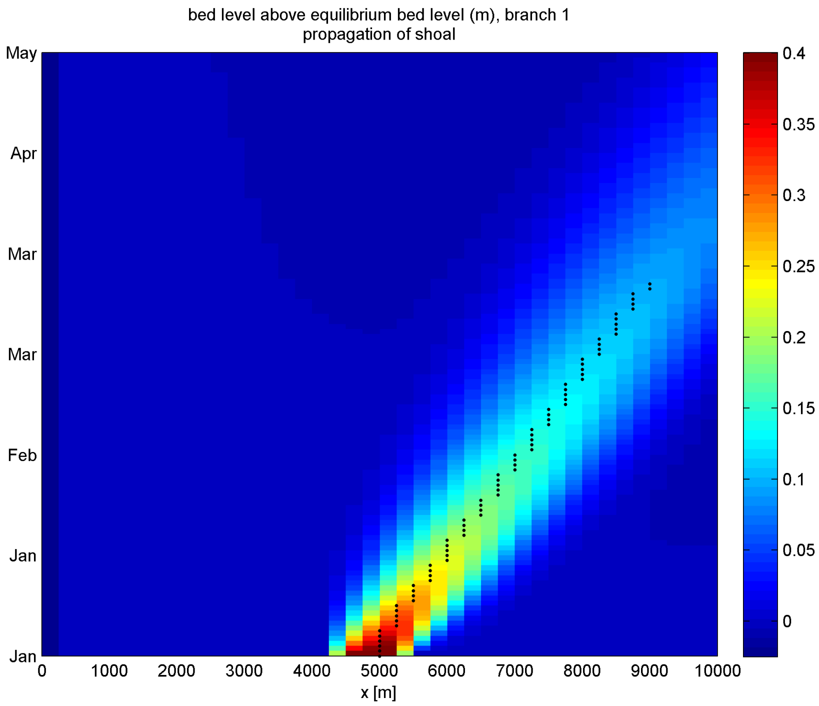


Figure 4.27: *Longitudinal profile of bed level relative to equilibrium bed level (horizontal axis) over time (vertical axis) for T1. [NOTE: COPIED FROM SOBEK3 TEST CASE*

4.6 Case idealized Waal

Quality Assurance

Date	Author	Initials	Review	Initials	Approval	Initials
08 Dec 2017	Andries Paarlberg		Bert Jagers		Aukje Spruyt	

Version information

Date of study : 22 Dec 2017
Executable : Deltares, D-Flow FM Version 1.1.261.53873M, Dec 19 2017, 23:18:32
Location : https://repos.deltares.nl/repos/DSCTestbench/trunk/cases/e02_dflowfm/f27_mor1d_tabulated_crosssections/c51_fp_IdealizedWaal
SVN revision : -

Purpose

D-Flow FM-1D (mor) can use so-called tabulated cross-sections (cf SOBEK3), where the flow width is specified as a function of the water level. The bed level is updated in the main channel only.
The purpose of this test case is to provide a simple test case with dimensions similar to the Waal River. We compare model results (hydraulics only) with SOBEK3.

Linked claims

◇ Simulated water levels in SOBEK3 and D-Flow FM-1D, where the schematization of D-Flow FM is read from SOBEK3, are identical.

Approach

We schematize a very simple channel in SOBEK3, and D-Flow FM-1D. The water levels are compared between SOBEK3 and D-Flow FM-1D for 4 discharge levels.

Model description

The model consists of a single branch with a length of 100 km and a bed level slope of 1×10^{-4} (Figure 4.13). Grid points are evenly spaced at a distance of 500 m.

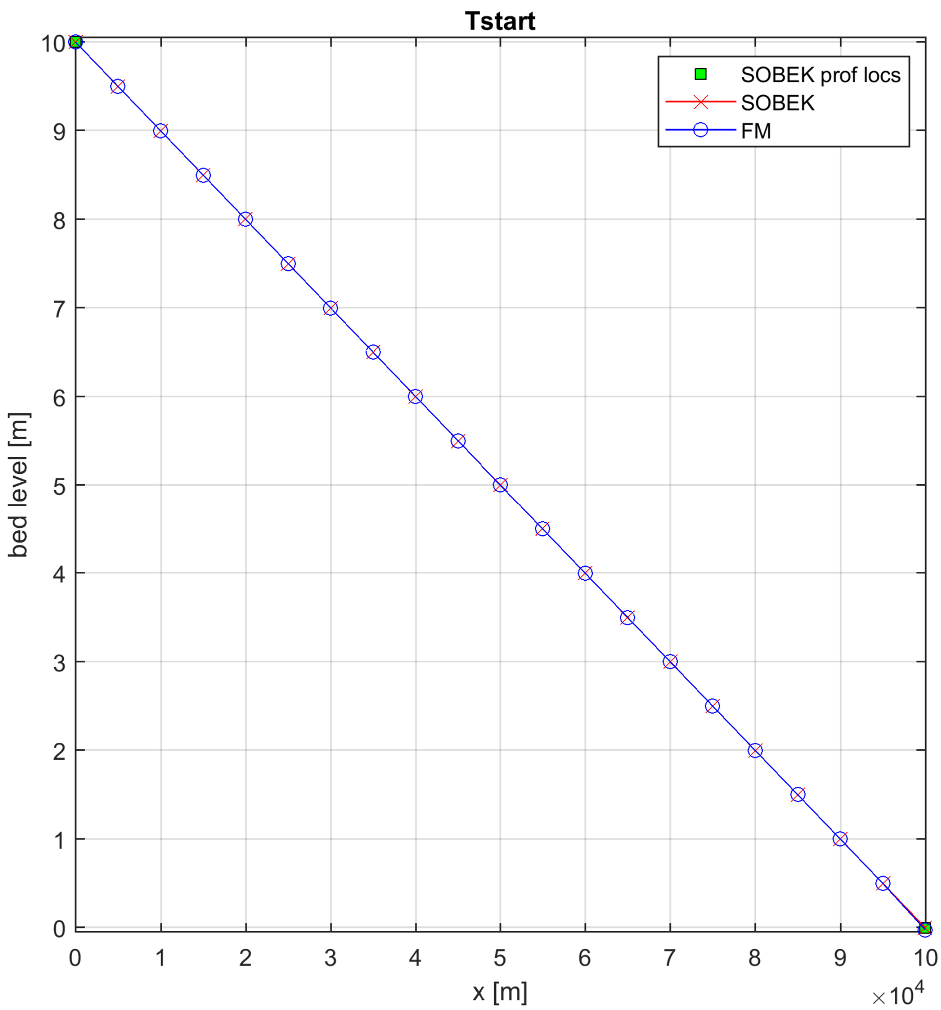


Figure 4.28: *One branch of 100 km.*

The single branch has one cross-section which consist of a main channel and a floodplain on either side (cross-section only specified at start and end node). The main channel is 100 m wide, the floodplains 500 m in total (250 m each side). The hydraulic roughness of the main channel (Chézy) is 50 $m^{1/2}$/s and for the floodplain we use C = 35 $m^{1/2}$/s. The upstream boundary condition is given by a discharge timeseries: Q1=250, Q2=500, Q3=1000, Q4=2000, each run for 1 day. The downstream boundary condition is given by a water level timeseries (2.0, 4.5, 7.0, 8.0 m w.r.t. a certain reference. Together the boundary conditions describe a quasi-stationary computation with four distinct stationary situations. For the first two discharge, the water remains in the main channel, for the third discharge the floodplains just start to flood and for the fourth discharge the floodplains convey quite some water.

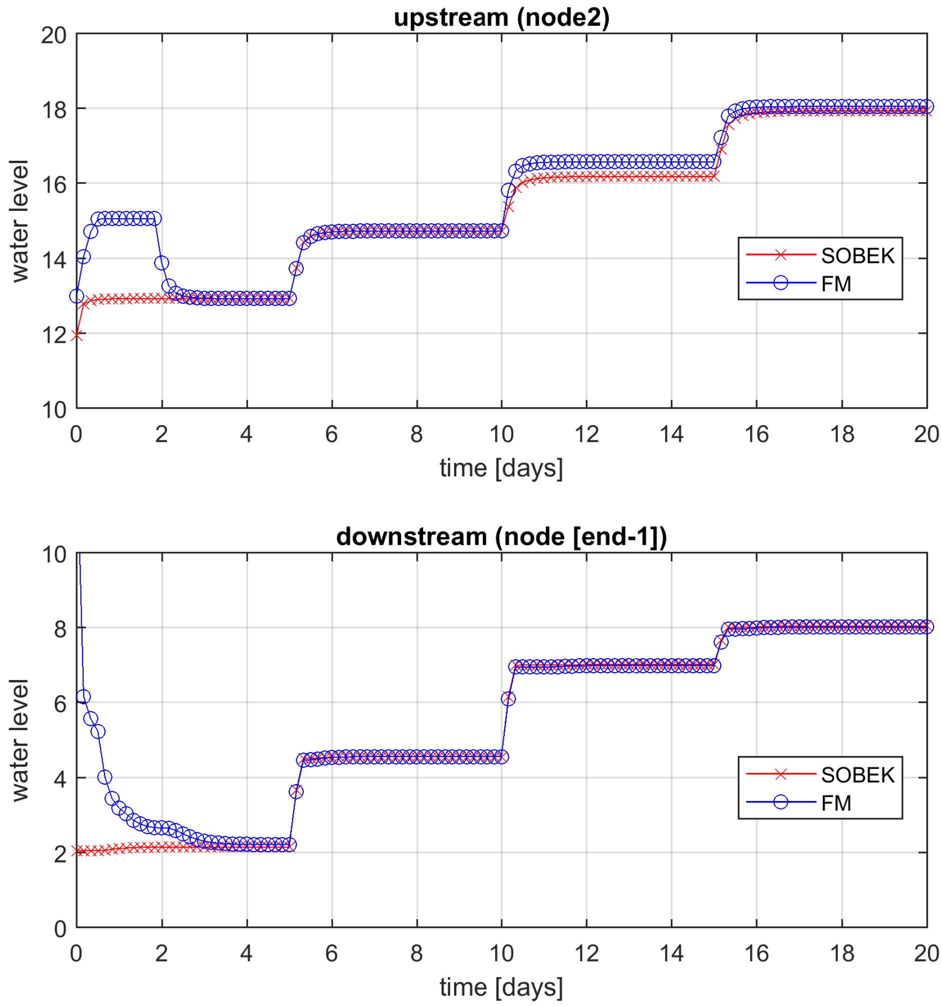


Figure 4.29: *Comparison of water levels.*

Results

Figure 4.29 shows the water level for the 4 discharge levels in SOBEK3 and D-Flow FM-1D. Comparison is well in main channel. Deviations when flow in floodplain.

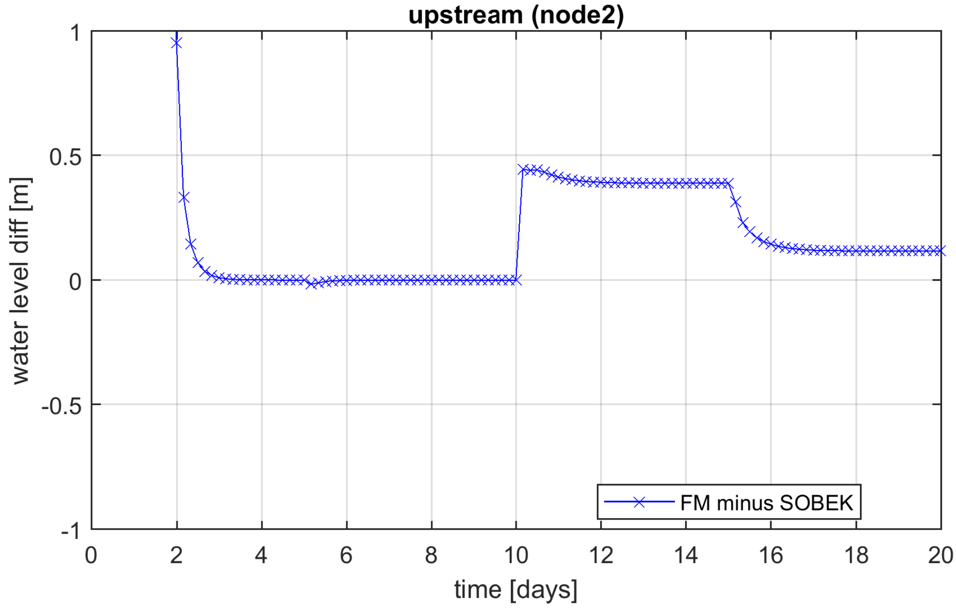
The following four figures show the model behaviour in some more detail:

- ◇ Figure 4.30: largest difference for Q3 when water is just in the floodplain.
- ◇ Figure 4.31: water level along the channel in D-Flow FM has similar shape as in SOBEK3.
- ◇ Figure 4.32: water level difference along the channel. For flow IN main channel (Q1) a relatively arge difference at the downstream boundary; for flow in the floodplain the difference builds up along the domain, which might be related to e.g. differences in how the flow equations are solved, the computation of the Chézy coefficient, or the computation of the hydraulic radius in D-Flow FM. Since this might be / is related to the issues with U_{main}, this is STILL UNDER INVESTIGATION.
- ◇ Figure 4.33: Water level differences logically also show up in the water *depth* differences.

Conclusion

Flow in main channel:OK. In floodplain quite so differences. Probably this has to do with computation of hydraulic radius when water in the flood plain.

SOME ASPECTS OF THIS CASE STILL UNDER INVESTIGATION.



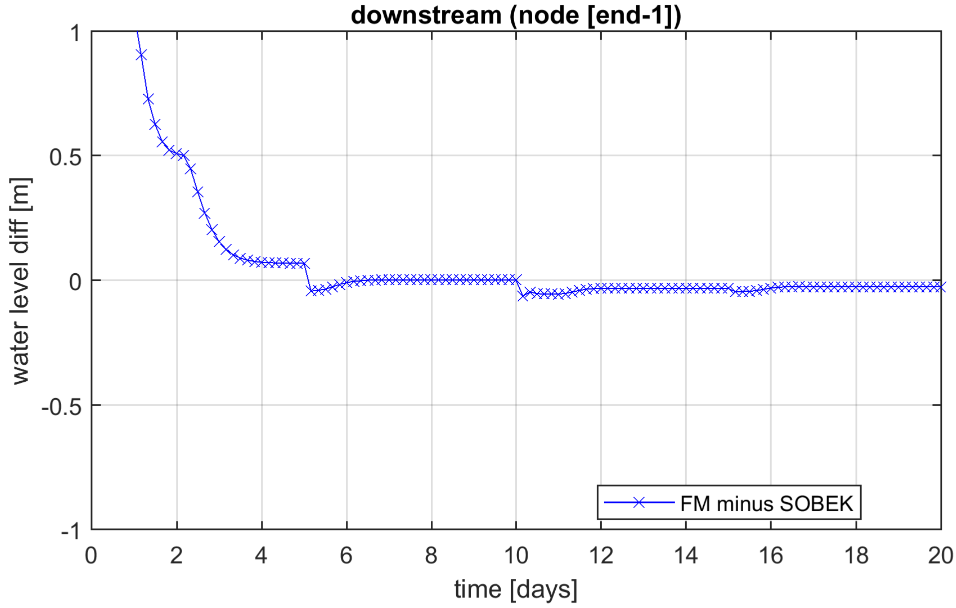


Figure 4.30: *Water level differences upstream (top) and downstream (bottom).*

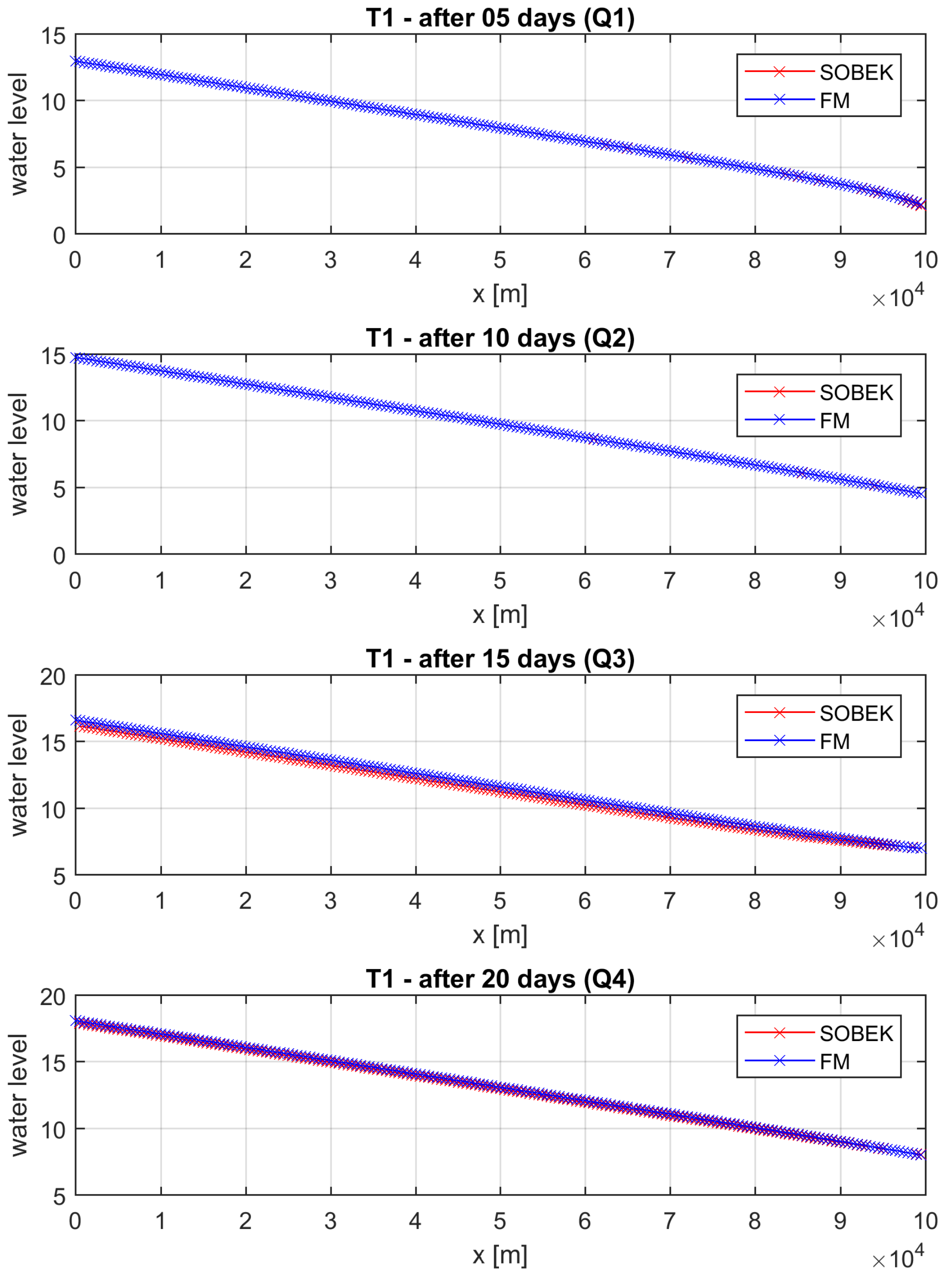


Figure 4.31: *Water level along model domain for 4 discharges.*

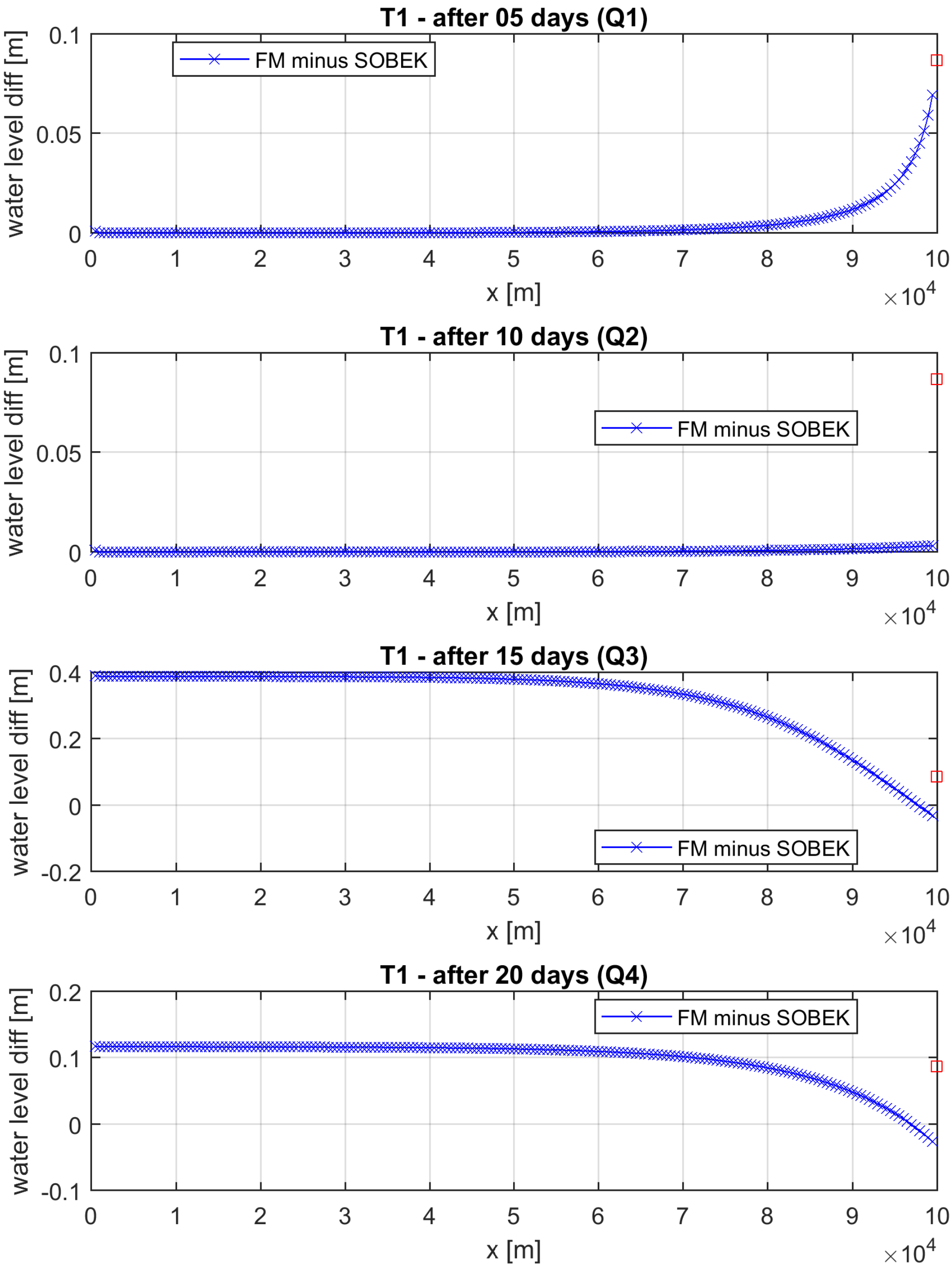


Figure 4.32: *Water level differences along model domain for 4 discharges (the square gives the difference* at *the boundary).*

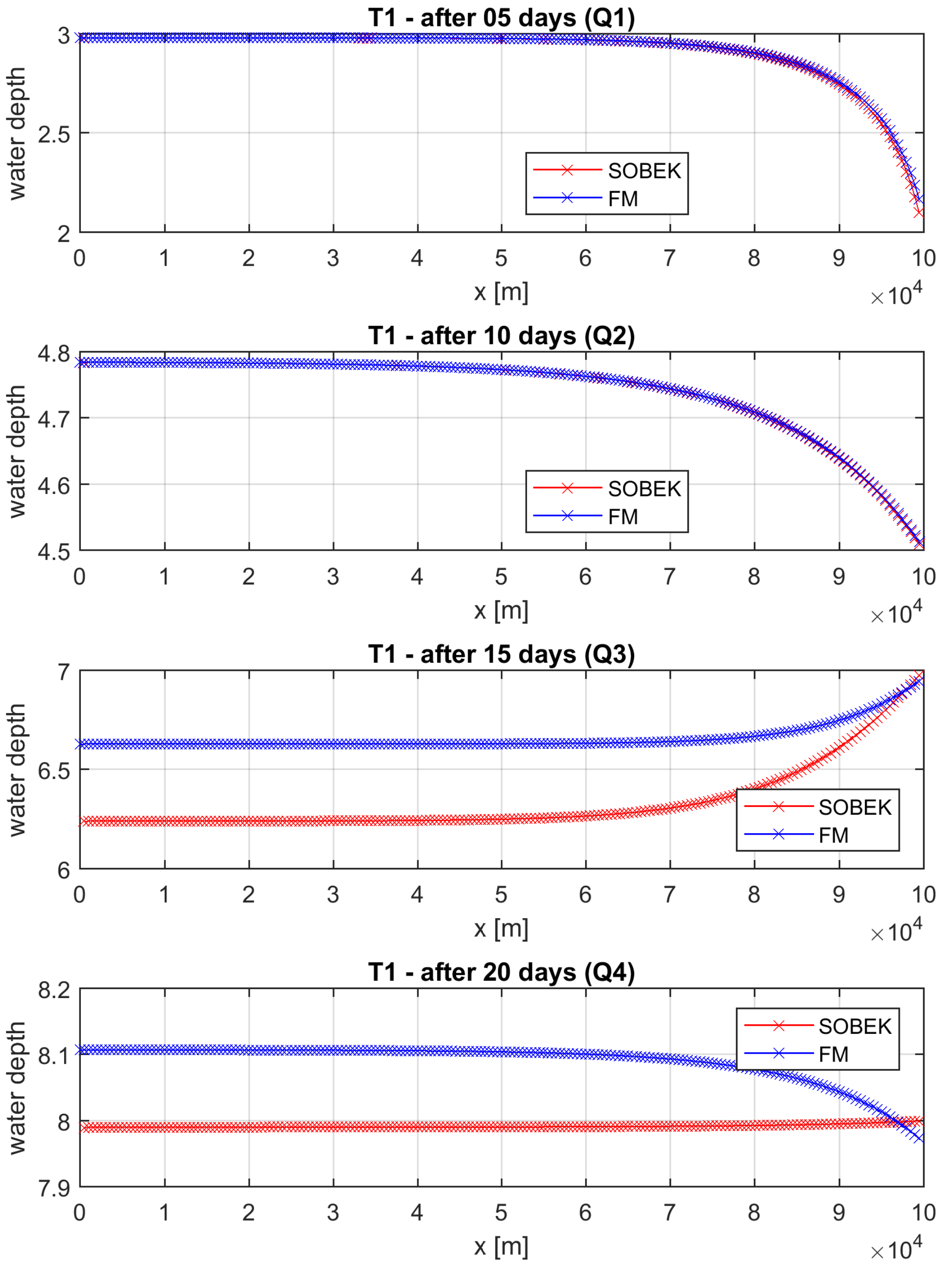


Figure 4.33: *Water* depth *differences along model domain for 4 discharges.*

References

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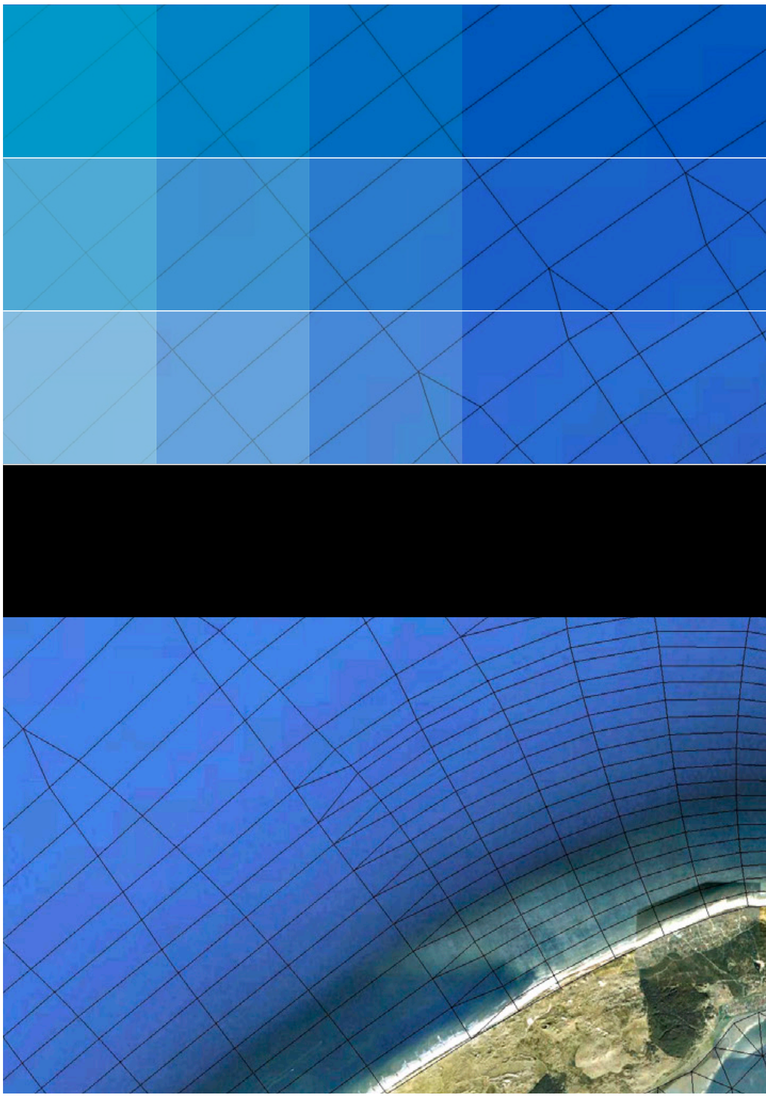
Meyer-Peter, E. and R. Müller (1948). “Formulas for bed load transport”. In: *Proceedings of the 2nd Congress IAHR, Stockholm*. Vol. 2, pp. 39–64.



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