



Simulation software for safe, sustainable and future deltas

# DELFT3D FM SUITE 2D3D

Deltares systems

D-Morphology



# **D-Morphology, 1D/2D/3D**

## **User Manual**

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## D-Morphology, 1D/2D/3D, User Manual

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# 1 A guide to this manual

## 1.1 Introduction

This is the User Manual of D-Morphology. It describes the processes and equations implemented, provides information on how to use the module, and gives a detailed overview of the associated input files and options. The sediment transport and morphology module is closely integrated with the hydrodynamics module, D-Flow Flexible Mesh, part of the Delft3D Flexible Mesh Suite or D-HYDRO Suite. The two modules are provided as one software component. The D-Morphology interface is basically an extension of the interface of D-Flow Flexible Mesh. The user is, therefore, advised to read and be accustomed with the D-Flow FM User Manual.

This module is part of several Modelling suites, released by Deltares as Deltares Systems or Dutch Delta Systems. These modelling suites are built with use of the Delta Shell framework. The framework enables to develop a range of modeling suites, each distinguished by the components and — most significantly — the (numerical) modules, which are plugged in. The modules which are compliant with the Delta Shell framework are released as *D-Name of the module*, for example: D-Flow Flexible Mesh, D-Waves, D-Water Quality, D-Real Time Control and D-Rainfall Runoff.

Therefore, this User Manual is shipped with several modelling suites. On the *Start Page* links are provided to all relevant User Manuals (and Technical Reference Manuals) for that modelling suite. Other user manuals can be referenced. In that case, you need to open the specific user manual from the *Start Page* in the central window. Some texts are shared in different user manuals, in order to improve the readability.

## 1.2 Overview

To make this manual more accessible we will briefly describe the contents of each chapter.

**Chapter 3: Getting started**, contains a reference to the corresponding chapter of the D-Flow FM User Manual where the user will find an overview of the GUI, the dockable views and the ribbons and toolbars.

**Chapter 4: Tutorial**, gives you hands-on experience in using the D-Morphology GUI to define the input of a simple problem, in validating this input, in executing the simulation and in inspecting the results.

**Chapter 5: All about the modelling process**, provides practical information on the GUI, extending a D-Flow FM model with parameters on sediment transport and morphology and tuning the model.

**Chapter 6: Running a model**, discusses how to validate and execute a model run. It contains a reference to the corresponding chapter of the D-Flow FM User Manual.

**Chapter 7: Visualize results**, explains in short the visualization of results within the GUI and by using Quickplot, MATLAB and Python. Again, it contains a reference to the corresponding chapter of the D-Flow FM User Manual.

**Chapter 8: Sediment transport and morphology**, describes the mathematical background of three-dimensional transport of suspended sediment, bedload transport and morphological updating of the bed (level).




### 1.3 Manual version and revisions

This manual applies to:

- ◇ the D-HYDRO Suite, version 2019.01
- ◇ the Delft3D Flexible Mesh Suite, version 2019.01

### 1.4 Typographical conventions

Throughout this manual, the following conventions help you to distinguish between different elements of text.

Example	Description
<b>Module</b> <b>Project</b>	Title of a window or a sub-window are in given in <b>bold</b> . Sub-windows are displayed in the <b>Module</b> window and cannot be moved. Windows can be moved independently from the <b>Module</b> window, such as the <b>Visualisation Area</b> window.
Save	Item from a menu, title of a push button or the name of a user interface input field. Upon selecting this item (click or in some cases double click with the left mouse button on it) a related action will be executed; in most cases it will result in displaying some other (sub-)window. In case of an input field you are supposed to enter input data of the required format and in the required domain.
<\tutorial\wave\swan-curvi> <siu.mdw>	Directory names, filenames, and path names are expressed between angle brackets, <>. For Linux environments a forward slash (/) is used instead of the backward slash (\) for Windows environments.
"27 08 1999"	Data to be typed by you into the input fields are displayed between double quotes. Selections of menu items, option boxes etc. are described as such: for instance 'select Save and go to the next window'.
delft3d-menu	Commands to be typed by you are given in the font Courier New, 10 points.
	In this User manual, user actions are indicated with this arrow.
[m s <sup>-1</sup> ] [-]	Units are given between square brackets when used next to the formulae. Leaving them out might result in misinterpretation. Most units will be in SI notation. [m AD] stands for 'meter Above Datum', which denotes a level relative to the vertical reference system in the model.

Command prompts and terminal output are shown in framed boxes with typewriter font:

```
> ./dflowfm --version
Deltares, D-Flow FM Version 1.1.149.41663, Sep 02 2015, 10:40:42
Compiled with support for:
IntGUI: no
OpenGL: no
OpenMP: yes
MPI    : yes
PETSc  : yes
METIS  : yes
```

### 1.5 Changes with respect to previous versions

This is the first release of a separate User Manual for the module D-Morphology.

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## 2 Introduction to D-Morphology

D-Morphology, the sediment transport and morphology module supports both bedload and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments due to waves and currents. The module is implemented as an extension of the hydrodynamic module D-Flow Flexible Mesh.

In the schematisation process we distinguish "mud" (cohesive suspended load transport), "sand" (non-cohesive bedload and suspended load transport) and "bedload" (non-cohesive bedload only or total load transport) fractions. The simulation may include an arbitrary number of these fractions as computer memory and simulation time allow. Sediment interactions are taken into account, although this is still an active research area.

The advection-diffusion equation is solved to determine the suspended transport due to currents for "sand" and "mud" fractions. If the dynamic effect of the suspended load is known to be negligible (either due to sediment diameter or sediment transport formula chosen), the "bedload" approach is more efficient. The advection-diffusion equation is not solved for those fractions which therefore require less memory and less simulation time. If the selected sediment transport formula includes a suspended component, this component is added to the bedload to obtain a total load behaviour.

The bed composition may be modelled either as a single well-mixed layer, or as a multi-layer bed to keep track of the development of different layers of sediment over time. The latter option is not (yet) supported by the user interface. It is particularly useful for tracking deposits over long time scales, and for studying beds with strongly varying erodibility due to variations in bed composition.

D-Morphology includes an extensive set of features for sediment management using dredging, dumping and nourishment operations.



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### 3 Getting started

We refer to *Getting started* of the D-Flow Flexible Mesh User Manual on the *Start* page.

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## 4 Tutorial

### 4.1 Introduction

The user is advised to start with the basic tutorials on setting up and running a hydrodynamic simulation (see D-Flow Flexible Mesh, User Manual).

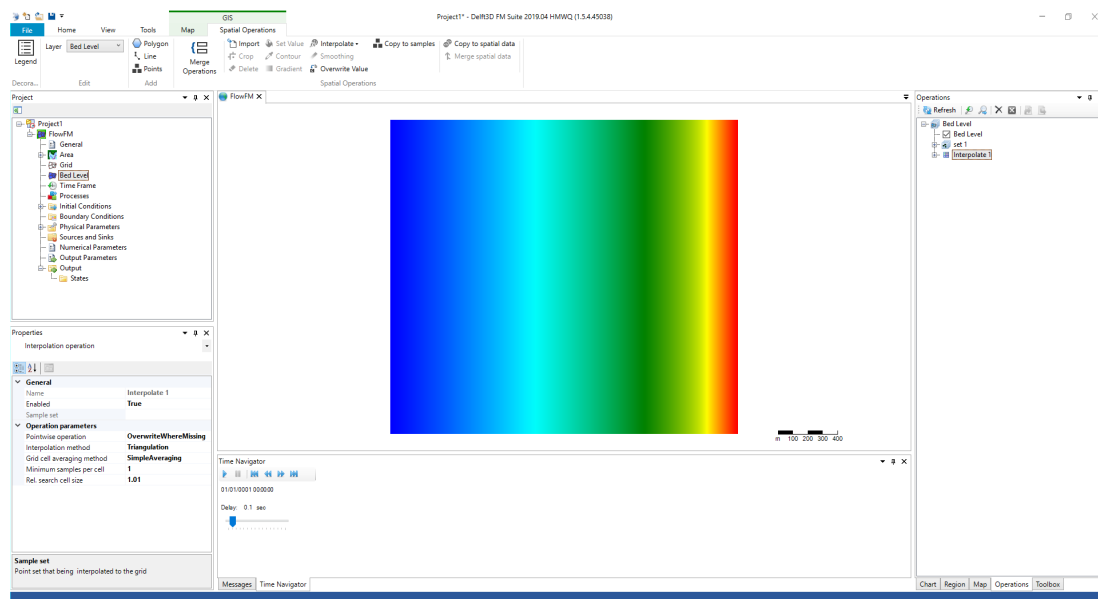
This chapter continues with a more advanced tutorial on performing a simulation including sediment transport and morphology. QUICKPLOT, a separate post-processing tool will be used to inspect the results. So, be prepared to have it installed.

### 4.2 Tutorial: Offshore breakwater

In this tutorial you'll set up a simple model for an offshore breakwater. This tutorial is a first step in a coupled flow-morphology-wave tutorial. We'll start by opening D-HYDRO Suite, creating a new D-Flow Flexible Mesh model instance, and importing the grid.

- Double click on the D-HYDRO Suite or Delft3D Flexible Mesh Suite icon on the desktop of your computer.
- Click on *New Model* → Double click on *Flow Flexible Mesh Model* or select and click *OK*.
- Load the grid file from the folder <Tutorial\_D-Morphology> by means of a right click on *Grid* → *Import...* and select file <straight\_coast\_net.nc>. The selected grid file doesn't include the bed levels, so let's add it.
- Double click on the *Bed Level* in the *Project* panel; this will select the *Bed Level* in the list box in the *Spatial Operations* section of the *GIS Map* toolbar.
- Click on the *Import* icon and open <straight\_coast\_net.xyz> without any coordinate transformation on import.
- Bring the *Operations* panel docked on the right side of the screen to the front by clicking on the tab with that name and subsequently expand the *set 1* item to show the *Import samples 1* item. Selecting that item will enable the *Interpolate* icon in the *Spatial Operations* section of the toolbar.
- Select *Interpolate* → *Interpolate selected set* and choose to use the default triangular interpolation. The interpolated bed level is visualized on the map; see [Figure 4.1](#). You have interpolated the bed level samples to the nodes of the grid; we will change this in a minute.

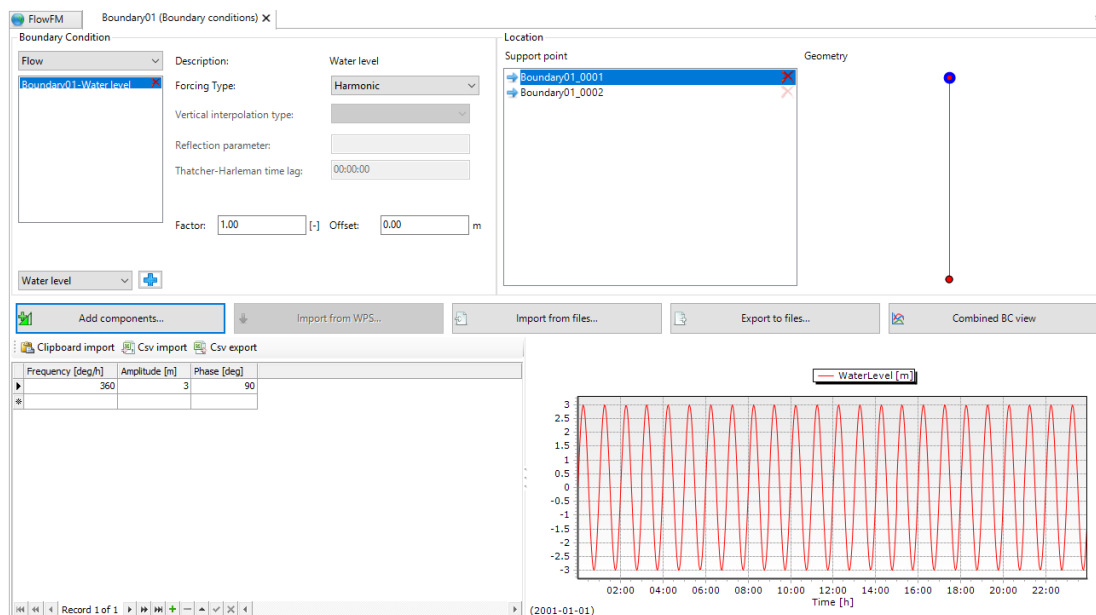




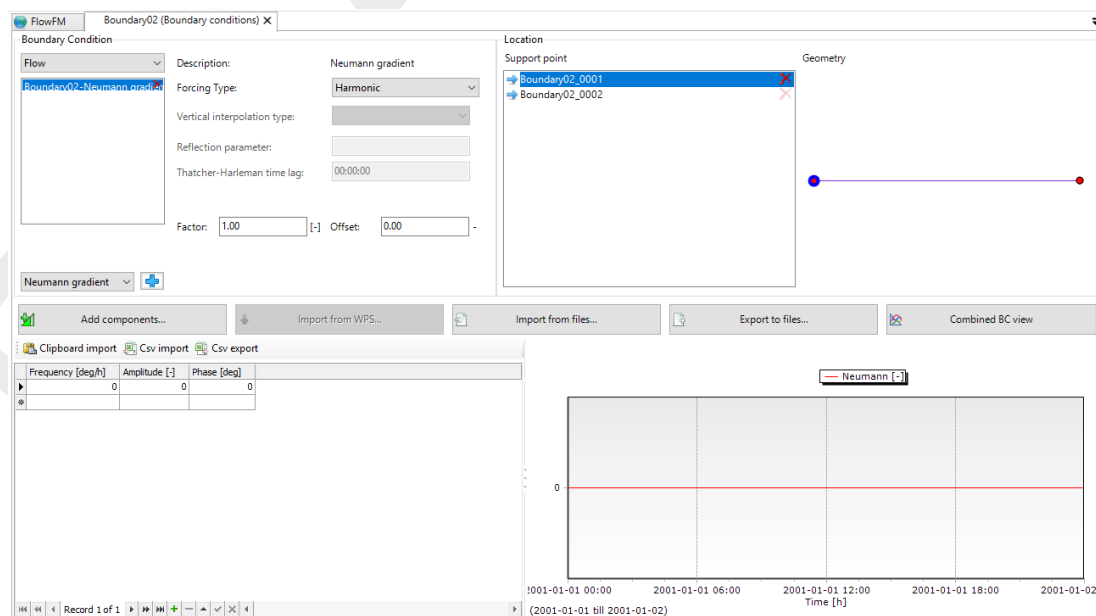
**Figure 4.1:** Overview initial bed levels.

The model contains a sloping bed that is uniform along the coast (on the right). For the boundary conditions, we'll use a water level boundary along the left edge of the grid, and Neumann boundaries along the top and bottom edges of the grid.

- Click on the *Add (2D) Flow Boundary* icon (located in the *GIS / Map* ribbon, the left end (*FM Region*)) and insert a polyline along the left edge of the grid by means of a single click just outside the model at the top left corner of the domain, followed by a double click just outside the model at the bottom left corner of the domain.
- Switch back to selection mode by clicking on the *Select* icon in the *Tools* section of the ribbon.
- Double click on the boundary line you just drew; this will open the boundary dialog window.
- Click on the + button to add a water level boundary along this sea boundary.
- Tides are most easily prescribed using *Harmonic* or *Astronomic* forcing conditions. In this case set the *Forcing type* to *Harmonic*.
- Press the *Add components ...* button and set the *Frequency* to 360 deg/h, the *Amplitude* to 3 m, and finally the *Phase* to 90 deg. Press *OK* to close the dialog, and choose to apply the changes to *All support points*. See Figure 4.2.
- Close the *Boundary conditions* tab, and repeat the aforementioned steps for the boundaries along the top and bottom edges of the grid respectively. Choose a *Neumann gradient* type boundary instead of the water level boundary. Impose a constant forcing equal to 0. This can also be done through the selection of *Harmonic* forcing type with frequency, amplitude and phase equal to zero. See Figure 4.3.



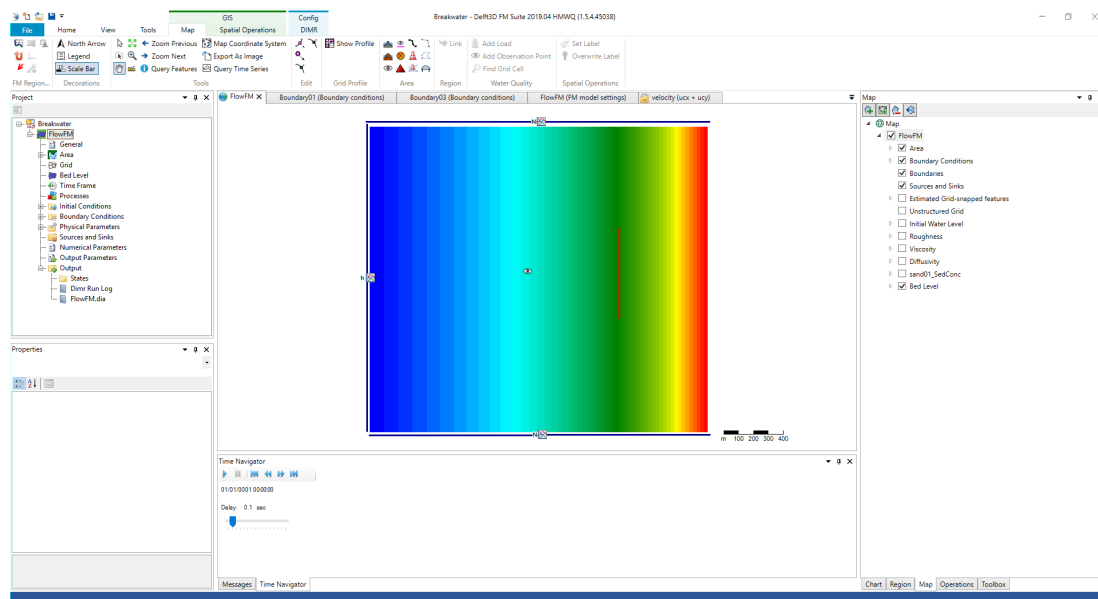
**Figure 4.2:** Harmonic water level boundary conditions for the left boundary.



**Figure 4.3:** Harmonic Neumann boundary conditions for the top or bottom boundary.

As the final geospatial step let us add an observation point in the middle of the domain.

- Click on the *Add new observation point (2D)* icon in the *Area* section in the right part of the *GIS Map* ribbon and click once in the middle of the domain.
- Switch back to selection mode by clicking on the *Select* icon. See [Figure 4.4](#).



**Figure 4.4:** All boundaries and the observation point added.

It's now time to open the settings window to set various simulation parameters.

- Open the *FM model settings* window by double clicking on the *FlowFM* → *Physical Parameters* item in the *Project* panel.
- As the first action in the opened tab, change the setting of the *Bed level locations* to *faces (cell centers)*. This change is required for the morphological simulation that we want to do in the end, so let's start by setting up a model consistent with that requirement. Note that triggered by this change, the bed level samples will be re-interpolated to the cell centres.
- To see the change in the bed levels, switch to the *FlowFM* tab, bring the *Map* panel on the right to the front and check the box for *Bed Level* in the *Map* panel. Since the bed levels are now defined in the cell centres, the visualization will have switched to flat colours per cell. You may have to refresh the view to see the result properly. The most thorough way to do this is by closing the FlowFM window and reopening it.
- Back in the *FlowFM (FM model settings)* panel, we continue in the *Physical Parameters* tab. Change the bed roughness (uniform friction) type from *Manning* to *Chézy* and set the uniform friction coefficient value above it to  $65 \text{ m}^{1/2}/\text{s}$ .
- As the final action in the *Physical Parameters* tab, we will use a user specified constant water density. Switch *Equation of state* to *Uniform* and set the *Default water density* equal to  $1025 \text{ kg/m}^3$ . Alternatively, the water density can be computed from the background salinity and temperature by means of the Eckhart or UNESCO formula.
- In the *Numerical Parameters* tab, set the *Boundary smoothing time* to 720 s.
- In the *Output Parameters* tab, set the *His(tory) output Interval* equal to the *Map output interval*, i.e. 20 minutes.
- In the *Miscellaneous* tab, set the *Dry cell threshold* to 0.01 m to indicate that for a cell should be switched to dry if the computed water depth drops below that value.
- Save the project as <Breakwater.dsproj> by selecting *File* → *Save*.

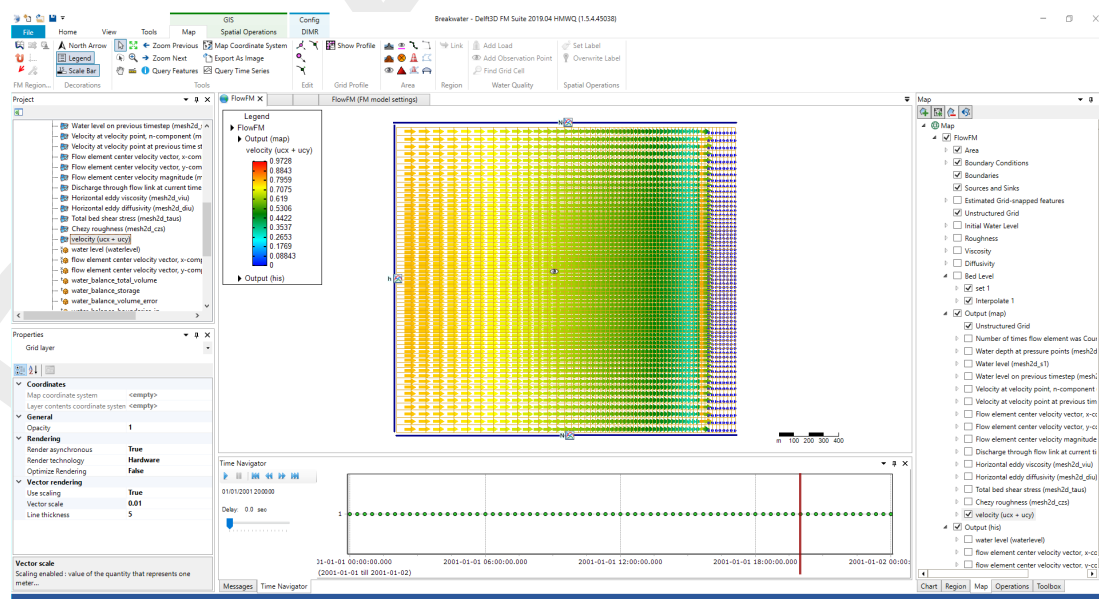
Run the simulation

- Start the simulation by means of a right click on the *FlowFM* model in the *Project* panel and selecting *Run Model*.

Viewing results

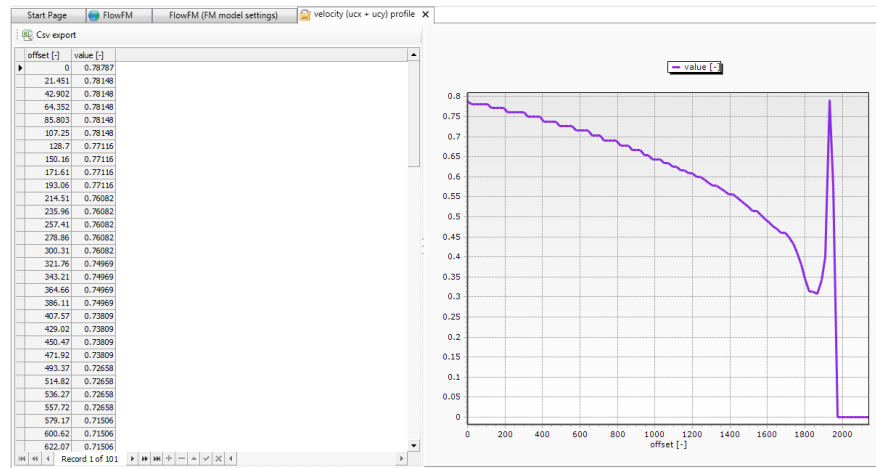


- When the simulation has ended, a list of output quantities is added to the *Output* item of the *FlowFM* model in the *Project* panel on the left. Double click on the item *velocity (ucx + ucy)* item in that list of output quantities. The map view will open or come to top again.
- If you look at the bed levels before, the figure will be still showing them. Switch off the initial *Bed Level* in the *Map* panel.
- This will show the arrows representing the velocities computed during the simulation. By default we'll see the initial velocities all equal to zero, and hence plotted as dots. When we move the time slider in the *Time Navigator* panel at the bottom of the screen, the dots change into coloured arrows scaled such that a velocity of 1 m/s is drawn as an arrow of 1 m on the map. For our model with grid cell size in the order of 20 to 200 m, these arrows still look like dots.
- To change the arrow length we have to first select the *velocity (ucx + ucy)* quantity in the *Map* panel on the right. Expand the *Output (map)* item in the *Map* panel to show it, and subsequently select *velocity (ucx + ucy)* quantity. The properties of this map layer are now shown in the *Properties* panel in the lower left corner of the screen. Set the value of *Vector scale* to 0.01 such that a velocity of 0.01 m/s is drawn as a vector of 1 m on the map, or equivalently that a velocity of 1 m/s is drawn as a vector of 100 m on the map. Set 'Use scaling' to True.
- Play the time animation of the velocity vectors by clicking on the *Play* button in the *Time Navigator* panel. Check the *Legend* (which can be activated from the *Decorations* section of the *GIS Map* toolbar) to see that the velocities vary from 0 to 1 m/s. See [Figure 4.5](#).



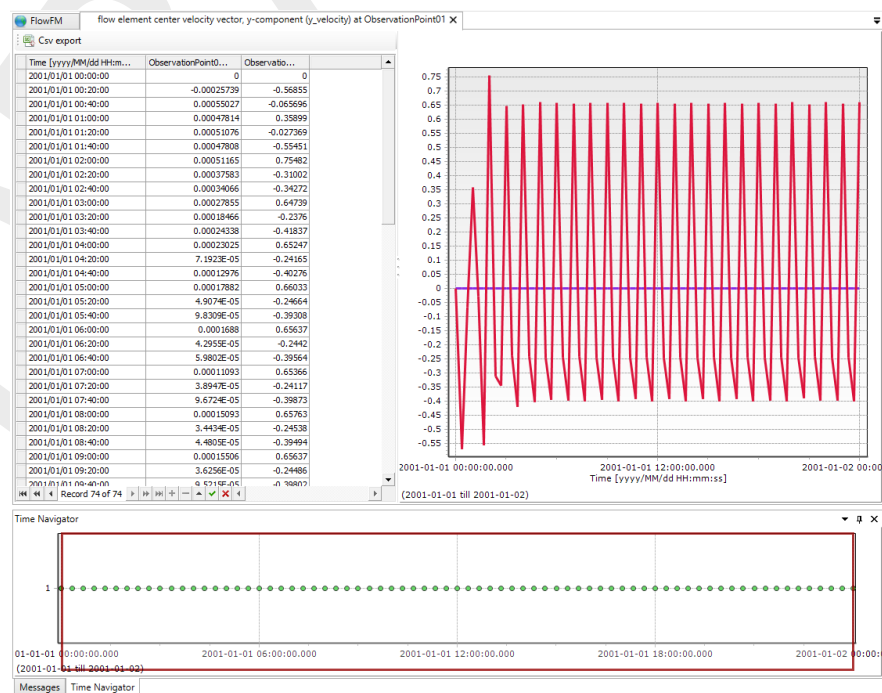
**Figure 4.5:** Velocity vectors showing the inflow of water when the water level at the sea boundary rises.

- View a cross-section by clicking on the *Show Profile* icon in the *Grid Profile* section of the *GIS Map* toolbar and drawing a line on the map perpendicular to the coast (use a single click for the first point) and a double click for the last point). See [Figure 4.6](#). You may notice that the graph is updated when you scroll through the times in the *Time Navigation* panel when viewing the map.



**Figure 4.6:** Graph showing the velocity magnitude along the sketched cross section.

- View the time-series at an observation point by selecting the observation point and right clicking on the observation point, choose *Query timeseries*, select both *flow element center velocity vector x- and y-components* in the subsequent dialog, and press OK. The new figure shows the cross-shore velocity vary (after the spin-up period) periodically between 0.6 m/s onshore to 0.4 m/s offshore, whereas the alongshore velocity remains negligible. See Figure 4.7.



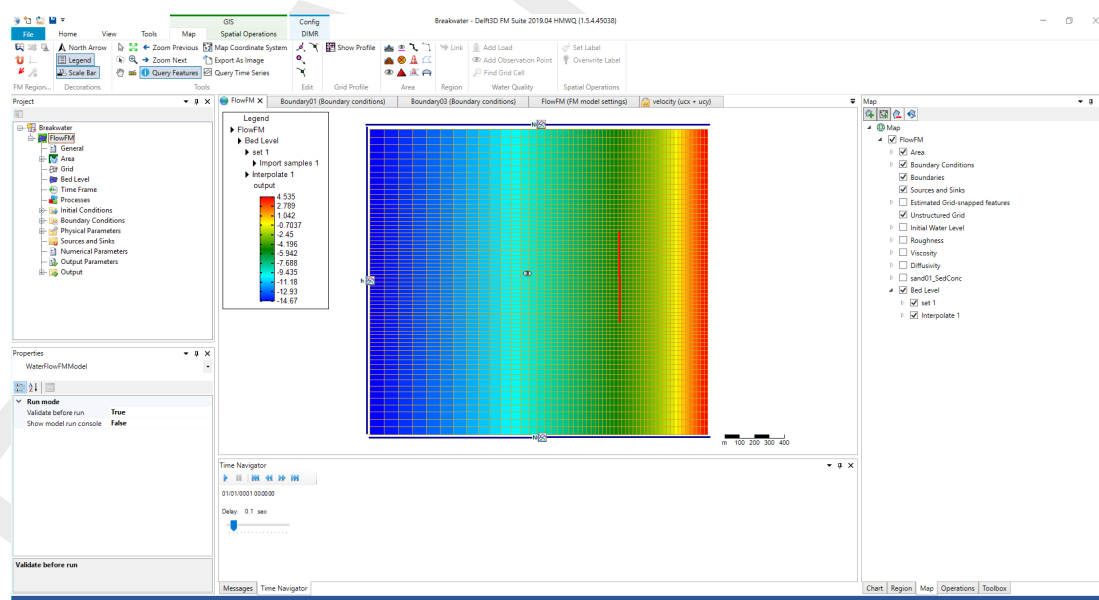
**Figure 4.7:** Graph showing the time-variation of the x- and y-components of the velocity at the observation point.

So far we only simulated the hydrodynamics. Now we're going to add sediment transport and morphology. Let's close any open windows for cross sections and time-series at observation points.

- Open the *FM model settings* window again by double clicking on the *Processes* item in

the *Project* panel.

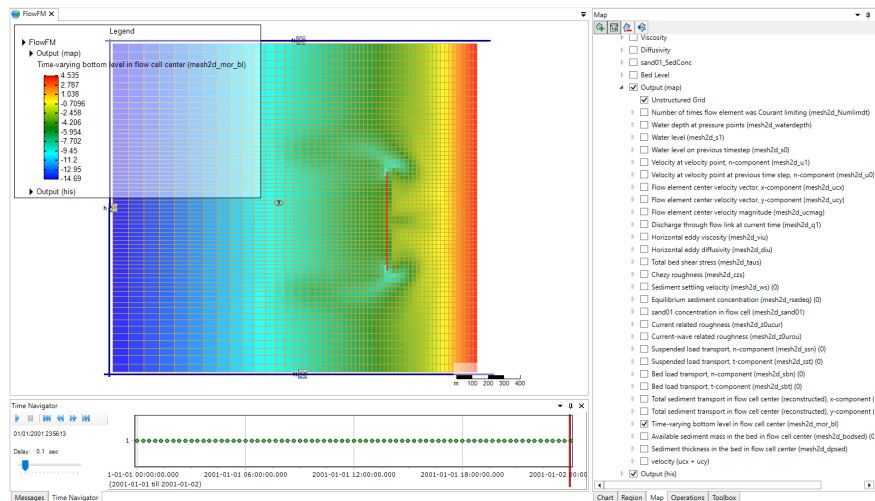
- In the *Processes* tab, switch on the *Sediment/Morphology* process; this will add *Morphology* and *Sediment* tabs to the model settings window.
- In the *Sediment* tab, add a sediment fraction by typing the name "sand01" and clicking *New*. Use the default sediment characteristics such a median diameter of 200  $\mu\text{m}$  and Van Rijn (1993) sediment transport formula. However, set the *Initial sediment layer thickness at bed* equal to uniform 10 m.
- In the *Morphology* tab, set the *Morphological scale factor* equal to 100 to speed up the morphological developments by a factor hundred.
- Set the *Spin-up before morphological changes* equal to 0.
- Switch to the map view by clicking on the *FlowFM* tab, or by double clicking on the *FlowFM* item in the *Project* panel.
- Click on the *Add new thin dam (2D)* icon in the *Area* section of the *GIS Map* toolbar.
- Draw a breakwater by clicking once to start drawing the location and clicking twice to end drawing. Position the construction such that it is located at about the 500 m from the right edge of the domain (just right of the  $-5$  m bed level contour), and length of about 600 m. See Figure 4.8.



**Figure 4.8:** A breakwater has been added to the model.

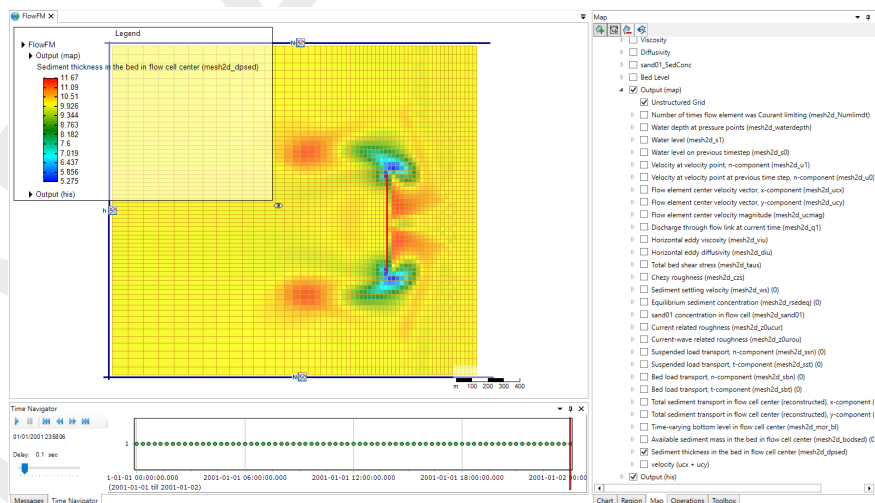
Run the model again. Since the model now includes sediment transport and morphology, it will run a bit slower than the previous flow only simulation.

- Visualize the morphological change by selecting *Time-varying bottom level in flow cell center* and scroll through time. Observe that scour holes are formed at both ends of the breakwater with sedimentation occurring behind the breakwater. See Figure 4.9.



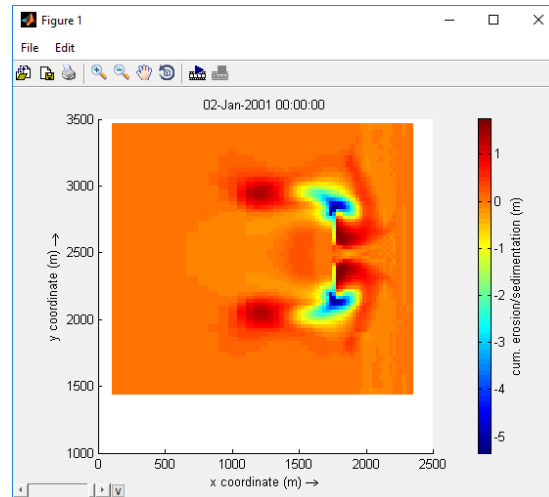
**Figure 4.9:** Figure showing the bed levels at the end of the simulation.

- Switch to the *Sediment thickness in the bed in flow cell center* to observe that by the end of the simulation the sediment thickness has locally increased to over 12 m behind the breakwater and dropped below 6 m in the scour holes. See Figure 4.10.



**Figure 4.10:** Figure showing the sediment thickness at the end of the simulation.

- For the final step of the visualization we'll use QUICKPLOT. Save the project by going to *File* → *Save As* and selecting a location and a name for the project.
- Open QUICKPLOT (separate installation process) and select *File* → *Open File....* Search for the location where you saved the project, e.g. <d:\MyPath\Project1.dsproj>. Enter subsequently the <d:\MyPath\Project1.dsproj\_data> folder, the subfolder <FlowFM> (the name of the model in your project) and finally the <output> folder to locate the <FlowFM\_map.nc> file. Open that file. In the *data field* list box, search for the quantity *cum. erosion/sedimentation* just below *Time-varying bottom level in flow cell center*. Press *Quick View*, see Figure 4.11. The figure shows the erosion and sedimentation patterns.



**Figure 4.11:** Figure showing the cumulative erosion and sedimentation (bed levels at the end of the simulation minus those at the beginning).

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## 5 All about the modelling process

### 5.1 Introduction

As a D-Morphology model is an extension of an hydrodynamic model, you must start with a D-Flow Flexible Mesh model. Then, activate sediment and morphology under the *Processes* tab and specify the sediment transport and morphology parameters. The input data is collected into the Master Definition Unstructured file, called a \*.mdu file. For a description of this file we refer to the D-Flow Flexible Mesh User Manual.

### 5.2 Setting up a D-Morphology model

#### 5.2.1 Selecting a D-Flow Flexible Mesh model

We refer to the D-Flow Flexible Mesh User Manual on the *Start Page*, on how to create a D-Flow FM model. Here we further assume that you have already created a basic D-Flow FM model that you want to extend with sediment transport and morphology. Open the associated project (<\*.dsproj>) and select the D-Flow FM model in the **Project** window.

**Note:** it is strongly advised to validate the model, perform a calculation and inspect the results.

Then, click the plus sign (+) before the name of the model to expand all model attributes in the **Project** window. If you click on one of them the D-Flow FM editor will open; this editor consists of multiple tabs that partially match the model attributes listed in the **Project** window. Here, we describe only the D-Flow FM editor tabs that are relevant for a D-Morphology model: Processes, Sediment and Morphology.

#### 5.2.2 Processes

In the processes tab (Figure 5.1) you can specify which processes, such as tidal forcing and waves, you want to incorporate into the D-Flow FM simulation. This is the place where you need to activate sediment/morphology by ticking the associated check box.

**Note:** that when ticking the sediment/morphology check box, two tabs for setting sediment and morphology parameters appear.

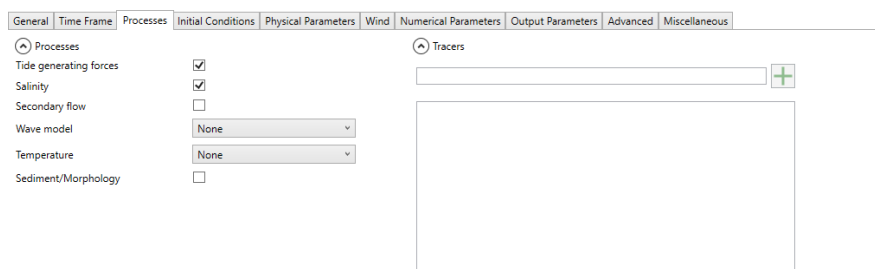


Figure 5.1: Overview processes tab

### 5.2.3 Sediment

If you have activated the process sediment/morphology in the *Processes* tab (section 5.2.2), the tab *Sediment* appears. In this tab, you can add, delete and modify sediment fractions and the parameters and settings that are associated to the individual sediment fractions. In order to add and define a sediment fraction, the following steps can be taken:

- 1 Specify the name of the new sediment fraction, and press *New*.
- 2 If needed, adjust the reference density for hindered settling calculations.
- 3 Select the type of fraction (either Sand, Mud or Bed-load).
- 4 Specify the parameters associated with the selected type of fraction.
- 5 Select a transport formula to be used with the sediment fraction.
- 6 Specify the parameters associated with the selected transport formula.

You can repeat these steps in case you want to incorporate multiple fractions within your model. A sediment fraction can be deleted by first selecting the fraction you wish to remove, and then clicking the *Remove Fraction* button.

After selection of the *Sediment* tab and adding a new sediment fraction, the window given by (Figure 5.2) is shown. The left column contains a list of sediment fraction specific settings that are independent of the transport formula. The right column contains a list of parameters that are specific for the transport formula. See section A.3 for an overview of the parameters per transport formula.

**Figure 5.2:** Overview of the *Sediment* tab, showing a sediment of type 'sand'.

Below, an overview of keywords that are associated to different types of sediment is provided

**Table 5.1:** List of sediment specific parameters (not related to sediment transport formula).

Parameter	Lower limit	Upper limit	Default	Unit	Type of sediment
Reference density hindered settling	100	10000	1600	kg/m <sup>3</sup>	Uniform for all fractions

(continued on next page)



Table 5.1 – continued from previous page

Parameter	Lower limit	Upper limit	Default	Unit	Type of sediment
Initial sediment layer thickness at bed	0	$\infty$	0	m	Sand, mud and bed-load
Specific density	100	4000	2650	kg/m <sup>3</sup>	Sand, mud and bed-load
Dry bed density	0	10000	1600	kg/m <sup>3</sup>	Sand and bed-load
	0	10000	500	kg/m <sup>3</sup>	Mud
Initial concentration	0	Inf	0	kg/m <sup>3</sup>	Sand and mud
Median sediment diameter $D_{50}$	0.000063	0.002	0.0002	m	Sand and bed-load
Salinity for saline settling velocity	0.01	391	31	ppt	Mud
Settling velocity fresh water	0	1	0.00025	m/s	Mud
Settling velocity saline water	0	1	0.00025	m/s	Mud

*Reference density for hindered settling*

In high concentration mixtures, the settling velocity of a single particle is reduced due to the presence of other particles. In order to account for this hindered settling effect [Richardson and Zaki \(1954\)](#) are followed. The reference density is a parameter in their formulation. See [section 8.1.5](#).

*Specific density*

For sediment transport the Eckart relation is extended to include the density effect of sediment fractions in the fluid mixture, see [section 8.1.4](#). The specific density of each sediment fraction is part of this formulation.

*Dry bed density*

The thickness of the sediment above the fixed layer is calculated by dividing the mass of sediment available at the bed by the user specified dry bed density.

*Initial concentration*

The initial suspended sediment concentration of the fraction. It can be specified as uniform or spatially varying.

*Median sediment diameter ( $D_{50}$ )*

**Note:** Currently only the option of a spatially varying initial concentration work. Please specify a constant field to use a constant value. The settling velocity of a non-cohesive ("sand") sediment fraction is computed following the method of [Van Rijn \(1993\)](#). The formulation used depends on the diameter of the sediment in suspension: See [section 8.3.1](#)

*Settling velocity*

The settling velocity of the cohesive sediment, note that this is specified in m/s

*Initial sediment layer thickness at bed*

The initial sediment layer thickness at the bed in metre, can be specified as uniform or spatially varying.



**Remark:**

- ◇ When adding multiple sediment fractions with an initial sediment layer thickness, the layers are completely mixed by default. E.g. a uniform layer of 4 m present for one sediment fraction, and a uniform layer of 6 m for another fraction, results in an initial sediment layer of 10 m, in which 40 % and 60 % of the respective sediment fractions is present. If you wish to have the model behave differently, options for bed stratigraphy are available, refer to [section 8.6.6](#).

**Spatially varying variables**

As indicated above, some variables can be defined as spatially varying. Note that when activating a variable as spatially varying, the selected variable is added to the list of spatially varying variables in the spatial editor. A detailed description on how to work with this spatial editor is provided in one of the appendices of the D-Flow FM User Manual. Note that you can no longer specify a uniform value for a variable that is selected as spatially varying.

**5.2.4 Morphology**

If you have activated the process sediment/morphology in the *Processes* tab ([section 5.2.2](#)), the tab *Morphology* appears. In this tab, you can modify sediment transport and morphology parameters/settings that are independent of the sediment fractions. After selection of the *Morphology* tab, the window given by ([Figure 5.3](#)) is shown.

Section	Parameter	Value	Unit
General	Morphological scale factor	1	[-]
	Spin-up before morphological changes	50	[s]
	Minimum depth for sediment computations	0.1	[m]
	Include sediment concentration on density	<input type="checkbox"/>	
	Update bed levels during simulation	<input checked="" type="checkbox"/>	
	Update bed composition during simulation	<input checked="" type="checkbox"/>	
	Neumann boundaries for mud influx	<input checked="" type="checkbox"/>	
	Neumann boundaries for sand influx	<input checked="" type="checkbox"/>	
	Morphology boundary condition file		
	Hiding and exposure formulation	No hiding and exposure	
Sediment transport parameters	Threshold sediment thickness	0.05	[m]
	Multiplication (calibration) factors		
Bed load transport	Bed slope formulation	Koch & Folkstra formulation	
	Streamwise bed gradient factor	1	[-]
	Ashld	0.85	[-]
	Bshld	0.5	[-]
	Cshld	0	[-]
	Dshld	0	[-]
Multiplication (calibration) factors	Effect of secondary flow on bed load direction	1E-36	[-]
	Current related reference concentration factor	1	[-]
	Current related transport vector factor	1	[-]
	Factor for erosion of adjacent dry cells	1	[-]
	HMaxTh	1.5	[m]

**Figure 5.3:** Default view of the Morphology tab.

With the feedback of bed level changes to the hydrodynamic computation you can execute a full morphodynamic computation. You can also include the influence of waves by running this version of D-Flow FM in combination with the D-Waves module. See [section 8.6](#) for details. A description of the various morphological parameters follows below.

**General**

One of the complications inherent in carrying out morphological projections on the basis of hydrodynamic flows is that morphological developments take place on a time scale several times longer than typical flow changes (for example, tidal flows change significantly in a period of hours, whereas the morphology of a coastline will usually take weeks, months, or years to change significantly). One technique for approaching this problem is to use a *Morphological time scale factor* whereby the speed of the changes in the morphology is scaled up to a rate that it begins to have a significant impact on the hydrodynamic flows.

*Morphological scale factor* The above can be achieved by specifying a non-unity value. The *Morphological scale factor* can also be time-varying, see [section A.8](#). This feature is not yet supported by the GUI.

The implementation of the *Morphological time scale factor* is achieved by simply multiplying the erosion and deposition fluxes from the bed to the flow and vice-versa by this scale factor, at each computational time-step. This allows accelerated bed-level changes to be incorporated dynamically into the hydrodynamic flow calculations.

Frequently, a hydrodynamic simulation will take some time to stabilise after transitioning from the initial conditions to the (dynamic) boundary conditions. It is likely that during this stabilisation period the patterns of erosion and accretion that take place do not accurately reflect the true morphological development and should be ignored.

*Spin-up before morphological changes* Specify a time interval (in seconds<sup>1</sup> after the start time) after which the bed updating will begin. During this time interval all other calculations will proceed as normal (sediment will be available for suspension for example) however the effect of the sediment fluxes on bed level and bed composition will not be taken into account.

*Include sediment concentration on density* Option to include the sediment concentration on the fluid density. This option is typically switched off.

*Minimum depth for sediment calculation* In the case of erosion near dry points a threshold depth for computing sediment transport can be used, see [section 8.6.2](#).

*Morphological boundary condition file* Name of the file in which the morphological boundary conditions are stored. The value is indicated for your information; it can't be edited.

## Sediment transport parameters

This section currently only contains one parameter.

*Threshold sediment thickness* If the thickness of the layer of sediment in the bed is less than the specified value, the bed-load transport fluxes out of the grid cell and entrainment fluxes of the suspended load component are reduced as indicated in [section 8.4.4](#).

## Unlabelled block

This block contains a second set of general parameters.

*Update bathymetry during simulation* Option to select whether you want to update the bed levels (and hence provide morphological feedback to the hydrodynamics) during the simulation. This option is enabled by default. The bed level updating is always switched off during the spin-up interval.

*Update bed composition during simulation* Option to select whether you want to update the bed composition during the simulation. This option is enabled by default. The bed composition updating is always switched off during the spin-up interval.

It can be difficult to specify appropriate sediment concentrations for all sediment fractions at the inflow boundaries of the model. In the ideal case the sediment load entering through the boundaries will be near-perfectly adapted to the local flow conditions, and very little accre-

<sup>1</sup> The time unit actually matches the unit selected by the keyword `Tunit` in the mdu-file. By default this unit is set to seconds. The unit used is reported in the diagnostic output file.

tion or erosion should be experienced near the model boundaries. Specifying an equilibrium concentration would clearly be very useful, but the concept of “equilibrium concentration” is poorly defined. Therefore, we have implemented in D-Morphology the equilibrium concentration option as a mathematically well defined zero-gradient concentration boundary condition.

*Neumann boundaries for mud influx* Option to use a zero-gradient Neumann boundary condition for the mud fractions at inflow boundaries. Switched off by default since mud concentrations have a weak local coupling to the bed composition potentially erroneous results. When not activated the inflow concentrations specified in Data Group *Boundaries* → *Transport conditions* will be used.

*Neumann boundaries for sand influx* Option to use a zero-gradient Neumann boundary condition for the sand fractions at inflow boundaries. Switched on by default since sand concentrations have typically a strong enough local coupling to the bed composition to guarantee stable results. When not activated the inflow concentrations specified in Data Group *Boundaries* → *Transport conditions* will be used.

The local bed slope influences the bedload transport magnitude and direction. Different options have been implemented. See [section 8.4.7](#) for details on the formulations that have been implemented.

*Bed slope formulation* Select the bed slope formulation that you want to apply in the simulation. By default the Bagnold formulation is selected.

### Bed load transport

This section lists the parameters associated with the bed slope formulation selected above. See [section 8.4.7](#) for details on the parameters.

### Hiding and exposure formulation

In this section you can select the hiding and exposure formulation. See [section 8.4.3](#) for details on the formulations that have been implemented.

### Multiplication (calibration) factors

*Effect of secondary flow on bed load direction* Calibration factor for the effect of parametrized secondary flow in a 2D model on the bed load transport direction (make sure to switch on the *Secondary flow* process in the *Processes* tab).

*Current related reference concentration factor* Calibration factor for the suspended sediment transport due to currents.

*Current related transport vector factor* Calibration factor for the bedload transport due to currents.

In the case of erosion near a dry beach or bank, the standard scheme will not allow erosion of the adjacent cells, even when a steep scour hole would develop right next to the beach. Therefore a scheme has been implemented, where for each wet cell, if there are dry points adjacent to it; the erosion volume is distributed over the wet cell and the adjacent dry cells.

*Factor for erosion of adjacent dry cells* The distribution is governed by a user-specified *factor for erosion of adjacent dry cells*, which determines the fraction of the erosion to assign (evenly) to the adjacent cells; if this factor equals zero, the standard scheme is used; if this factor equals 1, all erosion that

*HMaxTH*

would occur in the wet cell is assigned to the adjacent dry cells. Maximum water depth in metres up to which the factor for erosion of adjacent dry cells is applied. The applied factor is linearly reduced from the specified maximum value to 0 as the water depth increases to the specified threshold value.

**Domain:**

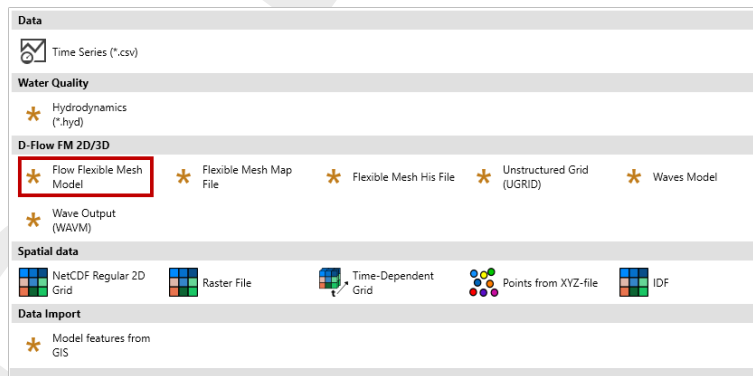
Parameter	Lower limit	Upper limit	Default	Unit
Morphological scale factor	0.0	10000.0	1.0	-
Spin-up interval	0		$\infty$	s
Include sediment concentration on density	yes or no		no	none
Minimum depth for sediment calculation	0.1	10.0	0.1	m
Threshold sediment thickness	0.005	10.0	0.05	m
Update bathymetry during simulation	yes or no		yes	none
Update bed composition during simulation	yes or no		yes	none
Neumann boundaries for mud influx	yes or no		no	none
Neumann boundaries for sand influx	yes or no		yes	none
Bed slope formulation	1	4	2	-
Hiding and exposure formulation	1	5	1	-
Effect of secondary flow	0	$\infty$	0.5	-
Current related reference concentration factor	0	$\infty$	1	-
Current related transport vector magnitude factor	0	$\infty$	1	-
Factor for erosion of adjacent dry cells	0	1	0	-

### 5.3 Save project, MDU file and attribute files

To save your project, navigate the menu ribbons to *File* and click *Save as*. Choose a location, specify a name and click *Save*. Your project will now be saved in a folder called `<name.dsproj_data>` and a `<name.dsproj>` file is written. Within this folder you will find all input ASCII input files of your model, output files of your model (if the model was run using the GUI) and zip folders containing your restart files. Be aware that the output files are stored within a separate folder in which the input files of your model are stored. The output folder on the same level as the folder containing model input files is empty.

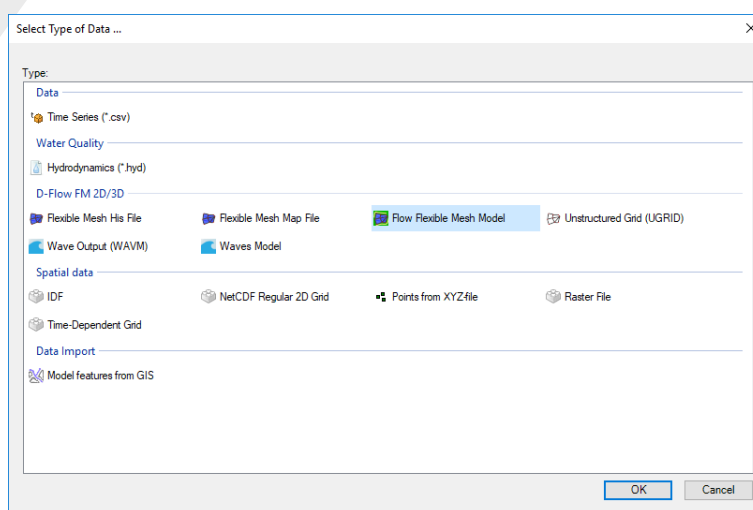
To open a project, navigate the menu ribbons to *File* and click *Open*. Select the `<*.dsproj>`-file of choice and click *Open*.

Importing model or data within a project can be achieved in two ways. In the *Home* ribbon, click *Import* icon to launch a drop-down menu with all the import options as shown in [Figure 5.4](#).



**Figure 5.4:** Model/data import drop-down menu

Alternatively, you can also right mouse click on the name of your project in the *Project* window and select *Import*. The import wizard appears, allowing you to select what you want to import ([Figure 5.5](#)).



**Figure 5.5:** Model/data import wizard

Exporting your model can be achieved in the same fashion as importing your model. All model

input files will be written to the folder you select. Be aware that model files exported to a folder in which other model files with the same names are present will be overwritten.

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## 6 Running a model

We refer to *Running a model* of the D-Flow Flexible Mesh User Manual on the *Start* page.

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## 7 Visualize results

We refer to *Visualize results* of the D-Flow Flexible Mesh User Manual on the *Start* page.

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## 8 Sediment transport and morphology

### 8.1 General formulations

#### 8.1.1 Introduction

The sediment transport and morphology module supports both bedload and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments. For schematisation we distinguish between cohesive suspended load transport (associated with sediment types "clay" and "silt", or "mud") and non-cohesive bedload and suspended load transport (associated with sediment types "sand" and "gravel"). For the latter category, the user may opt for bedload only, or total load transport approach. If the suspended load is known to be negligible (due to sediment diameter, selected sediment transport formula, or analysis of spatial scales of the relevant physical processes), the latter approach is more efficient. A model may contain a mixture of arbitrary number of fractions as computer memory and simulation time allows (the number of sediment fractions transported in suspension is currently limited to 99 in Delft3D-FLOW).

#### 8.1.2 Assumptions

The sediment transport and morphology in D-Morphology is based on the following assumptions:

- ◇ The flow time scale is much larger than the morphological time scales such that a decoupled approach is acceptable.
- ◇ The sediment concentrations are small enough to ignore the volume of sediment in suspension.
- ◇ Sediment can be represented using one or more immutable sediment fractions of the following three types: *clay*, *silt*, *sand* and *gravel*.
- ◇ The behaviour of *clay* (and optional *silt*) fractions is well approximated by suspended load transport only with entrainment and deposition terms.<sup>1</sup>
- ◇ The behaviour of *sand* fractions is well approximated by a combination of suspended and bed load with the suspended load concentration tending to a dynamic equilibrium with the bed composition.
- ◇ The behaviour of bedload fractions is well approximated by bed/total load formulations. The bedload transport rates adapt instantaneously to the forcing conditions (no spatial or temporal relaxation; particle momentum neglected).
- ◇ The bed composition is assumed well mixed over the thickness of the transport/active layer (which is by default the complete thickness of the alluvial substratum, but there is an option to subdivide the substratum into multiple layers – within each layer the bed material is assumed to be well mixed).
- ◇ The volume of sediment transported as bedload is matched by an equivalent volume of water net flowing in the opposite direction; this volume is neglected in the computation of (effective) water fluxes, i.e. discharges.
- ◇ The dominant factor in the interaction of sediment fractions is via the bed composition.

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<sup>1</sup> Mud clasts can't be simulated yet.



### 8.1.3 Suspended transport

Three-dimensional transport of suspended sediment is calculated by solving the three-dimensional advection-diffusion (mass-balance) equation for the suspended sediment:

$$\frac{\partial c^{(\ell)}}{\partial t} + \frac{\partial uc^{(\ell)}}{\partial x} + \frac{\partial vc^{(\ell)}}{\partial y} + \frac{\partial \left( w - w_s^{(\ell)} \right) c^{(\ell)}}{\partial z} + \frac{\partial}{\partial x} \left( \varepsilon_{s,x}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon_{s,y}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} \right) = S^{(\ell)}, \quad (8.1)$$

in 2D this simplifies to

$$\frac{\partial c^{(\ell)}}{\partial t} + \frac{\partial uc^{(\ell)}}{\partial x} + \frac{\partial vc^{(\ell)}}{\partial y} + \frac{\partial}{\partial x} \left( \varepsilon_{s,x}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon_{s,y}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial y} \right) = S^{(\ell)}, \quad (8.2)$$

where:

$c^{(\ell)}$	mass concentration of sediment fraction ( $\ell$ ) [kg/m <sup>3</sup> ]
$\varepsilon_{s,x}^{(\ell)}, \varepsilon_{s,y}^{(\ell)}$ and $\varepsilon_{s,z}^{(\ell)}$	eddy diffusivities of sediment fraction ( $\ell$ ) [m <sup>2</sup> /s]
$S^{(\ell)}$	source and sink term representing the exchange with the bed, i.e. entrainment and deposition [kg/s]
$u, v$ and $w$	flow velocity components [m/s]
$w_s^{(\ell)}$	(hindered) sediment settling velocity of sediment fraction ( $\ell$ ) [m/s]



**Note:** Note that the sediment concentration  $c^{(\ell)}$  in the depth averaged [Equation \(8.2\)](#) should not be interpreted as the depth averaged concentration, but as the concentration that when multiplied by the depth averaged velocity gives the correct depth averaged suspended sediment transport.

The local flow velocities and eddy diffusivities are based on the results of the hydrodynamic computations. The suspended sediment transport is computed largely in the same way as the transport of any other conservative constituent, such as salinity, heat, and constituents. There are, however, a number of important differences between sediment and other constituents, for example, the exchange of sediment between the bed and the flow, and the settling velocity of sediment under the action of gravity. These additional processes for sediment are obviously of critical importance. Other processes such as the effect that sediment has on the density of the fluid-sediment mixture, and hence on turbulence damping, can also be taken into account. In addition, a net flux of sediment from the bed to the flow, or vice versa, results in bed level changes which subsequently influence the hydrodynamic calculations. The formulation of several of these processes (such as, settling velocity, sediment deposition and pick-up) are sediment-type specific, this especially applies for sand and mud. Furthermore, the interaction of sediment fractions is important for many processes, for instance the simultaneous presence of multiple suspended sediment fractions has implications for the calculation of the local hindered settling velocity of any one sediment fraction as well as for the resulting mixture density.

The following sections describe, at a conceptual level, the differences between the suspended transport of sediments and the transport of other conservative constituents. At the same time we discuss some of the differences in general terms and refer for the details of the mathematical formulations to [section 8.2](#) and [section 8.3](#).

**Remarks:**

- ◇ The presence of multiple sediment fractions considerably complicates the calculation of the density of the bed and the availability of a particular class of sediment at the bed. See the sections on sediment interaction ([section 8.4.3](#)) and bed composition models ([section 8.6.6](#)).
- ◇ Small negative sediment concentrations ( $-1 \times 10^{-3} \text{ kg/m}^3$ ) can be found in a computation. These negative concentrations can be suppressed by applying a horizontal Forester filter. However, this can result in a substantially larger computing time. It is suggested to accept small negative concentrations and to apply a Forester filter only when the negative concentrations become unacceptably large.
- ◇ A *vertical* Forester filter applied in a sediment transport computation will not affect the sediments. Since this filter smoothes the vertical profile and thus can have a strong influence on the vertical mixing processes, this vertical filter has been de-activated for sediments.

#### 8.1.4 Effect of sediment on fluid density

D-Flow FM uses an empirical relation, such as [Eckart \(1958\)](#) or [UNESCO \(1981\)](#), to adjust the density of water in order to take into account varying temperature and salinity. For sediment transport this relation is extended to include the density effect of sediment fractions in the fluid mixture. This is achieved by adding (per unit volume) the mass of all sediment fractions, and subtracting the mass of the displaced water. As a mathematical statement this translates as:

$$\rho_{mix}(S, c^{(\ell)}) = \rho_w(S) + \sum_{\ell=1}^{l_{sed}} c^{(\ell)} \left( 1 - \frac{\rho_w(S)}{\rho_s^{(\ell)}} \right) \quad (8.3)$$

where:

$\rho_w(S)$	specific density of water with salinity concentration $S$ [kg/m <sup>3</sup> ]
$S$	salinity concentration [ppt]
$\rho_s^{(\ell)}$	specific density of sediment fraction ( $\ell$ ) [kg/m <sup>3</sup> ]
$l_{sed}$	number of sediment fractions

Horizontal density gradients (now also due to differences in sediment concentrations) can create density currents. Vertical density gradients can also have a significant effect on the amount of vertical turbulent mixing present, as discussed below.

You can include or neglect the effect of sediment on the fluid density by setting the `DENSIN` flag in the morphology input file.

#### Remark:

- ◇ This option is included as it has been found that a secondary effect of including sediment in the density calculations is a reduction of the flow velocity in the lower computational layers (when compared with a standard logarithmic velocity profile) and a consequent reduction in the computed bed shear stress. This reduction in bed shear stress is particularly pronounced when the  $k-\varepsilon$  turbulence closure model is used, and leads to an increase in overall flow velocity and a consequent lowering of the free surface. Our experience shows that this change in the free surface level (even if very slight) can lead to calibration problems when converting an existing 2DH model to 3D if the model is driven using water level boundary conditions. A simple method of circumventing these problems can be achieved by setting `DENSIN = false` which has the effect of preventing the sediment from having any effect on the density of the water/sediment mixture.

### 8.1.5 Sediment settling velocity

The settling velocity  $w_s^{(\ell)}$  for sand and mud are strongly different in formulation; see Sections 8.2.1 and 8.3.1 for details. In high concentration mixtures, the settling velocity of a single particle is reduced due to the presence of other particles. In order to account for this hindered settling effect we follow [Richardson and Zaki \(1954\)](#) and determine the settling velocity in a fluid-sediment mixture as a function of the sediment concentration and the non-hindered settling fall velocity:

$$w_s^{(\ell)} = \left(1 - \frac{C_s^{tot}}{C_{soil}}\right)^5 w_{s,0}^{(\ell)}. \quad (8.4)$$

where  $C_{soil}$  is the reference density (input parameter),  $w_{s,0}$  is the 'basic' sediment fraction specific settling velocity. The total mass concentration  $C_m^{tot}$  is the sum of the mass concentrations of the sediment fractions:

$$C_m^{tot} = \sum_{\ell=1}^{l_{sed}} C_s^{(\ell)}. \quad (8.5)$$

As the fall velocity is now a function of the sediment fractions concentration, this implies that each sediment fraction has a fall velocity which is a function of location and time.

**Remark:**

- ◇ The process of sediment settling is computed with a first-order upwind numerical scheme. While use of the upwind settling formulation does slightly under-predict the mass of sediment settling, the magnitude of this error has been shown to be rather small ([Lesser et al., 2000](#)).

### 8.1.6 Dispersive transport

The eddy diffusivities  $\varepsilon_{s,x}^{(\ell)}$ ,  $\varepsilon_{s,y}^{(\ell)}$  and  $\varepsilon_{s,z}^{(\ell)}$  depend on the flow characteristics (turbulence level, taking into account the effect of high sediment concentrations on damping turbulent exchange processes) and the influence of waves (due to wave induced currents and enhanced bottom shear stresses). D-Flow FM supports four so-called "turbulence closure models":

- 1 Constant coefficient.
- 2 Algebraic eddy viscosity closure model.
- 3  $k$ - $L$  turbulence closure model (only in Delft3D-FLOW).
- 4  $k$ - $\varepsilon$  turbulence closure model.
- 5  $k$ - $\tau$  turbulence closure model ( $\beta$ -functionality; only in D-Flow FM).

The first is a simple constant value which is specified by you. A constant eddy viscosity will lead to parabolic vertical velocity profiles (laminar flow). The other three turbulence closure models are based on the eddy viscosity concept of [Kolmogorov \(1942\)](#) and [Prandtl \(1945\)](#) and offer zero, first, and second order closures for the turbulent kinetic energy ( $k$ ) and for the mixing length ( $L$ ). All three of the more advanced turbulence closure models take into account the effect that a vertical density gradient has on damping the amount of vertical turbulent mixing. See the documentation of the hydrodynamics for a full description of the available turbulence closure models.

The output of a turbulence closure model is the eddy viscosity at each layer interface; from this the vertical sediment mixing coefficient is calculated:

$$\varepsilon_s^{(\ell)} = \beta \varepsilon_f, \quad (8.6)$$



where:

$\varepsilon_s^{(\ell)}$	vertical sediment mixing coefficient for the sediment fraction ( $\ell$ )
$\beta$	non-cohesive sediment: Van Rijn's 'beta' factor or effective 'beta' factor. cohesive sediment fractions and fine sand ( $< 150 \mu\text{m}$ ): 1.0.
$\varepsilon_f$	vertical fluid mixing coefficient calculated by the selected turbulence model.

**Remarks:**

- ◇ For cohesive sediment fractions the extra turbulent mixing due to waves is not yet included in the eddy diffusivity. This is a limitation of the present implementation. See also [section 8.2.10](#).
- ◇ For non-cohesive sediment the effect of waves is accounted for by using a modified or effective 'beta' factor of Van Rijn ( $k$ - $\varepsilon$  model) or by using a separate formula to compute  $\varepsilon_f$  (algebraic or  $k$ - $L$ ) model. See also [section 8.3.2](#).

### 8.1.7 Three-dimensional wave effects



**Note:** Three-dimensional sediment transport is not yet supported in D-Flow FM.

Traditionally wave effects were only incorporated in a depth-averaged manner via a (breaking) wave induced shear stress at the surface, a wave induced mass flux and an increased bed shear stress. Important wave effects such as streaming in the wave boundary layer and wave induced turbulence were not accounted for. The problem of three dimensional wave effects has been studied by [Walstra and Roelvink \(2000\)](#); their main suggestions for improvement are:

- 1 The wave induced mass flux is corrected with the second order Stokes drift.
- 2 The production of turbulent energy associated with wave breaking is incorporated by introducing an extra source term in the kinetic energy and dissipation equations of the  $k$ - $\varepsilon$  turbulence model.
- 3 The production of turbulent energy associated with dissipation in the near-bed wave boundary layer is incorporated by introducing an extra source term in the kinetic energy and dissipation equations of the  $k$ - $\varepsilon$  turbulence model.
- 4 Streaming (a wave induced current in the wave boundary layer directed in the wave propagation direction) is modelled as a time averaged shear stress.

These effects are important when computing the transport of sediment in wave and current situations; see Sections [8.2.13](#) and [8.3.4](#) for full details regarding their effect on cohesive and non-cohesive sediments respectively.

### 8.1.8 Initial and boundary conditions

To solve [Equation \(8.1\)](#) you need to prescribe initial and boundary conditions for each suspended sediment fraction.

**8.1.8.1 Initial condition**

The initial conditions for the sediment fractions are handled in exactly the same manner as those for any other conservative constituent, i.e. you can specify:

- ◇ One global initial concentration for each sediment fraction.
- ◇ Space-varying initial concentrations read from a restart file generated by a previous run.
- ◇ Space-varying initial concentrations read from a user-defined input file.

In these options cohesive and non-cohesive sediment fractions are treated in the same way.

In many practical applications the non-cohesive sediment concentrations adapt very rapidly to equilibrium conditions, so in the case of a cold start where the hydrodynamic model also takes some time to stabilise, a uniform zero concentration for the non-cohesive sediment fractions is usually adequate.

**8.1.8.2 Boundary conditions**

For each of the model boundaries you must prescribe the boundary condition for each sediment fraction. We discuss in short the general type of conditions and refer for the details to the sections to follow.

***Water surface boundary***

The vertical diffusive flux through the free surface is set to zero for all conservative constituents (except heat, which can cross this boundary). This is left unchanged for suspended sediment.

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = 0, \quad \text{at } z = \zeta \quad (8.7)$$

where  $z = \zeta$  is the location of the free surface.

***Bed boundary condition***

The exchange of material in suspension and the bed is modelled by calculating the sediment fluxes from the bottom computational layer to the bed, and vice versa. These fluxes are then applied to the bottom computational layer by means of a sediment source and/or sink term in each computational cell. The calculated fluxes are also applied to the bed in order to update the bed level. The boundary condition at the bed is given by:

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = D^{(\ell)} - E^{(\ell)}, \quad \text{at } z = z_b \quad (8.8)$$

where:

- |              |  |
|--------------|--|
| $D^{(\ell)}$ | sediment deposition rate of sediment fraction $(\ell)$ . |
| $E^{(\ell)}$ | sediment erosion rate of sediment fraction $(\ell)$ .    |

The formulations of  $D^{(\ell)}$  and  $E^{(\ell)}$  strongly differ for cohesive and non-cohesive sediment; for the details you are referred to Sections 8.2.11 and 8.3.4 respectively.

***Open boundaries***

The advection-diffusion equation for the suspended sediment requires a boundary condition at all *inflow* boundaries. Basically there are two options for these boundary conditions:

- ◇ a Dirichlet boundary condition where you specify the concentration at the open boundary, and
- ◇ a Neumann boundary condition where the gradient of the concentration normal to the boundary is specified (here implemented as always being 0). By setting the sediment concentrations at the boundary equal to those just inside model domain, a near-perfectly adapted flow will enter the domain and very little accretion or erosion should be experienced near the model boundaries. For this reason this boundary condition is sometimes also referred to as giving an equilibrium concentration profile (under steady conditions).

Delft3D-FLOW and D-Flow FM differ slightly with respect to the way in which these boundary conditions are to be specified.

Delft3D-FLOW requires you to always explicitly specify concentrations for all open boundaries via the `<*.bcc>` file (i.e. the input for a Dirichlet boundary condition) even if you actually want to make use of Neumann boundary conditions. Zero-gradient Neumann boundary conditions can be applied to sand fractions by setting `NeuBcSand` (previously, `EgmBc`) in the morphology input file to true and to mud fractions by setting `NeuBcMud` to true. Note that in Delft3D-FLOW Neumann boundary conditions can only be applied globally, i.e. to all open boundaries and applies to *all* fractions of the selected sediment type.

D-Flow FM allows you to decide per sediment fraction and per boundary what type of boundary condition you want to apply. This flexibility enables you to specify, for instance, the sediment concentrations at a river inflow while using Neumann conditions along the sea boundaries within the same model. If you specify concentrations for a sediment fraction at a boundary in D-Flow FM then it will apply the Dirichlet boundary condition for that particular sediment fraction at that boundary. If you don't specify concentrations for a sediment fraction at a boundary, the zero-gradient Neumann boundary condition will automatically be applied for that sediment fraction at that open boundary. This is independent of any `NeuBcSand`, `EgmBc` or `NeuBcMud` setting specified in the morphology input file – these keywords are considered obsolete for D-Flow FM.

When explicitly specifying the concentrations at the open boundary (Dirichlet condition) in a 3D model you may choose how the sediment concentration varies over the vertical. You may also choose to specify a “Thatcher-Harleman” return time to approximate the re-entry of material that was transported out of the model after the flow reverses direction by gradually changing from the concentration during outflow to the prescribed boundary condition during inflow. These options are also available for sediment constituents, although they are probably more appropriate for fine, cohesive sediment than for sand-sized particles. For coarser material the Neumann condition is typically preferred, but it doesn't allow you to specify exactly how much sediment enters the model.

The boundary conditions are also applied during *outflow* conditions. When the advective transport is dominant over the dispersive transport, this boundary condition will have little effect. When using the Neumann boundary condition the dispersive term will become zero.

## 8.2 Cohesive sediment

### 8.2.1 Cohesive sediment settling velocity

The settling velocity of clay fractions depends on the degree of flocculation and the total amount of sediment in suspension (hindered settling). For the hindered settling, the reader is referred to [Section 8.2.3](#). Here we continue and elaborate a bit further on the topic of flocculation. It's often too time consuming to model the flocculation in detail using a population balance model, so over the years different approaches have been formulated to approximate the effect that flocculation has on the settling velocity. A number of these approaches are available in our code.

- 1 Approach 1: constant settling velocity, see [Section 8.2.4](#)
- 2 Approach 2: settling velocity depending on environmental conditions, see [Section 8.2.5](#)
- 3 Approach 3a: macro- and microflocs in dynamic equilibrium, see [Section 8.2.6](#)
- 4 Approach 3b: interacting macro- and microflocs, see [Section 8.2.7](#)
- 5 Approach 4: population balance model (not yet available), see [Section 8.2.8](#)

The flocculation feature can be activated by selecting the desired flocculation option via the `FlocModel` keyword and specifying one or more sediment fractions with `SedTyp = clay`. Approach 1 is implemented as a special case of Approach 2. By default Approach 2 is selected. See the next section describing how to work with multiple sources of clay sediments.

### 8.2.2 Simulating multiple clay fractions

In the following, the word 'population' refers to a group of clay fractions that exchange mass due to flocculation and break-up; each fraction within a population represents a specific floc size. The population consists of two fractions for [Manning and Dyer \(2007\)](#) and [Chassagne and Safar \(2020\)](#) namely the micro- and macrofloc sizes. A population balance model such as defined by [Verney \*et al.\* \(2011\)](#) may include many more fractions, say  $N$ . The modeler may decide to use a single population to represent all clay in the model, or to use multiple populations each representing the clay from one source, for instance the clay initially in the bed, or the clay entering the domain via boundary 1, 2, etc. When multiple populations are used, all those populations must use the same representation for flocculation, e.g. they all follow [Manning and Dyer \(2007\)](#) or they all follow [Verney \*et al.\* \(2011\)](#) with an identical number of  $N$  classes. This is necessary because all clay mass interacts towards one overall dynamic equilibrium.

### 8.2.3 Hindered settling

The settling velocity  $w'_s$  per sediment fraction  $i$  as obtained from the settling formula is modified by the hindered settling effect as

$$w_s = w'_s f_{hs} \quad (8.9)$$

where  $f_{hs}$  is determined using [Richardson and Zaki \(1954\)](#) as

$$f_{hs} = \max \left( 0, 1 - \frac{c_{tot}}{c_{soil}} \right)^5 \quad (8.10)$$

where  $c_{tot}$  is the current total sediment concentration [ $\text{kg m}^{-3}$ ], and  $c_{soil}$  is a reference concentration [ $\text{kg m}^{-3}$ ] at which the settling of sediment stops. The hindered settling effect can effectively be switched off by setting  $c_{soil}$  to a very large value.

### 8.2.4 Flocculation Approach 1: constant settling velocity

The most basic approach defines the settling velocity  $w'_s$  [ $\text{m s}^{-1}$ ] as

$$w'_s = w_{s,0} \quad (8.11)$$

where  $w_{s,0}$  is the user specified settling velocity [ $\text{m s}^{-1}$ ]. The settling velocity  $w_{s,0}$  may be different for each sediment fraction  $i$ . To use this approach, apply Approach 2 and set the  $w_{s,\max} = w_{s,0}$  and use the following dimensionless constants  $\alpha_T = 1$  and  $n = 0$ .

**Note:** Although the settling velocity is represented by a constant from the perspective of flocculation, the settling velocity may still vary due to hindered settling as described in [Section 8.2.3](#).



### 8.2.5 Flocculation Approach 2: settling velocity depending on environmental conditions

This approach includes the flocculation effect of salinity, water temperature and concentration as

$$w'_s = w_{s,0} f_S f_T f_c \quad (8.12)$$

where

$$\begin{aligned} f_S &= \frac{1}{2} \left[ a - b \cos\left(\pi \frac{S}{S_{\max}}\right) \right] && \text{flocculation effect of salinity} \\ f_T &= \alpha_T^{T-20} && \text{flocculation effect of temperature} \\ f_c &= \min\left[\left(\frac{c_{\text{clay}}}{c_{\text{cr,fl}}}\right)^n, 1\right] && \text{flocculation effect of concentration} \end{aligned}$$

with

$$a = 1 + \frac{w_{s,\max}}{w_{s,0}} \quad (8.13)$$

$$b = a - 2 \quad (8.14)$$

and  $w_{s,0}$  is the fresh settling velocity [ $\text{m s}^{-1}$ ] at 20 °C,  $S$  is the salinity [ppt],  $S_{\max}$  is the salinity [ppt] at which the settling velocity reaches the maximum value  $w_{s,\max}$  [ $\text{m s}^{-1}$ ],  $T$  is the water temperature [°C],  $c_{\text{clay}}$  is the current total clay concentration [ $\text{kg m}^{-3}$ ],  $c_{\text{cr,fl}}$  is the reference clay concentration for flocculation [ $\text{kg m}^{-3}$ ], and  $\alpha_T$  and  $n$  are dimensionless coefficients specified by the user. All parameters can be specified independently for each sediment fraction  $i$ .

**Note:** The settling velocity  $w'_s$  is further adjusted by hindered settling (see [Section 8.2.3](#)). The combined formula includes two concentration dependent terms: the flocculation term  $f_c$  and the hindered settling term  $f_{\text{hs}}$  that are active in two overlapping concentration ranges. The flocculation term  $f_c$  increases for total clay concentrations  $c_{\text{clay}}$  below  $c_{\text{cr,fl}}$ . The hindered settling term  $f_{\text{hs}}$  decreases for total sediment concentrations  $c_{\text{tot}}$  below  $c_{\text{soil}}$ . Typically, the former term is dominant for lower concentrations whereas the second term becomes dominant at higher concentrations.



### 8.2.6 Flocculation Approach 3a: macro- and microflocs in dynamic equilibrium

This approach conceptually splits the total clay mass into a microfloc fraction and a macrofloc fraction, but the distribution of mass over the macrofloc and microfloc classes is assumed to *always be* at equilibrium. Therefore, we can suffice by simulating only the total clay concentration governed by an effective settling velocity  $w'_s$ . This velocity is based on a weighted average of the settling velocities  $w_{s,\text{macro}}$  and  $w_{s,\text{micro}}$  for macroflocs and microflocs, respectively, using

$$w'_s = w_{s,\text{micro}} + f_{\text{macro}}(w_{s,\text{macro}} - w_{s,\text{micro}}) \quad (8.15)$$

where the equilibrium mass fraction of macroflocs  $f_{\text{macro}}$  depends on the total clay concentration. The individual settling velocities  $w_{s,\text{macro}}$  and  $w_{s,\text{micro}}$  may depend on various environmental conditions. The formulas for these three quantities are given in the next section which describes the approach followed when the distribution of mass over the macrofloc and microfloc classes cannot be assumed to be at equilibrium.

### 8.2.7 Flocculation Approach 3b: interacting macro- and microflocs

This approach explicitly splits the total clay mass into a microfloc fraction and a macrofloc fraction which are typically defined as, respectively, smaller and larger than a threshold diameter of 160  $\mu\text{m}$ . Both floc size fractions are thus explicitly represented individually as variables in the model. The settling velocity of the macrofloc fraction is given by

$$w'_s = w_{s,\text{macro}} \quad (8.16)$$

and the settling velocity of the microfloc fraction is given by

$$w'_s = w_{s,\text{micro}} \quad (8.17)$$

where the formulas for  $w_{s,\text{macro}}$  and  $w_{s,\text{micro}}$  are given below. The distribution of clay mass over the floc sizes is assumed *to tend towards* an equilibrium distribution of  $f_{\text{macro}}$  macroflocs and  $1 - f_{\text{macro}}$  microflocs at a user defined time scale  $T_{\text{floc}}$  [s]. At every time step  $\Delta t$  [s] the concentration  $c_i$  per floc size [ $\text{kg m}^{-3}$ ] is updated *before* the advection-diffusion step as

$$c_i = c_{i,\text{eq}}\alpha + c_{i,0}(1 - \alpha) = c_{i,0} + \alpha(c_{i,\text{eq}} - c_{i,0}) \quad (8.18)$$

where  $c_{i,\text{eq}}$  is the equilibrium concentration per floc size as specified by the formulation [ $\text{kg m}^{-3}$ ] and  $c_{i,0}$  is the corresponding concentration at the end of the previous time step [ $\text{kg m}^{-3}$ ]. In D-Morphology, the relaxation factor  $\alpha = 1 - e^{-\Delta t/T_{\text{relax}}}$  to be more robust in case of small relaxation time scale  $T_{\text{relax}}$  [s] and/or large time step  $\Delta t$ . The D-Water Quality implementation uses first-order approximation with  $\alpha = \Delta t/T_{\text{relax}}$ . The relaxation time scale  $T_{\text{relax}}$  is specified by the user in the input file and may be different for conditions with dominant flocculation  $T_{\text{floc}}$  [s] (macroflocs fraction increasing) or break-up  $T_{\text{break-up}}$  [s] (microflocs fraction increasing). The equilibrium fraction of macroflocs  $f_{\text{macro}}$  depends on the total sediment concentration. The settling velocity differs for the two floc sizes ( $w_{s,\text{macro}}$  and  $w_{s,\text{micro}}$ , respectively) and may depend on various environmental conditions. Two formulations have been implemented for computing  $f_{\text{macro}}$ ,  $w_{s,\text{macro}}$  and  $w_{s,\text{micro}}$ : [Manning and Dyer \(2007\)](#) and [Chassagne and Safar \(2020\)](#).

#### 8.2.7.1 Manning and Dyer (2007)

The equilibrium value  $f_{r,\text{eq}}$  [-] for the ratio of macrofloc mass concentration over microfloc mass concentration  $f_r = \frac{c_{\text{macro}}}{c_{\text{micro}}}$  [-] is given by Equation (4) of [Manning and Dyer \(2007\)](#) as

$$f_{r,\text{eq}} = 0.815 + 3.18 \cdot 10^{-3} \tilde{c}_{\text{clay}} - 0.14 \cdot 10^{-6} \tilde{c}_{\text{clay}}^2 \quad (8.19)$$

where  $\tilde{c}_{\text{clay}}$  (with tilde on the  $c$ ) is the current total clay concentration in  $\text{mg L}^{-1}$  (or  $\text{g m}^{-3}$ ) as opposed to  $c_{\text{clay}}$  (without tilde) in  $\text{kg m}^{-3}$  as used in [Section 8.2.5](#); this concentration is limited in this equation to at most  $100 \text{ kg m}^{-3}$ . The ratio  $f_{r,\text{eq}}$  is converted into an equilibrium macro floc mass fraction  $f_{\text{macro}}$  using

$$f_{\text{macro}} = \frac{f_{r,\text{eq}}}{1 + f_{r,\text{eq}}} \quad (8.20)$$

The settling velocity of macroflocs  $w_{s,\text{macro}}$  [ $\text{m s}^{-1}$ ] is computed using Equations (2a)-(2c) of Manning and Dyer (2007) as

$$w_{s,\text{macro}} = 10^{-3} \cdot \begin{cases} 0.644 + 0.000471\tilde{c}_{\text{clay}} + 9.36\tau_{\text{ss}} - 13.1\tau_{\text{ss}}^2 & \text{if } \tau_{\text{ss}} < 0.65 \\ 3.96 + 0.000346\tilde{c}_{\text{clay}} - 4.38\tau_{\text{ss}} + 1.33\tau_{\text{ss}}^2 & \text{if } 0.65 \leq \tau_{\text{ss}} < 1.45 \\ 1.18 + 0.000302\tilde{c}_{\text{clay}} - 0.491\tau_{\text{ss}} + 0.057\tau_{\text{ss}}^2 & \text{if } 1.45 \leq \tau_{\text{ss}} \end{cases} \quad (8.21)$$

where  $\tau_{\text{ss}}$  is the turbulent shear stress [ $\text{N m}^{-2}$ ]. The settling velocity of microflocs  $w_{s,\text{micro}}$  [ $\text{m s}^{-1}$ ] is computed using Equations (3a) and (3b) of Manning and Dyer (2007) as

$$w_{s,\text{micro}} = 10^{-3} \cdot \begin{cases} 0.244 + 3.25\tau_{\text{ss}} - 3.71\tau_{\text{ss}}^2 & \text{if } \tau_{\text{ss}} < 0.52 \\ 0.65\tau_{\text{ss}}^{-0.541} & \text{if } 0.52 \leq \tau_{\text{ss}} \end{cases} \quad (8.22)$$

What to do when the turbulent shear stress  $\tau_{\text{ss}}$  is not available is described in Section 8.2.9.

### 8.2.7.2 Chassagne and Safar (2020)



**Note:** Chassagne and Safar (2020) distinguish between three particle classes based on particle composition: fine mineral sediment  $m_1$ , flocculated mineral sediment particles  $m_2$  and organic matter  $m_3$ . Here we consider the case with both  $m_1 = 0$  and  $m_3 = 0$  and subdivide the flocculated mineral sediment  $m_2$  into macroflocs and microflocs as described in their paper largely in line with Soulsby *et al.* (2013).

The equilibrium macrofloc fraction  $f_{\text{macro}}$  is given by

$$f_{\text{macro}} = \begin{cases} 0.1 & \text{if } \tilde{c}_{\text{clay}} \leq 1 \\ \min(0.1 + 0.221 \log(\tilde{c}_{\text{clay}}), 1) & \text{if } \tilde{c}_{\text{clay}} > 1 \end{cases} \quad (8.23)$$

where  $\tilde{c}_{\text{clay}}$  is the total clay concentration [ $\text{mg L}^{-1}$ ]. Note that the formulation for  $\tilde{c}_{\text{clay}} > 1$  differs from what Chassagne and Safar (2020) write below their Equation (44). Their formulation is not continuous at  $c_{\text{clay}} = 1174 \text{ mg L}^{-1}$ , therefore, we have decided to stay closer to Equation (12) of Soulsby *et al.* (2013). For the settling velocities we also go back to the original work of Soulsby *et al.* (2013). The final settling velocity formulas reported by Soulsby *et al.* (2013) (and copied by Chassagne and Safar (2020) in Equation (48)) include approximations for the turbulent dissipation  $\varepsilon$  [ $\text{m}^2 \text{s}^{-3}$ ] and the turbulent shear  $\tau_{\text{ss}}$  [ $\text{N m}^{-2}$ ] based on the assumption of a uniform steady flow condition with a logarithmic velocity profile. We exclude those approximation for the formulas reported here, and only approximate the values of  $\varepsilon$  and  $\tau_{\text{ss}}$  using the equations given by Soulsby *et al.* (2013) if those variables are not available. The settling velocity of macroflocs  $w_{s,\text{macro}}$  [ $\text{m s}^{-1}$ ] is computed as

$$w_{s,\text{macro}} = 0.129 \left( \frac{\varepsilon d_{\text{micro}}^4}{\nu^3} \right)^{0.166} g \left( \frac{c_{\text{clay}}}{\rho_w} \right)^{0.22044} \left( \frac{\nu}{\varepsilon} \right)^{1/2} e^{-\left( \frac{\rho_w u_{*,\text{macro}}^2}{\tau_{\text{ss}}} \right)^{0.2315}} \quad (8.24)$$

and the settling velocity of microflocs  $w_{s,\text{micro}}$  [ $\text{m s}^{-1}$ ] is computed as

$$w_{s,\text{micro}} = 0.594 \left( \frac{\varepsilon d_1^4}{\nu^3} \right)^{0.39} g \left( \frac{\nu}{\varepsilon} \right)^{1/2} e^{-\left( \frac{\rho_w u_{*,\text{micro}}^2}{\tau_{\text{ss}}} \right)^{0.33}} \quad (8.25)$$

where  $\rho_w$  is the water density,  $u_{*,\text{macro}}$  is the characteristic shear velocity for macroflocs  $0.067 \text{ m s}^{-1}$ ,  $d_{\text{micro}}$  is the mean microfloc diameter  $100 \mu\text{m}$ ,  $u_{*,\text{micro}}$  is the characteristic shear



velocity for microflocs  $0.025 \text{ m s}^{-1}$ , and  $d_1$  is the mean primary particle diameter  $10 \mu\text{m}$ . What to do when the turbulent shear stress  $\tau_{ss}$  or turbulent dissipation  $\varepsilon$  is not available is described in [Section 8.2.9](#). The denominators  $\varepsilon$  and  $\tau_{ss}$  of the last two terms in Equations [8.24](#) and [8.25](#) are restricted in the software to values larger than  $10^{-12}$ .

### 8.2.8 Flocculation Approach 4: population balance model (multiple interacting floc sizes)

This approach splits the total clay mass into multiple floc sizes, usually more than 2. This option is conceptually based on [Verney et al. \(2011\)](#). Please contact support for the latest status of this option.

### 8.2.9 Missing turbulence quantities

What to do with the settling formulas in case the turbulent shear stress  $\tau_{ss}$  (note that we're using the subscript 'ss' here to avoid confusion with the turbulent eddy time scale  $\tau$  [ $\text{s}^{-1}$ ] of the  $k$ - $\tau$  turbulence model) and turbulent dissipation  $\varepsilon$  are missing?

3D model $k$ - $\varepsilon$ <sup>(a,b)</sup>	$\tau_{ss} = \gamma \rho_w k$ in line with <a href="#">Manning and Dyer (2007)</a> .
3D model $k$ - $\tau$ <sup>(b)</sup>	$\tau_{ss} = \gamma \rho_w k$ and $\varepsilon = k\tau$ .
3D model $k$ - $L$ <sup>(a)</sup>	$\tau_{ss} = \gamma \rho_w k$ and $\varepsilon = c_D \frac{k\sqrt{k}}{L}$ .
3D model algebraic <sup>(a,b)</sup>	linear decrease of $\tau_{ss}$ over the water depth $\tau_{ss} = \tau_b \xi$ and $\varepsilon = u_*^3 \xi / (\kappa z)$ .
2D model <sup>(a,b)</sup>	starting from 3D model algebraic: depth-averaged $\tau_{ss}$ value ( $\tau_{ss} = \frac{1}{2} \tau_b$ ) which equals the value at $h/2$ . For $\varepsilon$ those values do not match, so one has to choose. For consistency the value at $h/2$ is used: $\varepsilon = u_*^3 / (\kappa h)$ .

available in Delft3D-FLOW <sup>(a)</sup> and D-Flow FM <sup>(b)</sup>

where  $z$  is the elevation above the bed [m],  $\xi$  is the dimensionless relative depth given by  $1 - z/h$ ,  $\tau_b$  is the bed shear stress equal to  $\rho_w u_*^2$  [ $\text{kg m}^{-1} \text{s}^{-2}$ ],  $\rho_w$  is the water density [ $\text{kg m}^{-3}$ ],  $u_*$  is the bed shear velocity [ $\text{m s}^{-1}$ ],  $h$  is the water depth [m],  $\kappa$  is the von Kármán constant,  $k$  the turbulent kinetic energy [ $\text{m}^2 \text{s}^{-2}$ ],  $\gamma$  is the Soulsby parameter equal to 3, and  $c_D = c_\mu^{3/4} \approx 0.1643$  with  $c_\mu = 0.09$  ([Rodi, 1984](#)).

### 8.2.10 Cohesive sediment dispersion

The vertical mixing coefficient for sediment is equal to the vertical fluid mixing coefficient calculated by the selected turbulence closure model, i.e.:

$$\varepsilon_s^{(\ell)} = \varepsilon_f, \quad (8.26)$$

where:

$\varepsilon_s^{(\ell)}$	vertical sediment mixing coefficient for sediment fraction ( $\ell$ )
$\varepsilon_f$	vertical fluid mixing coefficient calculated by the selected turbulence closure model



### 8.2.11 Cohesive sediment erosion and deposition

For cohesive sediment fractions the fluxes between the water phase and the bed are calculated *per sediment fraction* with the well-known Partheniades-Krone formulations (Partheniades, 1965):

$$E = M \max \left( 0, \frac{\tau_{cw}}{\tau_{cr,e}} - 1 \right)^n, \quad (8.27)$$

$$D = w_s c_b \Gamma, \quad (8.28)$$

where:

$E$	erosion flux from the bed [ $\text{kg m}^{-2} \text{s}^{-1}$ ]
$M$	user-defined erosion parameter $\text{EroPar}$ [ $\text{kg m}^{-2} \text{s}^{-1}$ ]
$n$	user-defined power for erosion $\text{PowerN}$ , default 1 [-]
$D$	deposition flux [ $\text{kg m}^{-2} \text{s}^{-1}$ ]
$w_s$	fall velocity (including hindered settling) [ $\text{m s}^{-1}$ ]
$c_b$	average sediment concentration $c(\vec{x}, t)$ in the bottommost computational layer of thickness $\Delta z_b$ [ $\text{kg m}^{-3}$ ]
$\Gamma$	dimensionless reduction factor for deposition flux [-]

$$\Gamma = \begin{cases} 1 - \frac{\tau_{cw}}{\tau_{cr,d}} & \text{when } \delta < 0 \\ \delta & \text{when } 0 \leq \delta \leq 1 \end{cases} \quad (8.29)$$

$\tau_{cw}$	where $\delta$ is the user-defined dimensionless deposition efficiency $\text{DepEff}$ . maximum bed shear stress due to current and waves as calculated by the wave-current interaction model selected by the user.
$\tau_{cr,e}$	user-defined critical erosion shear stress $\text{TcrEro}$ [ $\text{N m}^{-2}$ ]
$\tau_{cr,d}$	user-defined critical deposition shear stress $\text{TcrSed}$ [ $\text{N m}^{-2}$ ]

The calculated erosion or deposition flux is applied to the bottommost computational cell of the water column by setting the appropriate sink and source term  $S^{(\ell)}$  for that cell in Equations 8.1 and 8.2. Advection, particle settling, and diffusion are all set to zero at the bed to prevent double counting these fluxes.

$$S^{(\ell)} = E - D \quad (8.30)$$

When the fluff layer is included in the simulation, a second erosion flux is included

$$E_f = \min(M_{f,0}, M_{f,1} m_f) \max(0, \tau_{cw} - \tau_{cr,e,f}) \quad (8.31)$$

where

$E_f$	erosion flux from the fluff layer [ $\text{kg m}^{-2} \text{s}^{-1}$ ]
$m_f$	mass of the fraction in the fluff layer per unit area [ $\text{kg m}^{-2}$ ]
$M_{f,0}$	user-defined zero order erosion parameter $\text{ParFluff0}$ [ $\text{s m}^{-1}$ ]
$M_{f,1}$	user-defined first order erosion parameter $\text{ParFluff1}$ [ $\text{m s kg}^{-1}$ ]
$\tau_{cr,e,f}$	user-defined critical shear stress for erosion of the fluff layer $\text{TcrFluff}$ [ $\text{N m}^{-2}$ ]

The overall deposition flux  $D$  is split into two fluxes  $D_f$  and  $D_b$  to the fluff layer and bed, respectively, via

$$D_f = (1 - \alpha_f) D \quad (8.32)$$

$$D_b = \alpha_f D \quad (8.33)$$

where  $\alpha_f$  is given by the dimensionless fluff layer deposition factor `DepFac`. When the fluff layer is included the source and sink term  $S^{(\ell)}$  for cohesive sediment fractions in Equations 8.1 and 8.2 thus becomes

$$S^{(\ell)} = E + E_f - D_b - D_f \quad (8.34)$$

#### 8.2.12 Interaction of sediment fractions

The following notes hold only in case of multiple sediment fractions. The formulations given in the previous section have been formulated for uniform cohesive sediment beds. However, often the bed will be made up of a range of sediment types and sizes. In such cases the erosion rate will be affected. If the bed stratigraphy is modelled in detail, it may be assumed that the erosion rate is proportional to the availability of the sediment fraction considered in the top-most layer of the bed stratigraphy. On the other hand if the bed stratigraphy is not explicitly included in the model and only the overall characteristics of the local bed composition is known, one must assume either that the bed composition is almost uniform (in which case the erosion rate can again be assumed to be proportional to the bed composition) or that the cohesive sediment fraction considered forms a layer that covers the other sediment fractions (in this case the erosion rate of the cohesive sediment will not be reduced). The former approach is nowadays the default approach for the online-morphology module, but the latter behaviour may be activated by setting the `OldMudFrac` keyword to true in the morphology input file.

##### Remarks:

- ◇ Assuming an erosion rate proportional to the availability of the sediment fraction considered may result in a significant underestimation of the erosion rate if the bed is modelled as a single uniformly mixed layer (default setting) and the mud contents is low.
- ◇ Assuming that the erosion rate is independent of the availability of the sediment fraction considered will lead to an overestimation of the erosion rate. For instance, if the model includes two equal cohesive sediment fractions their total transport rate will be double that of the rate observed in an identical simulation carried out using the total amount of the two sediment fractions in the former simulation.

#### 8.2.13 Influence of waves on cohesive sediment transport

For cohesive sediment fractions the sediment mixing coefficient will still be set following Equation (8.26). This implies that the extra turbulent mixing due to waves will not be included in the suspended sediment transport calculations (for these sediment fractions) except by way of the enhancement of the bed shear stress caused by wave-current interaction, see ?? for details. This is a limitation of the present implementation.

#### 8.2.14 Inclusion of a non-erodible (fixed) layer

A non-erodible or bedrock layer can be included by limiting the amount of sediment available. If the thickness of the sediment layer becomes small then the erosion flux is reduced by a factor  $f_{\text{FIXFAC}}$  as defined in section 8.4.4. This reduction factor is related to the formulations implemented for non-cohesive sediment transport (see Sections 8.3.6 and 8.4.4 for suspended and bedload transport respectively).

#### 8.2.15 Boundary conditions for cohesive sediment

Although it is general good advice to locate the open boundaries sufficiently far away from the area of interest, this is not always possible in long-term simulations. In such cases it is desirable to impose some kind of automatic equilibrium boundary condition instead of manu-

ally prescribing concentrations (Dirichlet boundary condition). This can be realised by means of the zero-gradient Neumann boundary condition which is available for both cohesive and non-cohesive sediment fractions. When such a condition is applied, the flow that enters the model domain will carry the same sediment concentration as computed in the interior of the model. However, mud concentrations are in general more loosely coupled to local morphology than the concentrations of coarser, non-cohesive sediment fractions. Depending on the specific flow conditions, bed level and other parameters, the mud concentrations based on the Neumann boundary condition may therefore still lead to unintended deposition or erosion along the model boundaries. In that case, Dirichlet boundary conditions may be the better option.

The way in which you activate the boundary conditions is described in the *Open boundaries* part of [section 8.1.8.2](#).

### 8.3 Non-cohesive sediment

For the transport of non-cohesive sediment, [Van Rijn et al. \(2000\)](#) approach is followed by default. You can also specify a number of other transport formulations (see [section 8.5](#))

#### 8.3.1 Non-cohesive sediment settling velocity

The settling velocity of a non-cohesive (“sand”) sediment fraction is computed following the method of [Van Rijn \(1993\)](#). The formulation used depends on the diameter of the sediment in suspension:

$$w_{s,0}^{(\ell)} = \begin{cases} \frac{(s^{(\ell)} - 1)gD_s^{(\ell)2}}{18\nu}, & 65 \mu\text{m} < D_s \leq 100 \mu\text{m} \\ \frac{10\nu}{D_s} \left( \sqrt{1 + \frac{0.01(s^{(\ell)} - 1)gD_s^{(\ell)3}}{\nu^2}} - 1 \right), & 100 \mu\text{m} < D_s \leq 1000 \mu\text{m} \\ 1.1\sqrt{(s^{(\ell)} - 1)gD_s^{(\ell)}}, & 1000 \mu\text{m} < D_s \end{cases} \quad (8.35)$$

where:

$s^{(\ell)}$	relative density $\rho_s^{(\ell)} / \rho_w$ of sediment fraction( $\ell$ )
$D_s^{(\ell)}$	representative diameter of sediment fraction ( $\ell$ )
$\nu$	kinematic viscosity coefficient of water [ $\text{m}^2/\text{s}$ ]

$D_s^{(\ell)}$  is the representative diameter of the suspended sediment given by the user-defined sediment diameter `SEDDIA` ( $D_{50}$  of bed material) multiplied by the user-defined factor `FACDSS` (see also remarks). This value of  $D_s^{(\ell)}$  will be overruled if `IOPSUS=1` and the transport formula of [Van Rijn \(1993\)](#) has been selected, see [section 8.5.3](#) for details.

#### Remark:

- ◇ In the case of non-uniform bed material [Van Rijn \(1993\)](#) concluded that, on the basis of measurements,  $D_s^{(\ell)}$  should be in the range of 60 to 100 % of  $D_{50}$  of the bed material. If the bed material is very widely graded (well sorted) consideration should be given to using several sediment fractions to model its behaviour more accurately.

### 8.3.2 Non-cohesive sediment dispersion

The output of a turbulence closure model is the eddy viscosity at each layer interface; from this the vertical sediment mixing coefficient is calculated using the following expressions:

#### 8.3.2.1 Using the algebraic or $k$ - $L$ turbulence model

The  $k$ - $L$  turbulence model is not yet available in D-Flow FM.

##### **Without waves**

If the algebraic or  $k$ - $L$  turbulence model is selected and waves are inactive then the vertical mixing coefficient for sediment is computed from the vertical fluid mixing coefficient calculated by the selected turbulence closure model. For non-cohesive sediment the fluid mixing coefficient is multiplied by Van Rijn's 'beta factor' which is intended to describe the different diffusivity of a fluid 'particle' and a sand grain. Expressed mathematically:

$$\varepsilon_s^{(\ell)} = \beta \varepsilon_f^{(\ell)}, \quad (8.36)$$

where:

$\varepsilon_s^{(\ell)}$	vertical sediment mixing coefficient for sediment fraction ( $\ell$ )
$\beta$	Van Rijn's 'beta' factor for the sediment fraction (see <a href="#">Equation (8.45)</a> )
$\varepsilon_f^{(\ell)}$	vertical fluid mixing coefficient calculated by the selected turbulence closure model

##### **Including waves**

If waves are included in a simulation using the algebraic or  $k$ - $L$  turbulence closure model then the sediment mixing coefficient for non-cohesive sediment fractions is calculated entirely separately from the turbulence closure model, using expressions given by [Van Rijn \(1993\)](#) for both the current-related and wave-related vertical turbulent mixing of sediment.

The current-related mixing is calculated using the 'parabolic-constant' distribution recommended by Van Rijn:

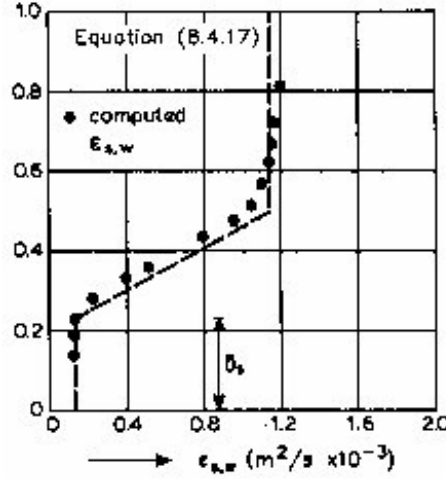
$$\varepsilon_{s,c}^{(\ell)} = \begin{cases} \kappa \beta u_{*,c} z (1 - z/h), & \text{when } z < 0.5h, \\ 0.25 \kappa \beta u_{*,c} h, & \text{when } z \geq 0.5h, \end{cases} \quad (8.37)$$

where:

$\varepsilon_{s,c}^{(\ell)}$	vertical sediment mixing coefficient due to currents (for this sediment fraction)
$u_{*,c}$	current-related bed shear velocity

In the lower half of the water column this expression should produce similar turbulent mixing values to those produced by the algebraic turbulence closure model. The turbulent mixing in the upper half of the water column is generally of little importance to the transport of 'sand' sediment fractions as sediment concentrations in the upper half of the water column are low.

The wave-related mixing is also calculated following [Van Rijn \(1993\)](#). In this case Van Rijn recommends a smoothed step type distribution over the vertical, with a linear transition between the two hinge points, see [Figure 8.1](#).



**Figure 8.1:** Sediment mixing coefficient in non-breaking waves (Source: Van Rijn (1993))

The expressions used to set this distribution are:

$$\varepsilon_{s,w}^{(\ell)} = \begin{cases} \varepsilon_{s,bed}^{(\ell)} = 0.004D_*\delta_s^{(\ell)} & \text{when } z \leq \delta_s^{(\ell)}, \\ \varepsilon_{s,bed}^{(\ell)} + \left( \varepsilon_{s,max}^{(\ell)} - \varepsilon_{s,bed}^{(\ell)} \right) \left( \frac{z - \delta_s^{(\ell)}}{0.5h - \delta_s^{(\ell)}} \right) & \text{when } \delta_s^{(\ell)} < z < 0.5h, \\ \varepsilon_{s,max}^{(\ell)} = \frac{0.035\gamma_{br}hH_s}{T_p} & \text{when } z \geq 0.5h, \end{cases} \quad (8.38)$$

where  $\delta_s^{(\ell)}$  (the thickness of the near-bed sediment mixing layer) is estimated using Van Rijn's formulation, given by:

$$\delta_s^{(\ell)} = \min [0.5, \max \{0.1, \max (5\gamma_{br}\delta_w, 10\gamma_{br}k_{s,w})\}] \quad (8.39)$$

where:

$\delta_w$  thickness of the wave boundary layer:

$$\delta_w = 0.072\hat{A}_\delta \left( \frac{\hat{A}_\delta}{k_{s,w}} \right)^{-0.25} \quad (8.40)$$

$\gamma_{br}$  empirical coefficient related to wave breaking:

$$\gamma_{br} = \begin{cases} 1 + \left( \frac{H_s}{h} - 0.4 \right)^{0.5} & \text{when } \frac{H_s}{h} > 0.4 \\ 1 & \text{when } \frac{H_s}{h} \leq 0.4 \end{cases} \quad (8.41)$$

$k_{s,w}$  wave-related bed roughness (as calculated for suspended sediment transport)

We calculate the total vertical sediment mixing coefficient by following Van Rijn and taking the sum of the squares:

$$\varepsilon_s^{(\ell)} = \sqrt{\varepsilon_{s,c}^{(\ell)2} + \varepsilon_{s,w}^{(\ell)2}}, \quad (8.42)$$

where  $\varepsilon_s$  is the vertical sediment diffusion coefficient used in the suspended sediment transport calculations for this sediment fraction.

### 8.3.2.2 Using the $k\text{-}\varepsilon$ turbulence model

In the case of the  $k\text{-}\varepsilon$  turbulence closure model the vertical sediment mixing coefficient can be calculated directly from the vertical fluid mixing coefficient calculated by the turbulence closure model, using the following expression:

$$\varepsilon_s^{(\ell)} = \beta_{eff}^{(\ell)} \varepsilon_f, \quad (8.43)$$

where:

$\varepsilon_s^{(\ell)}$  vertical sediment mixing coefficient of sediment fraction ( $\ell$ )  
 $\beta_{eff}^{(\ell)}$  the effective Van Rijn's 'beta' factor of sediment fraction ( $\ell$ ) As the beta factor should only be applied to the current-related mixing this is estimated as:

$$\beta_{eff}^{(\ell)} = 1 + (\beta^{(\ell)} - 1) \frac{\tau_c}{\tau_w + \tau_c}, \quad (8.44)$$

$\beta^{(\ell)}$  for non-cohesive sediment fractions  
 Van Rijn's 'beta' factor of the sediment fraction ( $\ell$ ), [Equation \(8.45\)](#)  
 $\tau_c$  bed shear stress due to currents  
 $\tau_w$  bed shear stress due to waves  
 $\varepsilon_f$  vertical fluid mixing coefficient calculated by the  $k\text{-}\varepsilon$  turbulence closure model

Van Rijn's 'beta' factor is calculated from ([Van Rijn, 1984b](#)):

$$\beta^{(\ell)} = 1 + 2 \left( \frac{w_s^{(\ell)}}{u_{*,c}} \right)^2. \quad (8.45)$$

Where  $w_s^{(\ell)}$  is the settling velocity of the non-cohesive sediment fraction, and  $u_{*,c}$  is the local bed shear stress due to currents.

This implies that the value of  $\beta^{(\ell)}$  is space (and time) varying, however it is constant over the depth of the flow. In addition, due to the limited knowledge of the physical processes involved, we follow [Van Rijn \(1993\)](#) and limit  $\beta^{(\ell)}$  to the range  $1 < \beta^{(\ell)} < 1.5$ .

#### Remarks:

- ◇ In a wave and current situation [Van Rijn \(1993\)](#) applies the  $\beta$ -factor to only the current-related turbulent mixing, whereas we apply it to the total turbulent mixing calculated by the selected turbulence closure model. However, little is known about the dependence of the  $\beta$ -factor on flow conditions; this discrepancy is expected to be of little importance in practical situations.
- ◇ The  $k\text{-}\varepsilon$  turbulence closure model has been extended by [Walstra et al. \(2000\)](#) to include the three-dimensional effects of waves. However the effect of wave asymmetry on the bedload transport is not yet included.

### 8.3.2.3 Using the $k\text{-}\tau$ turbulence model

The  $k\text{-}\tau$  model is not available in Delft3D-FLOW; the combination with sediment transport is not yet supported in D-Flow FM.

### 8.3.3 Reference concentration

For non-cohesive sediment (e.g. sand), we follow the method of [Van Rijn \(1993\)](#) for the combined effect of waves and currents. The reference height is given by:

$$a = \min \left[ \max \left\{ \text{AksFac} \cdot k_s, \frac{\Delta_r}{2}, 0.01h \right\}, 0.20h \right], \quad (8.46)$$

where:

$a$	Van Rijn's reference height
$\text{AksFac}$	user-defined proportionality factor (morphology input file)
$k_s$	user-defined current-related effective roughness height (see options below)
$\Delta_r$	wave-induced ripple height, set to a constant value of 0.025 m
$h$	water depth

**Remark:**

- ◇ Van Rijn's reference height  $a$  is limited to a maximum of 20 % of the water depth. This precaution is only likely to come into effect in very shallow areas.

With the keyword `IOPKCW` you have two options to calculate  $k_s$  (and  $k_w$ ):

- ◇  $k_s$  and  $k_w$  specified by you (constant in space).
- ◇  $k_s$  derived from current-related effective roughness height as determined in the D-Flow FM module (spatially varying) and  $k_w = R_{\text{WAVE}} \cdot \Delta_r$ .

#### **Calculation of the reference concentration**

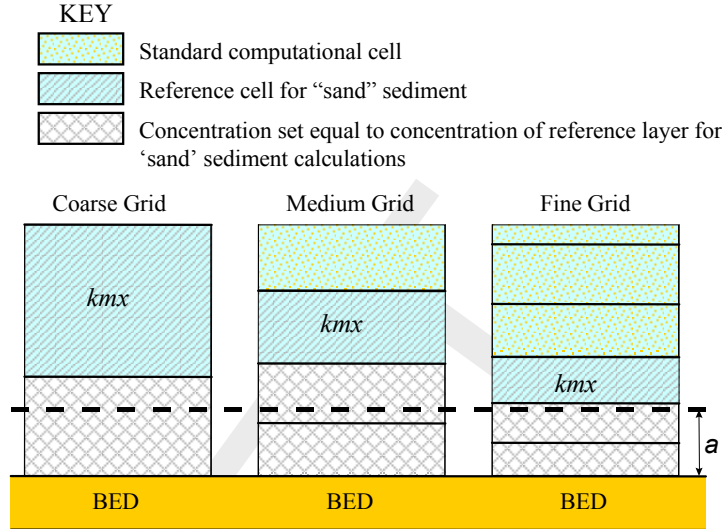
The reference concentration  $c_a$  is calculated directly by the sediment transport formula or it is derived from the suspended sediment transport rate given by the sediment transport formula as  $c_a = S_s/H_u$ . The default transport formula ([Van Rijn, 1993](#)) includes a formula for the reference concentration (see [section 8.5.3](#)). The reference concentration is adjusted proportional to the relative availability of the sediment fraction in the top-layer of the bed (see [section 8.6.6](#) on bed composition models).

**Remark:**

- ◇ The reference concentration and therefore the suspended load can be calibrated using the keyword `Sus` in the morphology input file.

### 8.3.4 Non-cohesive sediment erosion and deposition in 3D

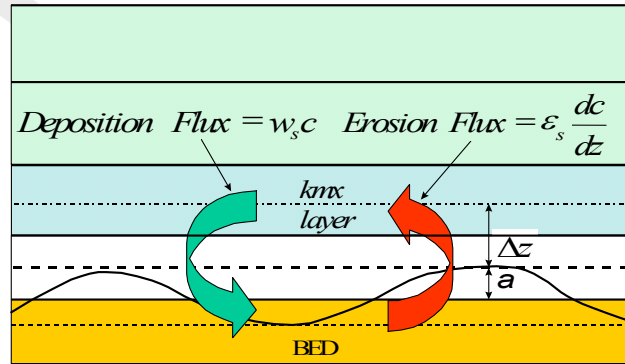
The transfer of sediment between the bed and the flow is modelled using sink and source terms acting on the near-bottom layer that is entirely above Van Rijn's reference height. This layer is identified as the reference layer and for brevity is referred to as the *k<sub>mx</sub>*-layer; see [Figure 8.2](#).



**Figure 8.2:** Selection of the  $kmx$  layer; where  $a$  is Van Rijn's reference height

The sediment concentrations in the layer(s) that lie below the  $kmx$  layer are assumed to rapidly adjust to the same concentration as the reference layer.

Each time-step (Delft3D-FLOW: half time-step) the source and sink terms model the quantity of sediment entering the flow due to upward diffusion from the reference level and the quantity of sediment dropping out of the flow due to sediment settling. A sink term is solved implicitly in the advection-diffusion equation, whereas a source term is solved explicitly. The required sink and source terms for the  $kmx$  layer are calculated as follows.



**Figure 8.3:** Schematic arrangement of flux bottom boundary condition

In order to determine the required sink and source terms for the  $kmx$  layer, the concentration and concentration gradient at the bottom of the  $kmx$  layer need to be approximated. We assume a standard Rouse profile between the reference level  $a$  and the centre of the  $kmx$  layer (see Figure 8.4).

$$c^{(\ell)} = c_a^{(\ell)} \left( \frac{a(h-z)}{z(h-a)} \right)^{A^{(\ell)}}, \quad (8.47)$$

where:

$c^{(\ell)}$  concentration of sediment fraction ( $\ell$ )



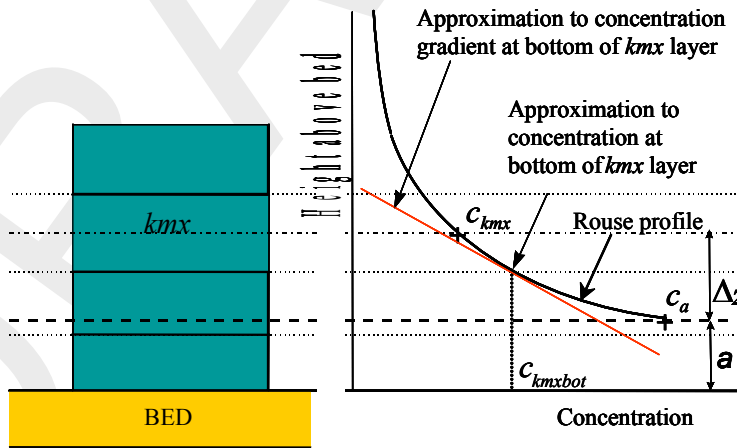
$c_a^{(\ell)}$	reference concentration of sediment fraction ( $\ell$ )
$a$	Van Rijn's reference height
$h$	water depth
$z$	elevation above the bed
$A^{(\ell)}$	Rouse number

As the reference concentration and the concentration in the centre of the  $k_{mx}$  layer  $c_{k_{mx}}$  are known, the exponent  $A^{(\ell)}$  can be determined.

$$c_{k_{mx}}^{(\ell)} = c_a^{(\ell)} \left( \frac{a(h - z_{k_{mx}})}{z_{k_{mx}}(h - a)} \right)^{A^{(\ell)}} \Rightarrow A^{(\ell)} = \frac{\ln \left( \frac{c_{k_{mx}}}{c_a} \right)}{\ln \left( \frac{a(h - z_{k_{mx}})}{z_{k_{mx}}(h - a)} \right)} \quad (8.48)$$

The concentration at the bottom of the  $k_{mx}$  layer is:

$$c_{k_{mx}(bot)}^{(\ell)} = c_a^{(\ell)} \left( \frac{a(h - z_{k_{mx}(bot)})}{z_{k_{mx}(bot)}(h - a)} \right)^{A^{(\ell)}} \quad (8.49)$$



**Figure 8.4:** Approximation of concentration and concentration gradient at bottom of  $k_{mx}$  layer

We express this concentration as a function of the known concentration  $c_{k_{mx}}$  by introducing a correction factor  $\alpha_1$ :

$$c_{k_{mx}(bot)}^{(\ell)} = \alpha_1^{(\ell)} c_{k_{mx}}^{(\ell)} \quad (8.50)$$

The concentration gradient of the Rouse profile is given by:

$$\frac{\partial c^{(\ell)}}{\partial z} = A^{(\ell)} c_a^{(\ell)} \left( \frac{a(h - z)}{z(h - a)} \right)^{A^{(\ell)} - 1} \cdot \left( \frac{-ah}{z^2(h - a)} \right) \quad (8.51)$$

The concentration gradient at the bottom of the  $k_{mx}$  layer is:

$$c'_{k_{mx}(bot)}^{(\ell)} = A^{(\ell)} c_a^{(\ell)} \left( \frac{a(h - z_{k_{mx}(bot)})}{z_{k_{mx}(bot)}(h - a)} \right)^{A^{(\ell)} - 1} \cdot \left( \frac{-ah}{z_{k_{mx}(bot)}^2(h - a)} \right) \quad (8.52)$$

We express this gradient as a function of the known concentrations  $c_a$  and  $c_{kmx}$  by introducing another correction factor  $\alpha_2$ :

$$c'_{kmx(bot)} = \alpha_2^{(\ell)} \left( \frac{c_{kmx}^{(\ell)} - c_a^{(\ell)}}{\Delta z} \right) \quad (8.53)$$

### **Erosive flux due to upward diffusion**

The upward diffusion of sediment through the bottom of the  $kmx$  layer is given by the expression:

$$E^{(\ell)} = \varepsilon_s^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z}, \quad (8.54)$$

where  $\varepsilon_s^{(\ell)}$  and  $\frac{\partial c^{(\ell)}}{\partial z}$  are evaluated at the bottom of the  $kmx$  layer.

We approximate this expression by:

$$E^{(\ell)} \approx \alpha_2^{(\ell)} \varepsilon_s^{(\ell)} \left( \frac{c_a^{(\ell)} - c_{kmx}^{(\ell)}}{\Delta z} \right), \quad (8.55)$$

where:

$\alpha_2^{(\ell)}$	correction factor for sediment concentration
$\varepsilon_s^{(\ell)}$	sediment diffusion coefficient evaluated at the bottom of the $kmx$ cell of sediment fraction( $\ell$ )
$c_a^{(\ell)}$	reference concentration of sediment fraction( $\ell$ )
$c_{kmx}^{(\ell)}$	average concentration of the $kmx$ cell of sediment fraction( $\ell$ )
$\Delta z$	difference in elevation between the centre of the $kmx$ cell and Van Rijn's reference height: $\Delta z = z_{kmx} - a$

The erosion flux is split in a source and sink term:

$$E^{(\ell)} \approx \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_a^{(\ell)}}{\Delta z} - \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_{kmx}^{(\ell)}}{\Delta z}. \quad (8.56)$$

The first of these terms can be evaluated explicitly and is implemented as a sediment source term. The second can only be evaluated implicitly and is implemented as a (positive) sink term. Thus:

$$Source_{erosion}^{(\ell)} = \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_a^{(\ell)}}{\Delta z} \quad (8.57)$$

$$Sink_{erosion}^{(\ell)} = \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_{kmx}^{(\ell)}}{\Delta z} \quad (8.58)$$

### **Deposition flux due to sediment settling**

The settling of sediment through the bottom of the  $kmx$  cell is given by the expression:

$$D^{(\ell)} = w_s^{(\ell)} c_{kmx(bot)}^{(\ell)}, \quad (8.59)$$

where  $w_s^{(\ell)}$  and  $c_{kmx(bot)}^{(\ell)}$  are evaluated at the bottom of the  $kmx$  layer.

We set:

$$c_{kmx(bot)}^{(\ell)} = \alpha_1^{(\ell)} c_{kmx}^{(\ell)}. \quad (8.60)$$

The deposition flux is approximated by:

$$D^{(\ell)} \approx \alpha_1^{(\ell)} c_{kmx}^{(\ell)} w_s^{(\ell)}. \quad (8.61)$$

This results in a simple deposition sink term:

$$Sink_{deposition}^{(\ell)} = \alpha_1^{(\ell)} c_{kmx}^{(\ell)} w_s^{(\ell)}. \quad (8.62)$$

The total source and sink terms is given by:

$$Source^{(\ell)} = \alpha_2^{(\ell)} c_a^{(\ell)} \left( \frac{\varepsilon_s^{(\ell)}}{\Delta z} \right), \quad (8.63)$$

$$Sink^{(\ell)} = \left[ \alpha_2^{(\ell)} \left( \frac{\varepsilon_s^{(\ell)}}{\Delta z} \right) + \alpha_1^{(\ell)} w_s^{(\ell)} \right] c_{kmx}^{(\ell)}. \quad (8.64)$$

These source and sink terms are both guaranteed to be positive. The total net source and sink term in the layer  $kmx$  of Equation 8.1 becomes

$$S^{(\ell)} = \alpha_2^{(\ell)} c_a^{(\ell)} \left( \frac{\varepsilon_s^{(\ell)}}{\Delta z} \right) - \left[ \alpha_2^{(\ell)} \left( \frac{\varepsilon_s^{(\ell)}}{\Delta z} \right) + \alpha_1^{(\ell)} w_s^{(\ell)} \right] c_{kmx}^{(\ell)}. \quad (8.65)$$

and  $S^{(\ell)}$  is equal to 0 in all other layers. Advection, particle settling, and diffusion are all set to zero at the bed to prevent double counting entrainment and deposition.

### 8.3.5 Non-cohesive sediment erosion and deposition in 2D

In 2D the entrainment and deposition terms discussed in the previous section, change into a relaxation towards an equilibrium concentration

$$S^{(\ell)} = \frac{c_{eq}^{(\ell)} - c^{(\ell)}}{T^{(\ell)}} \quad (8.66)$$

where

$c^{(\ell)}$	(depth-averaged) concentration of sediment fraction $(\ell)$ [ $\text{kg m}^{-3}$ ]
$c_{eq}^{(\ell)}$	equilibrium (depth-averaged) concentration of sediment fraction $(\ell)$ based on the selected transport formula [ $\text{kg m}^{-3}$ ]
$S^{(\ell)}$	total net source and sink term [ $\text{kg m}^{-3} \text{s}^{-3}$ ]
$T^{(\ell)}$	relaxation time scale [s] given by the ratio of the settling velocity $w_s^{(\ell)}$ over the water depth $h$ , times a dimensionless time scale $\tilde{T}^{(\ell)}$

$$T^{(\ell)} = \frac{w_s^{(\ell)}}{h} \tilde{T}^{(\ell)} \quad (8.67)$$

Unless noted otherwise, the dimensionless relaxation time scale is based on the work of [Galappatti \(1983\)](#)

$$\tilde{T}^{(\ell)} = \tilde{x} \exp \left[ (1.547 - 20.12\tilde{u}) \tilde{x}^3 + (326.832\tilde{u}^{2.2047} - 0.2) \tilde{x}^2 + (0.1385 \log(\tilde{u}) - 6.4061) \tilde{x} + 0.5467\tilde{u} + 2.1963 \right] \quad (8.68)$$

where

$\tilde{u}$	dimensionless ratio of shear velocity $u_*$ over the depth-averaged velocity magnitude $U$ [-]
$\tilde{x}$	dimensionless ratio of settling velocity $w_s^{(\ell)}$ over the shear velocity $u_*$ [-]

### 8.3.6 Inclusion of a non-erodible (fixed) layer

A non-erodible or bedrock layer can be included by limiting the amount of sediment available. The bedload transport is reduced if the thickness of the sediment layer becomes small (see [section 8.4.4](#)). The same effect has been implemented as a reduction for the entrainment and deposition terms as well as the equilibrium concentration by a factor  $f_{\text{FIXFAC}}$  if erosion is expected to occur.

### 8.3.7 Boundary conditions for non-cohesive sediment

Although it is general good advice to locate the open boundaries sufficiently far away from the area of interest, this is not always possible in long-term simulations. In such cases it is desirable to impose some kind of automatic equilibrium boundary condition instead of manually prescribing concentrations (Dirichlet boundary condition). This can be realised by means of the zero-gradient Neumann boundary condition which is available for both cohesive and non-cohesive sediment fractions. When such a condition is applied, the flow that enters the model domain will carry the same sediment concentration as computed in the interior of the model. This means that the sand load entering through the boundaries will be near-perfectly adapted to the local flow conditions and very little accretion or erosion should be experienced near the model boundaries. This is even the case when the turbulent mixing profile is clearly non-parabolic (advantage over explicitly imposing an “equilibrium” Rouse profile).

The way in which you activate the boundary conditions is described in the *Open boundaries* part of [section 8.1.8.2](#).

## 8.4 Bedload sediment transport of non-cohesive sediment

Bedload (or, for the simpler transport formulae, total load) transport is calculated for all “sand” and “bedload” sediment fractions by broadly according to the following approach: first, the magnitude and direction of the bedload transport at the cell centres is computed using the transport formula selected (See [section 8.5](#)), subsequently the transport rates at the cell interfaces are determined, corrected for bed-slope effect and upwind bed composition and sediment availability.

### 8.4.1 Basic formulation

For simulations including waves the magnitude and direction of the bedload transport on a horizontal bed are calculated using the transport formula selected assuming sufficient sediment and ignoring bed composition except for e.g. hiding and exposure effects on the critical shear stresses. The default sediment transport formula is [Van Rijn \(1993\)](#) as documented in [section 8.5.3](#).

Some of the sediment transport formulae prescribe the bedload transport direction whereas others predict just the magnitude of the sediment transport. In the latter case the initial transport direction will be assumed to be equal to the direction of the characteristic (near-bed) flow direction. In the case of a depth-averaged simulation, the secondary flow/spiral flow intensity  $I_s$  optionally computed by the flow module may be taken into account; the bedload transport direction  $\varphi_\tau$  is given by the following formula:

$$\tan(\varphi_\tau) = \frac{v - \alpha_I \frac{u}{U} I_s}{u + \alpha_I \frac{v}{U} I_s} \quad (8.69)$$

in which

$$\alpha_I = \frac{2}{\kappa^2} E_s \left( 1 - \frac{\sqrt{g}}{\kappa C} \right) \quad (8.70)$$

where:

$g$	gravitational acceleration
$\kappa$	Von Kármán constant
$C$	Chézy roughness
$U$	the depth-averaged velocity
$E_s$	coefficient to be specified by you as <code>Espir</code> keyword in the morphology input file

The default value of  $E_s$  is 0, which implies that the spiral flow effect on the bedload transport direction is not included. The spiral flow effect is of crucial importance in a depth-averaged simulation to get pointbar formation in river bends. This effect is only included for transport formulae that return the bedload transport rate but not its direction, i.e. Engelund & Hansen, Meyer-Peter & Muller, General formula, Van Rijn (1984), Ashida & Michiue and optionally the user-defined formula.

The [Van Rijn \(1993\)](#) formula distinguishes the following transport components that are all treated like bed or total load, i.e. without relaxation effects of an advection diffusion equation:

- ◇ bedload due to currents,  $S_{bc}$
- ◇ bedload due to waves,  $S_{bw}$
- ◇ suspended load due to waves,  $S_{sw}$ .

These three transport components can be calibrated independently by using the respective keywords `Bed`, `BedW` and `SusW` in the morphology input file.

#### 8.4.2 Suspended sediment correction vector

The Suspended sediment correction vector is not implemented yet in D-Flow FM.

The transport of suspended sediment is computed over the entire water column (from  $\sigma = -1$  to  $\sigma = 0$ ). However, for “sand” sediment fractions, Van Rijn regards sediment transported below the reference height  $a$  as belonging to “bedload sediment transport” which is computed separately as it responds almost instantaneously to changing flow conditions and feels the effects of bed slopes. In order to prevent double counting, the suspended sediment fluxes below the reference height  $a$  are derived by means of numerical integration from the suspended transport rates. The opposite of these fluxes are scaled with the upwind sediment availability and subsequently imposed as corrective transport. This suspended load correction is included in the depth-averaged suspended load written to the output files of the program.

### 8.4.3 Interaction of sediment fractions

The following notes hold only in case of multiple sediment fractions. Sediment fractions may interacted in several ways:

- ◇ reference concentrations, erosion rates and sediment transport rates will be reduced proportional to the availability of sediment fraction considered in the bed (less of the fraction available for transport)
- ◇ sediment fractions of different sizes influence each other by means of hiding and exposure: fine sediments hide among coarse sediments and are thereby partly shielded from the main flow while the coarser sediments are more exposed than they would be among other sediments of the same size. This effect is taken into account by increasing the effective critical shear stress for fine sediments while lowering it for coarse sediments. This adjustment is carried out using a multiplicative factor  $\xi$ . The following formulations have been implemented:
  - No hiding and exposure correction ( $\xi = 1$ )
  - Egiazaroff formulation

$$\xi = \left( \frac{{}^{10}\log 19}{{}^{10}\log 19 + {}^{10}\log (D_i/D_m)} \right)^2. \quad (8.71)$$

- Ashida & Michiue formulation

$$\xi = \begin{cases} 0.8429 \frac{D_m}{D_i} & \text{if } D_i/D_m < 0.38889 \\ \left( \frac{{}^{10}\log 19}{{}^{10}\log 19 + {}^{10}\log (D_i/D_m)} \right)^2 & \text{otherwise} \end{cases}. \quad (8.72)$$

- Parker, Klingeman & McLean or Soehngen, Kellermann & Loy formulation

$$\xi = \left( \frac{D_m}{D_i} \right)^\alpha. \quad (8.73)$$

where  $\alpha$  is given by the ASKLHE keyword in the morphology input file.

- Wu, Wang & Jia formulation

$$\varphi^{(\ell)} = \sum_i \eta^{(i)} \frac{D^{(i)}}{D^{(\ell)} - D^{(i)}} \quad (8.74)$$

$$\xi^{(\ell)} = \left( \frac{1 - \varphi^{(\ell)}}{\varphi^{(\ell)}} \right)^m \quad (8.75)$$

where  $m$  is given by the MWWJHE keyword in the morphology input file.

The hiding and exposure effect has been implemented for the following transport formulae containing a critical shear stress: Meyer-Peter & Muller, general formula, Ashida-Michiue and optionally the user-defined formula.

### 8.4.4 Inclusion of a fixed layer

Inclusion of a fixed layer implies that the quantity of sediment at the bed is finite and may, if excessive erosion occurs, become exhausted and be unavailable to supply sediment to suspended and bedload transport modes. In case the bed is covered by bedforms, the troughs of the bedforms will start to expose the non-erodible layer before sediment runs out completely. This results in a gradual reduction of the transport capacity over a certain sediment thickness

indicated by THRESH. This effect is taken into account in the bedload formulations by comparing the thickness of the sediment layer available at the bed with a user-defined threshold value. If the quantity of sediment available is less than the threshold then the magnitude of the calculated bedload transport vector is reduced as follows:

$$S_b'' = f_{\text{FIXFAC}} S_b'', \quad (8.76)$$

where:

$S_b''$	magnitude of the bedload transport vector (before correction for bed slope effects)
$f_{\text{FIXFAC}}$	upwind fixed layer proximity factor: $f_{\text{FIXFAC}} = \frac{\text{DPSSED}}{\text{THRESH}}$ , limited to the range $0 \leq f_{\text{FIXFAC}} \leq 1$ .
DPSSED	depth of sediment available at the bed
THRESH	user-defined erosion threshold

The equilibrium suspended load concentration in the sediment pickup term is reduced by the same fixed layer proximity factor (in this case of course the local value and not some upwind value is used since suspended sediment pickup has no associated horizontal direction).

In effect, because of the upwind approach used to transfer the bedload transport components to the velocity points, this method limits the sediment that can leave a computational cell, if the quantity of the sediment at the bed is limited. One implication of the use of this rather simple approach is that a finite (although always less than the user-defined threshold) thickness of sediment is required at the bed if a non-zero magnitude of the bedload transport vector is required.

#### Remarks:

- ◇ Areas may be initially specified as containing zero bottom sediment if non-erodible areas are required. It is likely that these areas will accrete a little sediment in order to allow an equilibrium bedload transport pattern to develop.
- ◇ This effect has also been included for cohesive and non cohesive suspended sediment as indicated in [section 8.2](#) and [section 8.3.6](#).

### 8.4.5 Calculation of bedload transport at open boundaries

At open boundaries the user may either prescribe the bed level development or the bedload transport rates. In the latter case the bedload transport rates are known from the model input, whereas in the former case the effective bedload transport rates at the boundary could be derived from the mass balance at the open boundary point. The bed level boundary condition is imposed at the same location where a water level boundary condition is imposed, that is at the grid cell just outside the model domain. A consequence of this approach is that the bed level at the first grid cell inside the model domain will not exactly behave as you imposed, but in general it will follow the imposed behaviour closely. In case of multiple sediment fractions, a boundary condition for the bed composition is also needed at inflow boundaries.

### 8.4.6 Bedload transport at velocity points

As the control volume for bed level change calculations is centred on the water level points, see [Figure 8.5](#), the bedload transport vector components are actually required at the velocity points, rather than at the water level points where  $S_x$  and  $S_y$  are calculated. By default, we use a simple “upwind” numerical scheme to set the bedload transport components at the velocity points as this ensures that the bed will remain stable. For each active velocity point the upwind direction is determined by summing the bedload transport components at the water level points on either side of the velocity point and taking the upwind *direction* relative to

the resulting net transport direction. The bedload transport component at the velocity point is then set equal to the component computed at the water level point immediately "upwind" (see Figure 8.5). In the example shown in Figure 8.5 the bedload transport normal component on the velocity point,  $S_{u,n}^1$ , is set equal to  $S_n^1$ , where  $S_n^1$  is the projection of bedload flux vector at point 1 in the normal direction of the corresponding velocity face. Based on the same method, the component  $S_{u,n}^2$  is set equal to  $S_n^2$ . It is possible to switch from upwind to central approach by setting the `UpwindBedload` keyword in the morphology input file to false; although the central approach is more accurate, it is less stable (less damping).

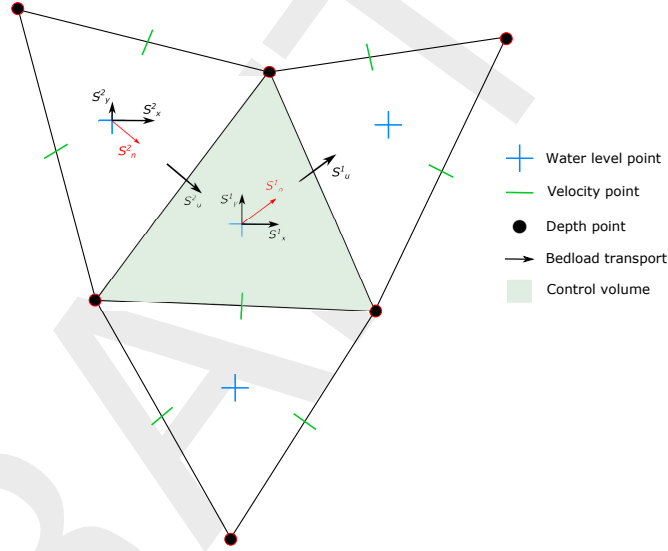


Figure 8.5: Setting of bedload transport components at velocity points

#### 8.4.7 Adjustment of bedload transport for bed-slope effects

Bedload transport is affected by bed level gradients. Two bed slope directions are distinguished: the slope in the initial direction of the transport (referred to as the longitudinal bed slope) and the slope in the direction perpendicular to that (referred to as the transverse bed slope). The longitudinal bed slope results in a change in the sediment transport rate as given by:

$$\vec{S}'_b = \alpha_s \vec{S}'', \quad (8.77)$$

or, in vector component form:

$$S'_{b,x} = \alpha_s S''_{b,x}, \quad (8.78)$$

$$S'_{b,y} = \alpha_s S''_{b,y}, \quad (8.79)$$

whereas the primary effect of the transverse bed slope is a change in transport towards the downslope direction (this may be accomplished by either a pure rotation of the transport vector or by adding a transverse transport component). You may choose one of the following formulations for these effects.

- 1 no effect of bed slope on bedload transport
- 2 [Bagnold \(1966\)](#) for longitudinal slope and [Ikeda \(1982, 1988\)](#) as presented by [Van Rijn \(1993\)](#) for transverse slopes. This is the default option for the bedload transport of all sediment transport formulae. In this case  $\alpha_s$  is given by

$$\alpha_s = 1 + \alpha_{bs} \left( \frac{\tan(\phi)}{\cos\left(\tan^{-1}\left(\frac{\partial z}{\partial s}\right)\right) \left(\tan(\phi) + \frac{\partial z}{\partial s}\right)} - 1 \right), \quad (8.80)$$



where  $\alpha_{bs}$  is a user-defined tuning parameter, ALFABS keyword in the morphology input file (default = 1.0). An additional bedload transport vector is subsequently calculated, perpendicular to the main bedload transport vector. The magnitude of this vector is calculated using a formulation based on the work of Ikeda (1982, 1988) as presented by Van Rijn (1993). Van Rijn's equation (7.2.52) is modified to Equation (8.81) by setting the reference co-ordinates  $s$  and  $n$  aligned with and perpendicular to the local characteristic flow direction respectively. This implies that there is no flow in the  $n$  direction: i.e.  $u_{b,n} = 0$ :

$$S_{b,n} = |S'_b| \alpha_{bn} \frac{u_{b,cr}}{|\vec{u}_b|} \frac{\partial z_b}{\partial n}, \quad (8.81)$$

where:

$S_{b,n}$	additional bedload transport vector. The direction of this vector is normal to the unadjusted bedload transport vector, in the down slope direction
$ S'_b $	magnitude of the unadjusted bedload transport vector (adjusted for longitudinal bed slope only): $ S'_b  = \sqrt{(S'_{b,x})^2 + (S'_{b,y})^2}$ .
$\alpha_{bn}$	user-defined coefficient, ALFABN (default = 1.5)
$u_{b,cr}$	critical (threshold) near-bed fluid velocity
$\vec{u}_b$	near-bed fluid velocity vector
$\frac{\partial z_b}{\partial n}$	bed slope in the direction normal to the unadjusted bedload transport vector

To evaluate Equation (8.81) we substitute:

$$\frac{u_{b,cr}}{|\vec{u}_b|} = \sqrt{\frac{\tau_{b,cr}}{|\vec{\tau}_b|}}, \quad (8.82)$$

where:

$\tau_{b,cr}$	critical bed shear stress
$\vec{\tau}_b$	bed shear stress due to current and waves: $\vec{\tau}_b = \mu_c \vec{\tau}_{b,cw} + \mu_w \vec{\tau}_{b,w}$ .

resulting in:

$$S_{b,n} = |S'_b| f_{norm}, \quad (8.83)$$

where:

$$f_{norm} = \alpha_{bn} \sqrt{\frac{\tau_{b,cr}}{|\vec{\tau}_b|}} \frac{\partial z_b}{\partial n}. \quad (8.84)$$

The two components of this vector are then added to the two components of the bedload transport vector as follows:

$$\begin{aligned} S_{b,x} &= S'_{b,x} - S'_{b,y} f_{norm} \\ S_{b,y} &= S'_{b,y} + S'_{b,x} f_{norm} \end{aligned} \quad (8.85)$$

where  $S_{b,x}$  and  $S_{b,y}$  are the components of the required bedload transport vector, calculated at the water level points

- 3 Koch and Flokstra (1980) as extended by Talmon *et al.* (1995). In this case  $\alpha_s$  is given by

$$\alpha_s = 1 - \alpha_{bs} \frac{\partial z}{\partial s}, \quad (8.86)$$

where  $\alpha_{bs}$  is a user-defined tuning parameter, ALFABS keyword in the morphology input file (default = 1.0). The direction of the bedload is adjusted according to the following formulation:

$$\tan(\varphi_s) = \frac{\sin(\varphi_\tau) + \frac{1}{f(\theta)} \frac{\partial z_b}{\partial y}}{\cos(\varphi_\tau) + \frac{1}{f(\theta)} \frac{\partial z_b}{\partial x}}, \quad (8.87)$$

in which  $\varphi_\tau$  is the original direction of the sediment transport and  $\varphi_s$  is the final direction and where  $f(\theta)$  equals:

$$f(\theta) = A_{sh} \theta_i^{B_{sh}} \left( \frac{D_i}{H} \right)^{C_{sh}} \left( \frac{D_i}{D_m} \right)^{D_{sh}}, \quad (8.88)$$

where  $A_{sh}$ ,  $B_{sh}$ ,  $C_{sh}$  and  $D_{sh}$  are tuning coefficients specified by you in the morphology input file as keywords `Ashld`, `Bshld`, `Cshld` and `Dshld`.

- 4 **Parker and Andrews (1985)**. The same formulae for  $\alpha_s$  and  $\varphi_s$  hold as in the previous case except for  $f(\theta)$  which now equals:

$$f(\theta) = \frac{c_L}{1 + \mu c_L} \sqrt{\frac{\theta}{\max\left(\frac{1}{10}\theta, \xi \theta_{cr}\right)}}, \quad (8.89)$$

where Coulomb friction parameter  $c_L$ , lift-drag ratio  $\mu$  and critical shields parameter  $\theta_{cr}$  should be specified by you in the morphology input file as keywords `CoulFri`, `FlFdRat` and `ThetaCr`. Note that this formula includes the hiding and exposure factor  $\xi$ .

This completes the calculation of the bedload transport field. The transports at the velocity points are then stored for use in the computation of bed level changes, as described in the [section 8.6](#). In all cases the bed slope has been defined as follows.

### **Longitudinal bed slope**

This bed slope is calculated as:

$$\frac{\partial z_b}{\partial s} = \frac{\partial z_{(u)}}{\partial x} \frac{S''_{b,x}}{|S''_b|} + \frac{\partial z_{(v)}}{\partial y} \frac{S''_{b,y}}{|S''_b|}, \quad (8.90)$$

$$\left( \frac{\partial z_b}{\partial s} \right)_{\max} = 0.9 \tan(\phi), \quad (8.91)$$

where:

$\frac{\partial z_b}{\partial s}$	bed slope in the direction of bedload transport
$\frac{\partial z_{(u)}}{\partial x}$	bed slope in the positive $x$ -direction
$\frac{\partial z_{(v)}}{\partial y}$	bed slope in the positive $y$ -direction
$\phi$	internal angle of friction of bed material (assumed to be $30^\circ$ )

### **Remarks:**

- ◇  $z_b$  is the depth down to the bed from a reference height (positive down), a downward bed slope returns a positive value).
- ◇ The bed slope is calculated at the velocity points as these are the locations at which the bedload transport vector components will finally be applied.

### **Transverse bed slope**

This bed slope is calculated as:

$$\frac{\partial z_b}{\partial n} = -\frac{\partial z_{(u)}}{\partial x} \frac{S''_{b,y}}{|S''_b|} + \frac{\partial z_{(v)}}{\partial y} \frac{S''_{b,x}}{|S''_b|}. \quad (8.92)$$

**Table 8.1:** Transport relations available in D-Flow FM.

Formula	Bedload	Waves
8.5.1, Van Rijn (2007)	Bedload + suspended	Yes
8.5.2, SANTOSS	Bedload + suspended	Yes
8.5.3, Van Rijn (1993)	Bedload + suspended	Yes
8.5.4, Engelund-Hansen (1967)	Total transport	No
8.5.5, Meyer-Peter-Muller (1948)	Total transport	No
8.5.6, General formula	Total transport	No
8.5.7, Bijker (1971)	Bedload + suspended	Yes
8.5.8, Van Rijn (1984)	Bedload + suspended	No
8.5.9, Soulsby/Van Rijn	Bedload + suspended	Yes
8.5.10, Soulsby	Bedload + suspended	Yes
8.5.11, Ashida-Michiue (1974)	Total transport	No
8.5.12, Wilcock-Crowe (2003)	Bedload	No
8.5.13, Gaeuman et al. (2009) laboratory calibration	Bedload	No
8.5.14, Gaeuman et al. (2009) Trinity River calibration	Bedload	No
8.5.15, Van Thiel / Van Rijn	Bedload + suspended	Yes
8.5.16, Soulsby / Van Rijn, XBeach flavour	Bedload + suspended	Yes

## 8.5 Transport formulations for non-cohesive sediment

A number of standard sediment transport formulations for non-cohesive sediment are available by default. [Table 8.1](#) gives a summary of the available formulae.

Additionally, you can implement your own sediment transport formula in a shared library (<dll> or <so>) and call it from D-Flow FM. See [section A.3](#) for this option. Now, let us continue with a general description of the sediment transport formulae included by default.

### 8.5.1 Van Rijn (2007)

[Van Rijn \(2007a,b\)](#) describe the TRANSPORT2004 sediment transport model for clay, silt, and sand. At this moment, it can only be used for sediment fractions labelled as 'sand' although doing so does not impose a restriction on the grain size. The conceptual model distinguishes between sediment transport below the reference height  $a$ , which is treated as bedload transport, and that above the reference height, which is treated as suspended-load. The exchange of sediment between the bed and the water column happens via a boundary condition imposed at the reference height.

#### 8.5.1.1 Reference concentration

The volumetric reference concentration is calculated as:

$$c_a = \max(c_{a,\max}, 0.015 f_{\text{silt}} \frac{D_{50}}{a} \frac{T_a^{1.5}}{D_*^{0.3}}) \quad (8.93)$$

where:

$a$  reference height [m] given by

$$a = \frac{k_{s,c}}{30} + \max(0.01, \frac{1}{2}k_{s,c,r}, \frac{1}{2}k_{s,w,r}) \quad (8.94)$$

where  $k_{s,c,w}$  and  $k_{s,c,r}$  are both set equal to the ripple roughness height, and  $k_{s,c}$  is the Nikuradse bed roughness height.

$c_a$  volumetric concentration at reference height  $a$  [m<sup>3</sup> rock/m<sup>3</sup> fluid]

$c_{a,\max}$  maximum volumetric concentration at reference height  $a$ , specified as CaMax in the mor-file [m<sup>3</sup> rock/m<sup>3</sup> fluid]

$f_{\text{silt}}$  dimensionless multiplication factor for silt fractions  $\max(1, D_{\text{sand}}/D_{50})$  [-]

This concentration is subsequently multiplied by the specific density  $\rho_s$  of the considered sediment fraction to arrive at the mass concentration at the reference height. In order to evaluate this expression the following quantities must be calculated:

$D_*$  non-dimensional particle diameter [-]

$$D_* = D_{50} \left[ \frac{(s-1)g}{\nu^2} \right]^{1/3} \quad (8.95)$$

$T_a$  non-dimensional bed-shear stress [-]

$$T_a = \frac{\tau'_{b,cw} - f_s \tau'_{cr}}{f_s \tau'_{cr}} \quad (8.96)$$

$\tau'_{b,cw}$  bed shear stress due to current in the presence of waves [N/m<sup>2</sup>]

$$\tau'_{b,cw} = \alpha_{cw} \mu_c \tau_{b,c} + \mu_w \tau_{b,w} \quad (8.97)$$

$\alpha_{cw}$  wave-current interaction factor [-]

$$\alpha_{cw} = \max(0, \min(T_1 T_2, 1)) \quad (8.98)$$

$$T_1 = \left( \frac{10 \log(30 \delta_m / r_a)}{10 \log(30 \delta_m / r_c)} \right)^2 \quad (8.99)$$

$$T_2 = \left( \frac{10 \log(30 h / r_c) - 1}{10 \log(30 h / r_a) - 1} \right)^2 \quad (8.100)$$

$\mu_c$  efficiency factor current [-]

$$\mu_c = \frac{f'_c}{f_c} \quad (8.101)$$

$f'_c$  gain related friction factor [-]

$$f'_c = 0.24 \left[ 10 \log \left( \frac{12h}{D_{90}} \right) \right]^{-2} \quad (8.102)$$

$f_c$  total current-related friction factor [-]

$$f_c = 0.24 \left[ 10 \log \left( \frac{12h}{k_s} \right) \right]^{-2} \quad (8.103)$$

$\tau_{b,c}$  bed shear stress due to currents [N/m<sup>2</sup>]

$$\tau_{b,c} = \frac{1}{8} \rho_w f_c u_{2D}^2 \quad (8.104)$$

$\mu_w$  wave-related efficiency factor [-]

$$\mu_w = \max(0.14, \min(0.7/D_*, 0.35)) \quad (8.105)$$

$\tau_{b,w}$  bed shear stress due to waves [N/m<sup>2</sup>]

$$\tau_{b,w} = \frac{1}{4} \rho_w f_w (\hat{U}_\delta)^2 \quad (8.106)$$

$f_w$  total wave-related friction factor [-] ( $\equiv$  Equations 8.188, 8.227 and 8.268):

$$f_w = \exp \left[ -6 + 5.2 \left( \frac{A_\delta}{k_{s,w}} \right)^{-0.19} \right] \quad (8.107)$$

$\hat{U}_\delta$  representative peak orbital velocity for reference concentration [m/s]

$$\hat{U}_\delta = \left( \frac{1}{2} u_{\text{on}}^3 + \frac{1}{2} u_{\text{off}}^3 \right)^{1/3} \quad (8.108)$$

$A_\delta$  peak orbital excursion at edge of wave boundary layer [m] according linear wave theory

$$A_\delta = \frac{H_s}{2 \sinh(\max(10^{-12}, \frac{2\pi h}{\lambda}))} \quad (8.109)$$

### 8.5.1.2 Bedload transport rate due to currents

The total bedload transport vector  $\vec{S}_{b,t}$  is split into a current related part  $\vec{S}_{b,c}$  and a waves related part  $\vec{S}_{b,w}$ . Here we focus on computing the former. The transport vector due to currents is computed as the average of the instantaneous total transport rates  $S_b(t)$  over a wave period subdivided into  $N_T$  sections weighted by the ratio of the flow velocity due to currents  $\vec{u}_{a,c}$  over the magnitude of the *total* instantaneous velocity due to both currents *and* waves  $U_{a,t}(t)$  both defined at the reference height  $a$

$$\vec{S}_{b,c} = \frac{1}{N_T} \sum_{t=1}^{N_T} \frac{\vec{u}_{a,c}}{U_{a,t}(t)} S_b(t) \quad (8.110)$$

with  $S_b(t)$  the intrawave instantaneous bedload transport rate given by

$$S_b(t) = \frac{1}{2} D_{50} \rho_s \frac{f_{\text{silt}}}{D_*^{0.3}} u'_*(t) T'(t) \quad (8.111)$$

where

$u'_*$  the intrawave instantaneous shear velocity

$$u'_*(t) = \sqrt{\tau'(t)/\rho_w} \quad (8.112)$$

$T'(t)$  the intrawave instantaneous dimensionless excess shear parameter

$$T'(t) = \max(10^{-3}, \frac{\tau'(t) - r_2 f_s \tau_{cr}}{f_s \tau_{cr}}) \quad (8.113)$$

where

$$r_2 = 0.8 + 0.2 \left( \frac{\tau'(t)}{f_s \tau_{cr}} - 0.8 \right) \quad (8.114)$$

is clipped to values between 0.8 and 1.

$\tau'(t)$  the intrawave instantaneous bed shear stress

$$\tau'(t) = \frac{1}{2} \rho_w f'_{c,w} U_{a,t}(t)^2 \quad (8.115)$$

with

$$f'_{c,w} = a_{cw} \beta_{cw} f'_c + (1 - a_{cw}) f_w \quad (8.116)$$

where

$$a_{cw} = \frac{U_{2D}}{\max(10^{-6}, U_\delta + U_{2D})} \quad (8.117)$$

and

$$\beta_{cw} = \frac{1}{4} \left[ \frac{-1 + \ln(30h/r_c)}{\ln(30a/r_c)} \right]^2 \quad (8.118)$$

with

$U_\delta$  near-bed peak orbital velocity [m/s] according linear wave theory

$$U_\delta = \frac{2\pi}{T_p A_\delta} \quad (8.119)$$

where  $A_\delta$  is given by [Equation \(8.109\)](#)

$U_{2D}$  effective depth averaged flow velocity [m/s]

$U_{a,t}(t)$  the magnitude of the total instantaneous velocity given at the reference height  $a$  by

$$U_{a,t}(t) = |\vec{u}_{a,t}| = \sqrt{u_{a,t}(t)^2 + v_{a,t}(t)^2} \quad (8.120)$$

with  $\vec{u}_{a,t} = (u_{a,t}, v_{a,t})$  equal to  $\vec{u}_{a,c} = (u_{a,c}, v_{a,c})$  if  $U_\delta = 0$  or  $T_p < 1$ , and otherwise given by

$$u_{a,t}(t) = u'_{b,w}(t) \cos(\phi_w) + u_{a,c} \quad (8.121)$$

$$v_{a,t}(t) = u'_{b,w}(t) \sin(\phi_w) + v_{a,c} \quad (8.122)$$

where time varying amplitude of the oscillatory velocity due to waves  $u'_{b,w}(t)$  is given by either [Equation \(8.139\)](#) or [Equation \(8.151\)](#) depending on the selected wave form, optionally modified by including a phase lead  $\phi_L$  for bed shear stress of ([Nielsen, 1992](#))

$$u'_{b,w}(t) = u_{b,w}(t) \cos(\phi_L) + \frac{u_{a,w}(t + dt) - u_{a,w}(t - dt)}{2dt} \frac{T_p}{2\pi} \sin(\phi_L) \quad (8.123)$$

and the effective velocity due to currents  $\vec{u}_{a,c} = (u_{a,c}, v_{a,c})$  at the reference height  $a$ , which is constant at the intrawave time scale, is derived from the depth averaged velocity magnitude  $U_{2D}$  by first shifting that velocity to  $\delta_m$

$$U_{\delta_m,c} = U_{2D} \frac{\ln(30\delta_m/r_a)}{\ln(30h/r_a) - 1} \quad (8.124)$$

and subsequently to the reference height  $a$

$$U_{a,c} = U_{\delta_m,c} \frac{\ln(30a/r_c)}{\ln(30\delta_m/r_c)} \quad (8.125)$$

unless  $30\delta_m < r_a$  in which case  $U_{a,c} = 0$ , and subsequently using that velocity magnitude in the direction of the simulated flow velocity that corresponds best with the reference height  $a$  (which corresponds to the depth averaged flow direction in a 2D model, but depends on the layer distribution in a 3D model).

The default wave velocity asymmetry is based on [Isobe and Horikawa \(1982\)](#) ( $W_{\text{form}} = 1$ ); this may optionally be switched to the description by [Boechat Albernaz et al. \(2019\)](#) ( $W_{\text{form}} = 2$ ) as described in Sections 8.5.1.5 and 8.5.1.6 respectively.

### 8.5.1.3 Bedload transport rate due to waves

The bedload transport vector due to waves  $\vec{S}_{b,w}$  is obtained by subtracting the bedload vector due to currents  $\vec{S}_{b,c}$  (computed by [Equation \(8.110\)](#)) from the total bedload transport vector  $\vec{S}_{b,t}$ , i.e.

$$\vec{S}_{b,w} = \vec{S}_{b,t} - \vec{S}_{b,c} \quad (8.126)$$

where the total bedload transport vector is computed as

$$\vec{S}_{b,t} = \frac{1}{N_T} \sum_{t=1}^{N_T} \frac{\vec{u}_{b,t}(t)}{U(t)} S_b(t) \quad (8.127)$$

See the previous section for a definition of a terms.

### 8.5.1.4 Suspended load transport rate due to waves

The suspended load transport vector due to the asymmetric oscillatory wave motion  $\vec{S}_{s,w}$  is obtained by multiplying the mean concentration  $c_{sl}$  in the suspension layer by the net flow velocity due to wave asymmetry  $\vec{u}_a$  for that layer

$$\vec{S}_{s,w} = c_{sl} \vec{u}_a \quad (8.128)$$

where the velocity vector  $\vec{u}_a = (u_a, v_a)$  is defined as

$$u_a = U_a \cos(\phi_w) \quad (8.129)$$

$$v_a = U_a \sin(\phi_w) \quad (8.130)$$

where the magnitude  $U_a$  of the net flow due to the velocity asymmetry is given by

$$U_a = 0.1p_2 \frac{u_{\text{on}}^4 - u_{\text{off}}^4}{u_{\text{on}}^3 + u_{\text{off}}^3} \quad (8.131)$$

if the effective velocity

$$v_{\text{eff}} = \sqrt{U_{2D}^2 + u_{\text{on}}^2} - v_{cr} \quad (8.132)$$

is larger than  $\varepsilon = 10^{-6}$ ; otherwise  $\vec{S}_{s,w} = 0$ . In these equations,  $u_{\text{on}}$  and  $u_{\text{off}}$  depend on the selected wave form (see Sections 8.5.1.5 or 8.5.1.6, and

$p$  phase lag parameter [-] is either user specified ( $F_{PCO}$ ), or computed as

$$p = -\tanh\left(100\left(\frac{k_{s,r}}{w_s T_p} - 0.1\right)\right) \quad (8.133)$$

based on ripple roughness height  $k_{s,r}$ , settling velocity  $w_s$  and wave peak period  $T_p$ .

$v_{cr}$  critical flow velocity [m/s] given by

$$v_{cr} = 5.75 \sqrt{sg D_{50} \theta_{cr}}^{10} \log(4h/D_{90}) \quad (8.134)$$

Furthermore, the mean concentration  $c_{sl}$  over the suspension layer with an assumed thickness of  $\delta = 3\delta_s$ , insofar as it's above the reference height  $a$ , is numerically approximated by

$$c_{sl} = \sum_{k=1}^{k_{max}} \begin{cases} c_k(3\delta_s - z_k - \frac{1}{2}d_k) & \text{if layer } k \text{ contains } 3\delta_s \\ c_k d_k & \text{if layer } k \text{ is fully between } a \text{ and } 3\delta_s \\ c_k^*(z_k + \frac{1}{2}d_k - a) & \text{if layer } k \text{ contains } a \\ 0 & \text{for layers above } 3\delta_s \text{ or below } a \end{cases} \quad (8.135)$$

where  $z_k$  is height of the centre of layer  $k$  above the bed (the layers are numbered from the bed upward). Because of the typically large concentration gradient at the bottom of the concentration profile, the concentration  $c_k^*$  of the bottommost partial layer is computed based on the assumption of a Rouse profile

$$c_k^* = c_k \left( \frac{z_k(h-z)}{z(h-z_k)} \right)^Z \quad (8.136)$$

where  $z$  is the characteristic average height above the bed for that layer

$$z = \frac{z_k + \frac{1}{2}d_k + a}{2} \quad (8.137)$$

and where  $Z$  is the suspension number derived from the computed concentrations of layers  $k$  and  $k+1$  as

$$Z = \frac{\ln(c_{k+1}/c_k)}{\ln(z_k/(h-z_{k+1}))} \quad (8.138)$$

#### 8.5.1.5 Wave asymmetry Isobe and Horikawa (1982)

Following [Isobe and Horikawa \(1982\)](#), the time variation of the velocity due to waves is modelled as a sine wave of which the first (onshore) and second (offshore) half are compressed/stretched relative to each other

$$u_{b,w}(t) = \begin{cases} u_{on} \sin\left(\frac{\pi}{T_{for}}t\right) & \text{for } 0 \leq t < T_{for} \\ u_{off} \sin\left(\frac{\pi}{T_{back}}(t - T_{for})\right) & \text{for } T_{for} \leq t < T_p \end{cases} \quad (8.139)$$

with the duration for onshore ( $T_{for}$ ) and offshore ( $T_{back}$ ) directed velocities are calculated as

$$T_{for} = \frac{u_{off}}{u_{on} + u_{off}} T_p \quad (8.140)$$

$$T_{back} = T_p - T_{for} \quad (8.141)$$



The associated maximum on- and offshore velocities are computed using

$$u_{\text{on}} = U_{\text{max}} \left[ \frac{1}{2} + \left( r_{\text{max}} - \frac{1}{2} \right) \tanh \left( \frac{r_a - \frac{1}{2}}{r_{\text{max}} - \frac{1}{2}} \right) \right] \quad (8.142)$$

$$u_{\text{off}} = U_{\text{max}} - u_{\text{on}} \quad (8.143)$$

Both values are clipped to be at least  $1 \cdot 10^{-5}$  [m/s]. Here the maximum velocity amplitude is computed as

$$U_{\text{max}} = 2rU_\delta \quad (8.144)$$

and the skewness  $r_a$  is given by

$$r_a = -5.25 - 6.1 \tanh(a_{11}u_1 - 1.76) \quad (8.145)$$

where  $r_a$  is clipped to values larger than 0.5, and the maximum skewness  $r_{\text{max}}$  is given by

$$r_{\text{max}} = -2.5 \frac{h}{\lambda} + 0.85 \quad (8.146)$$

following [Grasmeijer \(2002\)](#) where values are clipped within the range 0.62 to 0.75. In the various formulae the following symbols are used

$$r = -0.4 \frac{h_s}{h} + 1 \quad (8.147)$$

$$u_1 = \frac{u_{\text{max}}}{\sqrt{gh}} \quad (8.148)$$

$$a_{11} = -0.0049t_1^2 - 0.069t_1 + 0.2911 \quad (8.149)$$

$$t_1 = T_p \sqrt{\frac{g}{h}} \quad (8.150)$$

#### 8.5.1.6 Wave asymmetry Boechat Albernaz et al. (2019)

Following [Abreu et al. \(2010\)](#) and [Ruessink et al. \(2012\)](#), the time variation of the orbital velocity due to waves is modelled as

$$u_{b,w}(t) = u_{b,w,lt} f \left[ \frac{\sin(\omega t) + \frac{r}{1+f} \sin(\phi)}{1 - r \cos(\omega t + \phi)} \right] \quad (8.151)$$

where  $f = \sqrt{1 - r^2}$ ,  $\omega = 2\pi/T_p$  and the orbital velocity amplitude from linear theory is

$$u_{b,w,lt} = \frac{\pi H_{\text{rms}}}{T_p \sinh(kh)} \quad (8.152)$$

The times of maximum onshore (1) and offshore (2) flow are

$$t_1 = \omega^{-1} \arcsin(x_1) \quad (8.153)$$

$$t_2 = \omega^{-1} \arcsin(x_2) \quad (8.154)$$

such that the maximum onshore and offshore velocities,  $u_{\text{on}}$  and  $u_{\text{off}}$  are given by  $u_{b,w}(t_1)$  and  $u_{b,w}(t_2)$  respectively. Here,  $x_1$  and  $x_2$  are given by

$$x_1 = \min\left(-x_b - \frac{\sqrt{-x_b - 4x_a x_c}}{2x_c}, 1\right) \quad (8.155)$$

$$x_2 = \max\left(-1, -x_b + \frac{\sqrt{-x_b - 4x_a x_c}}{2x_c}\right) \quad (8.156)$$

with

$$x_a = b_s^2 + a_s^2 \quad (8.157)$$

$$x_b = -2b_s c_s \quad (8.158)$$

$$x_c = c_s^2 - a_s^2 \quad (8.159)$$

$$a_s = 1 + r_{\text{sf}} r \sin(\phi) \quad (8.160)$$

$$b_s = r_{\text{sf}} r \cos(\phi) \quad (8.161)$$

$$c_s = r \cos(\phi) \quad (8.162)$$

and

$$r_{\text{sf}} = \frac{r \sin(\phi)}{1 + \sqrt{1 - r^2}} \quad (8.163)$$

with

$$r = \frac{2}{1 + b^2} \quad (8.164)$$

$$b = \sqrt{\frac{2\beta^2}{9 + 2\beta^2}} \quad (8.165)$$

The total non-linearity  $\beta$  is computed as

$$\beta = p_1 + \frac{p_2 - p_1}{1 + \exp\left(\frac{p_3 - 10 \log(U_r)}{p_4}\right)} \quad (8.166)$$

with  $p_1 = 0$ ,  $p_2 = 0.857$ ,  $p_3 = -0.471$ ,  $p_4 = 0.297$  and the Ursell number

$$U_r = \frac{3}{4} a w \frac{k}{(kh)^3} \quad (8.167)$$

which is limited to values larger than  $10^{-12}$ .

The phase  $\phi$  is computed as

$$\phi = -\Psi - \frac{\pi}{2} \quad (8.168)$$

where

$$\Psi = \frac{\pi}{2} \left( \tanh\left(\frac{p_5}{U_r^{p_6}}\right) - 1 \right) \quad (8.169)$$

with  $p_5 = 0.815$  and  $p_6 = 0.672$ . Under these conditions the skewness and asymmetry are given by  $Sk = \beta \cos(\Psi)$  and  $As = \beta \sin(\Psi)$ .

### 8.5.2 SANTOSS

The SANTOSS formula is a practical sand transport formula for non-breaking waves and currents developed by [Van der A et al. \(2013\)](#). The formula accounts for all transport modes (wave- and current related bedload and suspended load) within the wave boundary layer, incorporating effects of wave skewness, wave asymmetry, specific surface wave effects (advection, boundary layer streaming) and phase-lag effects (fine sediments, ripple regime). For steady flow the model accounts for bedload only. The current-related suspended load above the wave boundary layer is computed in the same way as in Van Rijn (2007) as described in Section 8.5.1. The formula is developed using a database of 226 net transport rate measurements from large-scale oscillatory flow tunnels and a large wave flume, covering a wide range of full-scale flow conditions (oscillatory flows with superimposed collinear currents) and uniform and graded sands.

In the SANTOSS formula, the non-dimensional net transport rate is given by the following "velocity-load" equation:

$$\vec{\Phi} = \frac{\vec{q}_s}{\sqrt{(s-1)gd_{50}^3}} = \frac{\sqrt{|\theta_c|}T_c \left( \Omega_{cc} + \frac{T_c}{2T_{cu}}\Omega_{tc} \right) \frac{\vec{\theta}_c}{|\theta_c|} + \sqrt{|\theta_t|}T_t \left( \Omega_{tt} + \frac{T_t}{2T_{tu}}\Omega_{ct} \right) \frac{\vec{\theta}_t}{|\theta_t|}}{T} \quad (8.170)$$

where:

$\vec{q}_s$	volumetric net transport rate per unit width, [m <sup>2</sup> /s]
$s$	$s = (\rho_s - \rho)/\rho$ where $\rho_s$ and $\rho$ are the densities of sand and water respectively, [—]
$g$	acceleration due to gravity, [m/s <sup>2</sup> ]
$d_{50}$	sand median diameter, [m]
$\vec{\theta}$	non-dimensional bed shear stress (Shields parameter), with subscripts "c" and "t" implying "crest" and "trough" half cycle respectively, [—]
$T$	wave period, [s]
$T_c$	duration of the crest (positive) half cycle, [s]
$T_{cu}$	duration of accelerating flow within the crest half cycle, [s]
$T_t$	duration of the trough (negative) half cycle, [s]
$T_{tu}$	period of accelerating flow within the trough half cycle, [s] (see <a href="#">Van der A et al. (2013)</a> for an illustration of the durations during a wave period)
$\Omega_{cc}$	represents the sand load that is entrained during the wave crest period and transported during the crest period, [—]
$\Omega_{ct}$	represents the sand load that is entrained during the wave crest period and transported during the trough period, [—]
$\Omega_{tt}$	represents the sand load that is entrained during the wave trough period and transported during the trough period, [—]
$\Omega_{tc}$	represents the sand load that is entrained during the wave trough period and transported during the crest period, [—]

The sand load entrained in the flow during each half-cycle is related to the Shields parameter as follows:

$$\Omega_c = \begin{cases} 0 & \text{if } |\theta_c| \leq \theta_{cr} \\ m (|\theta_c| - \theta_{cr})^n & \text{if } |\theta_c| > \theta_{cr} \end{cases} \quad (8.171)$$

$$\Omega_t = \begin{cases} 0 & \text{if } |\theta_t| \leq \theta_{cr} \\ m (|\theta_t| - \theta_{cr})^n & \text{if } |\theta_t| > \theta_{cr} \end{cases} \quad (8.172)$$

where the critical Shields number,  $\theta_{cr}$ , is calculated following [Soulsby \(1997\)](#). The proportionality constant  $m = 11.0$  and power of the excess Shields parameter  $n = 1.2$  are two of the three main calibration coefficients of the transport formula. The bed shear stress is computed as part of the SANTOSS formula, as described in [Van der A \*et al.\* \(2013\)](#).

How much of the sand is transported within the half-cycle and how much remains in suspension to be transported in the following half-cycle is determined by the value of the phase lag parameter for the half-cycle,  $P_i$ , as follows:

$$\Omega_{cc} = \begin{cases} \Omega_c & \text{if } P_c \leq 1 \\ \frac{1}{P_c} \Omega_c & \text{if } P_c > 1 \end{cases} \quad (8.173)$$

$$\Omega_{ct} = \begin{cases} 0 & \text{if } P_c \leq 1 \\ (1 - \frac{1}{P_c}) \Omega_c & \text{if } P_c > 1 \end{cases} \quad (8.174)$$

$$\Omega_{tt} = \begin{cases} \Omega_t & \text{if } P_t \leq 1 \\ \frac{1}{P_t} \Omega_t & \text{if } P_t > 1 \end{cases} \quad (8.175)$$

$$\Omega_{tc} = \begin{cases} 0 & \text{if } P_t \leq 1 \\ (1 - \frac{1}{P_t}) \Omega_t & \text{if } P_t > 1 \end{cases} \quad (8.176)$$

Thus, when the phase lag parameter  $P_i$  exceeds 1, there is an exchange of sand from the present half-cycle to the following half-cycle. The phase lag parameter is given by:

$$P_c = \begin{cases} \alpha \left(1 - \frac{\xi \hat{u}_c}{c_w}\right) \frac{\eta}{2(T_c - T_{cu})w_{sc}} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha \left(1 - \frac{\xi \hat{u}_c}{c_w}\right) \frac{\delta_{sc}}{2(T_c - T_{cu})w_{sc}} & \text{if } \eta = 0 \text{ (sheet flow regime)} \end{cases} \quad (8.177)$$

$$P_t = \begin{cases} \alpha \left(1 + \frac{\xi \hat{u}_t}{c_w}\right) \frac{\eta}{2(T_t - T_{tu})w_{st}} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha \left(1 + \frac{\xi \hat{u}_t}{c_w}\right) \frac{\delta_{st}}{2(T_t - T_{tu})w_{st}} & \text{if } \eta = 0 \text{ (sheet flow regime)} \end{cases} \quad (8.178)$$

where:

- $\alpha$  calibration coefficient (= 8.2), [—]
- $\xi$  coefficient accounting for the shape of the velocity and concentration profile (= 1.7), [—]

$\hat{u}_c, \hat{u}_t$	peak crest and peak trough orbital velocities, [m/s]
$c_w$	wave celerity, [m/s]
$\eta$	ripple height, calculated using the ripple predictor of O'Donoghue <i>et al.</i> (2006), [m]
$\delta_{sc}, \delta_{st}$	sheet flow layer thickness for the respective half cycle, calculated using Dohmen-Janssen (1999), [m]
$w_{sc}, w_{st}$	sediment settling velocity within the respective half cycle, [m/s]

It is noted that Eqs. (8.177) and (8.178) differ from Eqs. (33) and (34) in Van der A *et al.* (2013) in which also the factor 1 is divided by  $c_w$ .

### 8.5.3 Van Rijn (1993)

Van Rijn (1993) distinguishes between sediment transport below the reference height  $a$  which is treated as bedload transport and that above the reference height which is treated as suspended-load. Sediment is entrained in the water column by imposing a reference concentration at the reference height.

#### Reference concentration

The volumetric reference concentration is calculated in accordance with Van Rijn *et al.* (2000) as:

$$c_a = \max(c_{a,\max}, 0.015 \frac{D_{50}}{a} \frac{T_a^{1.5}}{D_*^{0.3}}) \quad (8.179)$$

where:

$a$	reference height [m]
$c_a$	volumetric concentration at reference height $a$ [m <sup>3</sup> rock/m <sup>3</sup> fluid]
$c_{a,\max}$	maximum volumetric concentration at reference height $a$ , specified as CaMax in the mor-file [m <sup>3</sup> rock/m <sup>3</sup> fluid]

This concentration is subsequently multiplied by the specific density  $\rho_s$  of the considered sediment fraction to arrive at the mass concentration at the reference height. In order to evaluate this expression the following quantities must be calculated:

$D_*$  non-dimensional particle diameter:

$$D_* = D_{50} \left[ \frac{(s-1)g}{\nu^2} \right]^{1/3} \quad (8.180)$$

$T_a$  non-dimensional bed-shear stress:

$$T_a = \frac{(\mu_c \tau_{b,cw} + \mu_w \tau_{b,w}) - \tau_{cr}}{\tau_{cr}} \quad (8.181)$$

$\mu_c$  efficiency factor current:

$$\mu_c = \frac{f'_c}{f_c} \quad (8.182)$$

$f'_c$  gain related friction factor:

$$f'_c = 0.24 \left[ {}^{10}\log \left( \frac{12h}{3D_{90}} \right) \right]^{-2} \quad (8.183)$$

$f_c$  total current-related friction factor:

$$f_c = 0.24 \left[ {}^{10}\log \left( \frac{12h}{k_s} \right) \right]^{-2} \quad (8.184)$$

$\tau_{b,cw}$  bed shear stress due to current in the presence of waves. Note that the bed shear velocity  $u_*$  is calculated in such a way that Van Rijn's wave-current interaction factor  $\alpha_{cw}$  is not required.

$$\tau_{b,cw} = \rho_w u_*^2 \quad (8.185)$$

$\mu_w$  efficiency factor waves:

$$\mu_w = \max \left( 0.063, \frac{1}{8} \left( 1.5 - \frac{H_s}{h} \right)^2 \right) \quad (8.186)$$

$\tau_{b,w}$  bed shear stress due to waves:

$$\tau_{b,w} = \frac{1}{4} \rho_w f_w \left( \hat{U}_\delta \right)^2 \quad (8.187)$$

$f_w$  total wave-related friction factor ( $\equiv$  Equations 8.107, 8.227 and 8.268):

$$f_w = \exp \left[ -6 + 5.2 \left( \frac{\hat{A}_\delta}{k_{s,w}} \right)^{-0.19} \right] \quad (8.188)$$

To avoid the need for excessive user input, the wave related roughness  $k_{s,w}$  is related to the estimated ripple height, using the relationship:

$$k_{s,w} = \text{RWAVE} \cdot \Delta_r, \text{ with } \Delta_r = 0.025 \text{ and } 0.01 \text{ m} \leq k_{s,w} \leq 0.1 \text{ m} \quad (8.189)$$

where:

RWAVE the user-defined wave roughness adjustment factor. Recommended to be in the range 1–3, default = 2.

$\tau_{cr}$  critical bed shear stress:

$$\tau_{cr} = (\rho_s - \rho_w) g D_{50} \theta_{cr} \quad (8.190)$$

$\theta_{cr}$  threshold parameter  $\theta_{cr}$  is calculated according to the classical Shields curve as modelled by Van Rijn (1993) as a function of the non-dimensional grain size  $D_*$ . This avoids the need for iteration.

**Note:** for clarity, in this expression the symbol  $D_*$  has been used where  $D_*^{(\ell)}$  would be more correct:

$$\theta_{cr} = \begin{cases} 0.24 D_*^{-1}, & 1 < D_* \leq 4 \\ 0.14 D_*^{-0.64}, & 4 < D_* \leq 10 \\ 0.04 D_*^{-0.1}, & 10 < D_* \leq 20 \\ 0.013 D_*^{0.29}, & 20 < D_* \leq 150 \\ 0.055, & 150 < D_* \end{cases} \quad (8.191)$$

$a$  Van Rijn's reference height

$\hat{A}_\delta$  peak orbital excursion at the bed:  $\hat{A}_\delta = \frac{T_p \hat{U}_\delta}{2\pi}$ .



$D_{50}$	median sediment diameter
$D_{90}$	90 % sediment passing size: $D_{90} = 1.5D_{50}$
$h$	water depth
$k_a$	apparent bed roughness felt by the flow when waves are present. Calculated by Delft3D-FLOW using the wave-current interaction formulation selected; see ?? for details: $k_a \leq 10k_s$
$k_s$	user-defined current-related effective roughness height (space varying)
$k_{s,w}$	wave-related roughness, calculated from ripple height, see Equation (8.189)
$u_z$	velocity magnitude taken from a near-bed computational layer. In a current-only situation the velocity in the bottom computational layer is used. Otherwise, if waves are active, the velocity is taken from the layer closest to the height of the top of the wave mixing layer $\delta$ .
$\hat{U}_\delta$	peak orbital velocity at the bed: $\sqrt{2} \times RMS_{orbital\ velocity}$ at bed, taken from the wave module.
$z_u$	height above bed of the near-bed velocity ( $u_z$ ) used in the calculation of bottom shear stress due to current
$\Delta_r$	estimated ripple height, see Equation (8.189)
$\delta_m$	thickness of wave boundary mixing layer following Van Rijn (1993): $3\delta_w$ (and $\delta_m \geq k_a$ )
$\delta_w$	wave boundary layer thickness: $\delta_w = 0.072 \hat{A}_\delta \left( \frac{\hat{A}_\delta}{k_{s,w}} \right)^{-0.25}$

We emphasise the following points regarding this implementation:

- ◇ The bottom shear stress due to currents is based on a near-bed velocity taken from the hydrodynamic calculations, rather than the depth-averaged velocity used by Van Rijn.
- ◇ All sediment calculations are based on hydrodynamic calculations from the previous half time-step. We find that this is necessary to prevent unstable oscillations developing.

The apparent roughness felt by the flow ( $k_a$ ) is dependent on the hydrodynamic wave-current interaction model applied. At this time, Van Rijn's wave-current interaction model is not available in Delft3D-FLOW. This means that it is not possible for a user to exactly reproduce results obtained using Van Rijn's full formulations for waves and currents.

### Adjustment of the representative diameter of suspended sediment

The representative diameter of the suspended sediment  $D_s^{(\ell)}$  generally given by the user-defined sediment diameter `SEDDIA` ( $D_{50}$  of bed material) multiplied by the user-defined factor `FACDSS` (see also remarks) can be overruled in case the Van Rijn (1993) transport formula is selected. This achieved by setting `IOPSUS=1` the representative diameter of the suspended sediment will then be set to:

$$D_s = \begin{cases} 0.64D_{50} & \text{for } T_A \leq 1 \\ D_{50} (1 + 0.015 (T_A - 25)) & \text{for } 1 < T_A \leq 25 \\ D_{50} & \text{for } 25 < T_A \end{cases} \quad (8.192)$$

where  $T_a^{(\ell)}$  is given by equation 8.181.

### Bedload transport rate

For simulations including waves the magnitude and direction of the bedload transport on a horizontal bed are calculated using an approximation method developed by Van Rijn *et al.*

(2003). The method computes the magnitude of the bedload transport as:

$$|S_b| = 0.006 \rho_s w_s D_{50}^{(\ell)} M^{0.5} M_e^{0.7} \quad (8.193)$$

where:

$S_b$	bedload transport [ $\text{kg m}^{-1} \text{s}^{-1}$ ]
$M$	sediment mobility number due to waves and currents [-]
$M_e$	excess sediment mobility number [-]

$$M = \frac{v_{eff}^2}{(s-1) g D_{50}} \quad (8.194)$$

$$M_e = \frac{(v_{eff} - v_{cr})^2}{(s-1) g D_{50}} \quad (8.195)$$

$$v_{eff} = \sqrt{v_R^2 + U_{on}^2} \quad (8.196)$$

in which:

$v_{cr}$	critical depth averaged velocity for initiation of motion (based on a parameterisation of the Shields curve) [m/s]
$v_R$	magnitude of an equivalent depth-averaged velocity computed from the velocity in the bottom computational layer, assuming a logarithmic velocity profile [m/s]
$U_{on}$	near-bed peak orbital velocity [m/s] in onshore direction (in the direction on wave propagation) based on the significant wave height

$U_{on}$  (and  $U_{off}$  used below) are the high frequency near-bed orbital velocities due to short waves and are computed using a modification of the method of [Isobe and Horikawa \(1982\)](#). This method is a parameterisation of fifth-order Stokes wave theory and third-order cnoidal wave theory which can be used over a wide range of wave conditions and takes into account the non-linear effects that occur as waves propagate in shallow water ([Grasmeijer and Van Rijn, 1998](#)).

The direction of the bedload transport vector is determined by assuming that it is composed of two parts: part due to current ( $S_{b,c}$ ) which acts in the direction of the near-bed current, and part due to waves ( $S_{b,w}$ ) which acts in the direction of wave propagation. These components are determined as follows:

$$S_{b,c} = \frac{S_b}{\sqrt{1 + r^2 + 2|r|\cos\varphi}} \quad (8.197)$$

$$|S_{b,w}| = r |S_{b,c}| \quad (8.198)$$

where:

$$r = \frac{(|U_{on}| - v_{cr})^3}{(|v_R| - v_{cr})^3} \quad (8.199)$$

$S_{b,w} = 0$  if  $r < 0.01$ ,  $S_{b,c} = 0$  if  $r > 100$ , and  $\varphi$  = angle between current and wave direction for which [Van Rijn \(2003\)](#) suggests a constant value of  $90^\circ$ .

Also included in the “bedload” transport vector is an estimation of the suspended sediment transport due to wave asymmetry effects. This is intended to model the effect of asymmetric



wave orbital velocities on the transport of suspended material within about 0.5 m of the bed (the bulk of the suspended transport affected by high frequency wave oscillations).

This wave-related suspended sediment transport is again modelled using an approximation method proposed by [Van Rijn \(2001\)](#):

$$S_{s,w} = f_{\text{susw}} \gamma U_A L_T \quad (8.200)$$

where:

$S_{s,w}$	wave-related suspended transport [kg/(ms)]
$f_{\text{susw}}$	user-defined tuning parameter
$\gamma$	phase lag coefficient (= 0.2)
$U_A$	velocity asymmetry value [m/s] = $\frac{U_{on}^4 - U_{off}^4}{U_{on}^3 + U_{off}^3}$
$L_T$	suspended sediment load [kg/m <sup>2</sup> ] = $0.007 \rho_s D_{50} M_e$

The three separate transport modes are imposed separately. The direction of the bedload due to currents  $S_{b,c}$  is assumed to be equal to the direction of the current, whereas the two wave related transport components  $S_{b,w}$  and  $S_{s,w}$  take on the wave propagation direction. This results in the following transport components:

$$S_{bc,u} = \frac{u_{b,u}}{|u_b|} |S_{b,c}| \quad (8.201)$$

$$S_{bc,v} = \frac{u_{b,v}}{|u_b|} |S_{b,c}| \quad (8.202)$$

$$S_{bw,u} = S_{b,w} \cos \phi \quad (8.203)$$

$$S_{bw,v} = S_{b,w} \sin \phi \quad (8.204)$$

$$S_{sw,u} = S_{s,w} \cos \phi \quad (8.205)$$

$$S_{sw,v} = S_{s,w} \sin \phi \quad (8.206)$$

where  $\phi$  is the local angle between the direction of wave propagation and the computational grid. The different transport components can be calibrated independently by using the `Bed`, `BedW` and `SusW` keywords in the morphology input file.

#### 8.5.4 Engelund-Hansen (1967)

The Engelund-Hansen sediment transport relation has frequently been used in rivers and estuaries. It reads:

$$S = S_b + S_{s,eq} = \frac{0.05 \alpha q^5}{\sqrt{g} C^3 \Delta^2 D_{50}} \quad (8.207)$$

where:

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

The transport rate is imposed as bedload transport due to currents  $S_{bc}$ . The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)): calibration coefficient  $\alpha$  and roughness height  $r_k$ .

**Remarks:**

- ◇ The  $D_{50}$  grain size diameter is based on the sediment fraction considered.
- ◇ A second formula specific input parameter ( $r_k$ ) is required for the Engelund-Hansen formula. This parameter, which represents the roughness height for currents alone in [m], is only used to determine the  $C$  value when the Chézy friction in the flow has not been defined. Generally, this parameter can thus be treated as a dummy parameter.

### 8.5.5 Meyer-Peter-Muller (1948)

The Meyer-Peter-Muller sediment transport relation is slightly more advanced than the Engelund-Hansen formula, as it includes a critical shear stress for transport. It reads:

$$S = 8\alpha D_{50} \sqrt{\Delta g D_{50}} (\mu\theta - \xi\theta_{cr})^{3/2} \quad (8.208)$$

where:

$\alpha$	calibration coefficient (O(1))
$\Delta$	the relative density $(\rho_s - \rho_w)/\rho_w$
$\mu$	ripple factor or efficiency factor
$\theta_{cr}$	critical Shields' mobility parameter (= 0.047)
$\xi$	hiding and exposure factor for the sediment fraction considered

and the Shields' mobility parameter  $\theta$  given by

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} \quad (8.209)$$

in which  $q$  is the magnitude of the flow velocity [m/s]. The ripple factor  $\mu$  reads:

$$\mu = \min \left( \left( \frac{C}{C_{g,90}} \right)^{1.5}, 1.0 \right) \quad (8.210)$$

where  $C_{g,90}$  is the Chézy coefficient related to grains, given by:

$$C_{g,90} = 18^{10} \log \left( \frac{12(d + \xi)}{D_{90}} \right) \quad (8.211)$$

with  $D_{90}$  specified in [m]. The transport rate is imposed as bedload transport due to currents  $S_{bc}$ . The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)): calibration coefficient  $\alpha$  and a dummy value.

#### Remark:

- ◇ The  $D_{50}$  is based on the sediment fraction considered, the  $D_{90}$  grain size diameters is based on the composition of the local sediment mixture.

### 8.5.6 General formula

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

$$S = \alpha D_{50} \sqrt{\Delta g D_{50}} \theta^b (\mu\theta - \xi\theta_{cr})^c \quad (8.212)$$

where  $\xi$  is the hiding and exposure factor for the sediment fraction considered and

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} \quad (8.213)$$

in which  $q$  is the magnitude of the flow velocity.

The transport rate is imposed as bedload transport due to currents  $S_{bc}$ . The following parameters have to be specified in the input files of the Transport module (See [section A.3](#)): calibration coefficient  $\alpha$ , powers  $b$  and  $c$ , ripple factor or efficiency factor  $\mu$ , critical Shields' mobility parameter  $\theta_{cr}$ .

### 8.5.7 Bijker (1971)

The Bijker formula sediment transport relation is a popular formula which is often used in coastal areas. It is robust and generally produces sediment transport of the right order of magnitude under the combined action of currents and waves. Bedload and suspended load are treated separately. The near-bed sediment transport ( $S_b$ ) and the suspended sediment transport ( $S_s$ ) are given by the formulations in the first sub-section. It is possible to include sediment transport in the wave direction due to wave asymmetry and bed slope following the Bailard approach, see [Bailard \(1981\)](#), [Stive \(1986\)](#). Separate expressions for the wave asymmetry and bed slope components are included:

$$\vec{S}_b = \vec{S}_{b0} + \vec{S}_{b,asymm} + \vec{S}_{s,asymm} + \vec{S}_{b,slope} + \vec{S}_{s,slope} \quad (8.214)$$

$$\vec{S}_s = \vec{S}_{s0} \quad (8.215)$$

where  $S_{b0}$  and  $S_{s0}$  are the sediment transport in flow direction as computed according to the formulations of Bijker in the first sub-section, and the asymmetry and bed slope components for bedload and suspended transport are defined in the second sub-section. Both bedload and suspended load terms are incorporated in the bedload transport for further processing. The transport vectors are imposed as bedload transport vector due to currents  $S_{bc}$  and suspended load transport magnitude  $S_s$ , from which the equilibrium concentration is derived, respectively.

#### 8.5.7.1 Basic formulation

The basic formulation of the sediment transport formula according to Bijker is given by:

$$S_b = bD_{50} \frac{q}{C} \sqrt{g} (1 - \varepsilon) \exp(A_r) \quad (8.216)$$

$$S_s = 1.83S_b \left( I_1 \ln \left( \frac{33.0h}{r_c} \right) + I_2 \right) \quad (8.217)$$

where

$C$	Chézy coefficient (as specified in input of D-Flow FM module)
$h$	water depth
$q$	flow velocity magnitude
$\varepsilon$	porosity (by default equal to the bed porosity; optionally user specified)

and

$$A_r = \max(-50, \min(100, A_{ra})) \quad (8.218)$$

$$b = BD + \max \left( 0, \min \left( 1, \frac{(h_w/h) - C_d}{C_s - C_d} \right) \right) (BS - BD) \quad (8.219)$$

$$I_1 = 0.216 \frac{\left(\frac{r_c}{h}\right)^{z_*-1}}{\left(1 - \frac{r_c}{h}\right)^{z_*}} \int_{r_c/h}^1 \left( \frac{1-y}{y} \right)^{z_*} dy \quad (8.220)$$

$$I_2 = 0.216 \frac{\left(\frac{r_c}{h}\right)^{z_*-1}}{\left(1 - \frac{r_c}{h}\right)^{z_*}} \int_{r_c/h}^1 \ln y \left(\frac{1-y}{y}\right)^{z_*} dy \quad (8.221)$$

where

$BS$	Coefficient $b$ [-] for shallow water (default value 5)
$BD$	Coefficient $b$ [-] for deep water (default value 2)
$C_s$	Shallow water criterion $H_s/h$ [-] (default value 0.05)
$C_d$	Deep water criterion [-] (default value 0.4)
$r_c$	Roughness height for currents [m]

and

$$A_{ra} = \frac{-0.27 \Delta D_{50} C^2}{\mu q^2 \left(1 + \frac{1}{2} \left(\psi \frac{U_b}{q}\right)^2\right)} \quad (8.222)$$

$$\mu = \left(\frac{C}{18^{10} \log(12h/D_{90})}\right)^{1.5} \quad (8.223)$$

$$z_* = \frac{w}{\frac{\kappa q \sqrt{g}}{C} \sqrt{1 + \frac{1}{2} \left(\psi \frac{U_b}{q}\right)^2}} \quad (8.224)$$

$$U_b = \frac{\omega h_w}{2 \sinh(k_w h)} \quad (8.225)$$

$$\omega = \frac{2\pi}{T} \quad (8.226)$$

$$f_w = \exp\left(-5.977 + \frac{5.123}{a_0^{0.194}}\right) \quad (8.227)$$

( $\equiv$  Equations 8.107, 8.188 and 8.268):

$$a_0 = \max\left(2, \frac{U_b}{\omega r_c}\right) \quad (8.228)$$

$$\psi = \begin{cases} C \sqrt{\frac{f_w}{2g}} & \text{if wave effects are included } (T > 0) \\ 0 & \text{otherwise} \end{cases} \quad (8.229)$$

where

$C$	Chézy coefficient (as specified in input of D-Flow FM module)
$h_w$	wave height ( $H_{rms}$ ) [m]
$k_w$	wave number [-]

$T$	wave period computed by the waves model [s]; optionally specified by you as $T_{user}$ .
$U_b$	wave velocity [m/s]
$w$	sediment fall velocity [m/s] (by default equal to the sediment fall velocity; optionally user specified)
$\Delta$	relative density $(\rho_s - \rho_w)/\rho_w$ [-]
$\kappa$	Von Kármán constant (0.41) [-]

The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)):  $BS$ ,  $BD$ ,  $C_s$ ,  $C_d$ , and optionally  $w$ ,  $\varepsilon$  and  $T_{user}$ .  $r_c$  may either be given by the user, or derived from the Chézy coefficient  $C$  of D-Flow FM.

### 8.5.7.2 Transport in wave propagation direction (Bailard-approach)

If the Bijker formula is selected it is possible to include sediment transport in the wave direction due to wave asymmetry following the Bailard approach, see [Bailard \(1981\)](#) and [Stive \(1986\)](#). For a detailed description of the implementation you are referred to [Nipius \(1998\)](#).

Separate expressions for the wave asymmetry and bed slope components are included for both bedload and suspended load. Both extra bedload and suspended load transport vectors are added to the bedload transport as computed in the previous sub-section:

$$\vec{S}_b = \vec{S}_{b0} + \vec{S}_{b,asymm} + \vec{S}_{s,asymm} + \vec{S}_{b,slope} + \vec{S}_{s,slope} \quad (8.230)$$

where the asymmetry components for respectively the bedload and suspended transport in wave direction are written as:

$$S_{b,asymm}(t) = \frac{\rho_c f \varepsilon_b}{(\rho_s - \rho) g (1 - \phi) \tan \varphi} |u(t)|^2 u(t) \quad (8.231)$$

$$S_{s,asymm}(t) = \frac{\rho_c f \varepsilon_s}{(\rho_s - \rho) g (1 - \phi) w} |u(t)|^3 u(t) \quad (8.232)$$

from which the components in  $\xi$  and  $\eta$  direction are obtained by multiplying with the cosine and sine of the wave angle  $\theta w$  and the bed slope components as:

$$S_{b,slope,\xi}(t) = \frac{\rho_c f \varepsilon_b}{(\rho_s - \rho) g (1 - \phi) \tan \varphi} \frac{1}{\tan \varphi} |u(t)|^3 \frac{\partial z_b}{\partial \xi} \quad (8.233)$$

$$S_{s,slope,\xi}(t) = \frac{\rho_c f \varepsilon_s}{(\rho_s - \rho) g (1 - \phi) w} \frac{\varepsilon_s}{w} |u(t)|^5 \frac{\partial z_b}{\partial \xi} \quad (8.234)$$

and similar for the  $\eta$  direction, where:

$u(t)$	near bed velocity signal [m/s]
$\rho$	density of water [kg/m <sup>3</sup> ]
$\rho_s$	density of the sediment [kg/m <sup>3</sup> ]
$c_f$	coefficient of the bottom shear stress [-] (constant value of 0.005)
$\phi$	porosity [-] (constant value of 0.4)
$\varphi$	natural angle of repose [-] (constant value of $\tan \varphi = 0.63$ )
$w$	sediment fall velocity [m/s]
$\varepsilon_b$	efficiency factor of bedload transport [-] (constant value of 0.10)
$\varepsilon_s$	efficiency factor of suspended transport [-] (constant value of 0.02, but in implemented expression for suspended bed slope transport the second $\varepsilon_s$ is replaced by a user-defined calibration factor; see <a href="#">Equation (8.237)</a> ).

These transports are determined by generating velocity signals of the orbital velocities near the bed by using the [Rienecker and Fenton \(1981\)](#) method, see also [Roelvink and Stive \(1989\)](#).

The (short wave) averaged sediment transport due to wave asymmetry, Equations 8.231 and 8.232, is determined by using the following averaging expressions of the near bed velocity signal (calibration coefficients included):

$$\langle u | u|^2 \rangle = FacA \langle \tilde{u} |\tilde{u}|^2 \rangle + 3FacU \bar{u} \langle |\tilde{u}|^2 \rangle \quad (8.235)$$

$$\langle u | u|^3 \rangle = FacA \langle \tilde{u} |\tilde{u}|^3 \rangle + 4FacU \bar{u} \langle |\tilde{u}|^3 \rangle \quad (8.236)$$

in which:

$\tilde{u}$	orbital velocity signal
$\bar{u}$	averaged flow velocity (due to tide, undertow, wind, etc.)
$FacA$	user-defined calibration coefficient for the wave asymmetry
$FacU$	user-defined calibration coefficient for the averaged flow

The suspended transport relation due to the bed slope according to [Equation \(8.234\)](#) is implemented as:

$$S_{s;slope,\xi}(t) = \frac{\rho_c f \varepsilon_s}{(\rho_s - \rho) g (1 - \phi) w} \frac{\varepsilon_{sl}}{w} |u(t)|^5 \frac{\partial z_b}{\partial \xi} \quad (8.237)$$

where:

$\varepsilon_{sl}$	user-defined calibration coefficient EpsSL
--------------------	--

To activate this transport option, you have to specify the additional transport formula specific keywords `FacA`, `FacU` and `EpsSL`.

#### Remarks:

- ◇ the user-defined `FacU` value is currently treated as a dummy value, `FacU = 0.0` will always be used.
- ◇ In previous versions of D-Flow FM you had to create a separate file named `<coef.inp>` to trigger this feature. This file is no longer supported; an error will be generated when this file is present in the simulation folder.

A validation study ([Nipius, 1998](#)) showed that the following coefficient settings yielded the best results for the Dutch coast:

`FacA = 0.4`  
`FacU = 0.0`  
`EpsSL = 0.11`

If a relatively straight coast is considered the effect of the parameters is:

- ◇ The wave asymmetry causes onshore directed sediment transport (i.e. in the wave propagation direction). An increased `FacA` results in an increased onshore transport and hence steepening of the cross-shore bottom profile.
- ◇ The bed slope transport is in general offshore directed. By increasing `EpsSL` an increased flattening of the bottom profile occurs (i.e. increased offshore transports).
- ◇ The ratio between these parameters determines the balance between onshore and offshore transport and hence the shape and slope of the cross-shore bottom profile. The associated response time of the cross-shore morphology can be influenced by modifying the values of the two parameters, but maintaining a constant ratio. Increased values result

in increased gross transports and consequently a reduced morphological response time (and vice versa).

### 8.5.8 Van Rijn (1984)

The Van Rijn (1984a,b,c) sediment transport relation is a transport formula commonly used for fine sediments in situations without waves. Separate expressions for bedload and suspended load are given. The bedload transport rate is given by:

$$S_b = \begin{cases} 0.053 \sqrt{\Delta g D_{50}^3} D_*^{-0.3} T^{2.1} & \text{for } T < 3.0 \\ 0.1 \sqrt{\Delta g D_{50}^3} D_*^{-0.3} T^{1.5} & \text{for } T \geq 3.0 \end{cases} \quad (8.238)$$

where  $T$  is a dimensionless bed shear parameter, written as:

$$T = \frac{\mu_c \tau_{bc} - \tau_{bcr}}{\tau_{bcr}} \quad (8.239)$$

It is normalised with the critical bed shear stress according to Shields ( $\tau_{bcr}$ ), the term  $\mu_c \tau_{bc}$  is the effective shear stress. The formulas of the shear stresses are

$$\tau_{bc} = \frac{1}{8} \rho_w f_{cb} q^2 \quad (8.240)$$

$$f_{cb} = \frac{0.24}{(10 \log(12h/\xi_c))^2} \quad (8.241)$$

$$\mu_c = \left( \frac{18 \cdot 10 \log(12h/\xi_c)}{C_{g,90}} \right)^2 \quad (8.242)$$

where  $C_{g,90}$  is the grain related Chézy coefficient

$$C_{g,90} = 18 \cdot 10 \log \left( \frac{12h}{3D_{90}} \right) \quad (8.243)$$

The critical shear stress is written according to Shields:

$$\tau_{bcr} = \rho_w \Delta g D_{50} \theta_{cr} \quad (8.244)$$

in which  $\theta_{cr}$  is the Shields parameter which is a function of the dimensionless particle parameter  $D_*$ :

$$D_* = D_{50} \left( \frac{\Delta g}{\nu^2} \right)^{\frac{1}{3}} \quad (8.245)$$

The suspended transport formulation reads:

$$S_s = f_{cs} q h C_a \quad (8.246)$$

In which  $C_a$  is the reference concentration,  $q$  depth averaged velocity,  $h$  the water depth and  $f_{cs}$  is a shape factor of which only an approximate solution exists:

$$f_{cs} = \begin{cases} f_0(z_c) & \text{if } z_c \neq 1.2 \\ f_1(z_c) & \text{if } z_c = 1.2 \end{cases} \quad (8.247)$$

$$f_0(z_c) = \frac{(\xi_c/h)^{z_c} - (\xi_c/h)^{1.2}}{(1 - \xi_c/h)^{z_c} (1.2 - z_c)} \quad (8.248)$$

$$f_1(z_c) = \left( \frac{\xi_c/h}{1 - \xi_c/h} \right)^{1.2} \ln(\xi_c/h) \quad (8.249)$$

where  $\xi_c$  is the reference level or roughness height (can be interpreted as the bedload layer thickness) and  $z_c$  the suspension number:

$$z_c = \min \left( 20, \frac{w_s}{\beta \kappa u_*} + \phi \right) \quad (8.250)$$

$$u_* = q \sqrt{\frac{f_{cb}}{8}} \quad (8.251)$$

$$\beta = \min \left( 1.5, 1 + 2 \left( \frac{w_s}{u_*} \right)^2 \right) \quad (8.252)$$

$$\phi = 2.5 \left( \frac{w_s}{u_*} \right)^{0.8} \left( \frac{C_a}{0.65} \right)^{0.4} \quad (8.253)$$

The reference concentration is written as:

$$c_a = 0.015 \alpha_1 \frac{D_{50}}{\xi_c} \frac{T^{1.5}}{D_*^{0.3}} \quad (8.254)$$

The bedload transport rate is imposed as bedload transport due to currents  $S_{bc}$ , while the computed suspended load transport rate is converted into a reference concentration equal to  $f_{cs} c_a$ . The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)): calibration coefficient  $\alpha_1$ , dummy argument, reference level (bedload layer thickness) or roughness height  $\xi_c$  [m] and settling velocity  $w_s$  [m/s].

### 8.5.9 Soulsby/Van Rijn

The sediment transport relation has been implemented based on the formulations provided in [Soulsby \(1997\)](#). References in the following text refer to this book.

If the wave period  $T_p$  is smaller than  $10^{-6}$  s, the wave period  $T_p$  is set to 5 s and the root-mean-square wave height is set to 1 cm. Furthermore, the wave period is limited to values larger than 1 s. The root-mean-square wave height is limited to values smaller than  $0.4 H$ , where  $H$  is the water depth.

The sediment transport is set to zero in case of velocities smaller than  $10^{-6}$  m/s, water depth larger than 200 m or smaller than 1 cm.

The root-mean-square orbital velocity is computed as:

$$U_{rms} = \sqrt{2} \frac{\pi H_{rms}}{T_p \sinh(kH)} \quad (8.255)$$



Furthermore,  $D_*$  is defined as (Soulsby, 1997, p.104):

$$D_* = \left( \frac{g\Delta}{\nu^2} \right)^{1/3} D_{50} \quad (8.256)$$

Using the critical bed shear velocity according to Van Rijn (Soulsby, 1997, p.176):

$$U_{cr} = \begin{cases} 0.19 D_{50}^{0.1} 10 \log(4H/D_{90}) & \text{if } D_{50} \leq 0.5 \text{ mm} \\ 8.5 D_{50}^{0.6} 10 \log(4H/D_{90}) & \text{if } 0.5 \text{ mm} < D_{50} \leq 2 \text{ mm} \end{cases} \quad (8.257)$$

larger values of  $D_{50}$  lead to an error and to the halting of the program.

The sediment transport is split into a bedload and suspended load fraction. The direction of the bedload transport is assumed to be equal to the direction of the depth-averaged velocity in a 2D simulation and equal to the direction of the velocity at the reference height  $a$  (see section 8.3.3) in a 3D simulation (Soulsby, 1997, p.183):

$$S_{bx} = A_{cal} A_{sb} u \xi \quad (8.258)$$

$$S_{by} = A_{cal} A_{sb} v \xi \quad (8.259)$$

and the suspended transport magnitude is given by the following formula (this quantity is later converted to a reference concentration to feed the advection-diffusion equation for the suspended sediment transport as indicated in section 8.3.3):

$$S_s = A_{cal} A_{ss} \xi \sqrt{u^2 + v^2} \quad (8.260)$$

where

$A_{cal}$  a user-defined calibration factor  
 $A_{sb}$  bedload multiplication factor

$$A_{sb} = 0.005 H \left( \frac{D_{50}/H}{\Delta g D_{50}} \right)^{1.2} \quad (8.261)$$

$A_{ss}$  suspended load multiplication factor

$$A_{ss} = 0.012 D_{50} \frac{D_*^{-0.6}}{(\Delta g D_{50})^{1.2}} \quad (8.262)$$

$\xi$  a general multiplication factor

$$\xi = \left( \sqrt{U^2 + \frac{0.018}{C_D} U_{rms}^2} - U_{cr} \right)^{2.4} \quad (8.263)$$

where  $U$  is the total depth-averaged velocity and  $C_D$  is the drag coefficient due to currents, defined by:

$$C_D = \left( \frac{\kappa}{\ln(H/z_0) - 1} \right)^2 \quad (8.264)$$

where  $z_0$  equals 6 mm and the Von Kármán constant  $\kappa$  is set to 0.4.

The bedslope correction factor is not explicitly included in this formula as it is a standard correction factor available in the online morphology module. The method is intended for conditions in which the bed is rippled.

The following formula specific parameters have to be specified in the input files of the Transport module (See section A.3): the calibration factor  $A_{cal}$ , the ratio of the two characteristic grain sizes  $D_{90}/D_{50}$  and the  $z_0$  roughness height.

### 8.5.10 Soulsby

The sediment transport relation has been implemented based on the formulations provided in [Soulsby \(1997\)](#). References in the following text refer to this book.

If the wave period  $T_p$  is smaller than  $10^{-6}$  s, the wave period  $T_p$  is set to 5 s and the root-mean-square wave height is set to 1 cm. Furthermore, the wave period is limited to values larger than 1 s. The root-mean-square wave height is limited to values smaller than  $0.4 H$ , where  $H$  is the water depth.

The sediment transport is set to zero in case of velocities smaller than  $10^{-6}$  m/s, water depth larger than 200 m or smaller than 1 cm.

The root-mean-square orbital velocity  $U_{rms}$  and the orbital velocity  $U_{orb}$  are computed as

$$U_{rms} = \sqrt{2}U_{orb} = \sqrt{2} \frac{\pi H_{rms}}{T_p \sinh(kH)} \quad (8.265)$$

For a flat, non-rippled bed of sand the  $z_0$  roughness length is related to the grain size as ([Soulsby, 1997](#), eq.25, p.48) where  $\chi$  is a user-defined constant:

$$z_0 = \frac{D_{50}}{\chi} \quad (8.266)$$

The relative roughness is characterised using  $a_*$ :

$$a_* = \frac{U_{orb} T_p}{z_0} \quad (8.267)$$

which is subsequently used to determine the friction factor of the rough bed according to [Swart \(1974\)](#) ( $\equiv$  Equations 8.107, 8.188 and 8.227):

$$f_w = \begin{cases} 0.3 & \text{if } a_* \leq 30\pi^2 \\ 0.00251 \exp(14.1a_*^{-0.19}) & \text{if } a_* > 30\pi^2 \end{cases} \quad (8.268)$$

which corresponds to formulae 60a/b of Soulsby (p.77) using  $r = a_*/(60\pi)$  where  $r$  is the relative roughness used by Soulsby. The friction factor is used to compute the amplitude of the bed shear-stress due to waves as:

$$\tau_w = \frac{1}{2} \rho f_w U_{orb}^2 \quad (8.269)$$

Furthermore, the shear stress due to currents is computed as:

$$\tau_c = \rho C_D U^2 \quad (8.270)$$

where

$$C_D = \left( \frac{\kappa}{1 + \ln(z_0/H)} \right)^2 \quad (8.271)$$

as defined on [Soulsby \(1997, p.53–55\)](#). The interaction of the currents and waves is taken into account using the factor  $Y$  in the following formula for mean bed shear stress during a wave cycle under combined waves and currents ([Soulsby, 1997, p.94](#)):

$$\tau_m = Y (\tau_w + \tau_c) \quad (8.272)$$

**Table 8.2:** Overview of the coefficients used in the various regression models (Soulsby et al., 1993)

Model	b1	b2	b3	b4	p1	p2	p3	p4
1 (FR84)	0.29	0.55	-0.10	-0.14	-0.77	0.10	0.27	0.14
2 (MS90)	0.65	0.29	-0.30	-0.21	-0.60	0.10	0.27	-0.06
3 (HT91)	0.27	0.51	-0.10	-0.24	-0.75	0.13	0.12	0.02
4 (GM79)	0.73	0.40	-0.23	-0.24	-0.68	0.13	0.24	-0.07
5 (DS88)	0.22	0.73	-0.05	-0.35	-0.86	0.26	0.34	-0.07
6 (BK67)	0.32	0.55	0.00	0.00	-0.63	0.05	0.00	0.00
7 (CJ85)	0.47	0.29	-0.09	-0.12	-0.70	0.13	0.28	-0.04
8 (OY88)	-0.06	0.26	0.08	-0.03	-1.00	0.31	0.25	-0.26

**Table 8.3:** Overview of the coefficients used in the various regression models, continued (Soulsby et al., 1993)

Model	q1	q2	q3	q4	J
1 (FR84)	0.91	0.25	0.50	0.45	3.0
2 (MS90)	1.19	-0.68	0.22	-0.21	0.50
3 (HT91)	0.89	0.40	0.50	-0.28	2.7
4 (GM79)	1.04	-0.56	0.34	-0.27	0.50
5 (DS88)	-0.89	2.33	2.60	-2.50	2.7
6 (BK67)	1.14	0.18	0.00	0.00	3.0
7 (CJ85)	1.65	-1.19	-0.42	0.49	0.60
8 (OY88)	0.38	1.19	0.25	-0.66	1.50

The formula for  $Y$  is given by:

$$Y = X [1 + bX^p (1 - X)^q] \quad (8.273)$$

where:

$$X = \frac{\tau_c}{\tau_c + \tau_w} \quad (8.274)$$

and  $b$  is computed using:

$$b = \left( b_1 + b_2 |\cos \phi|^J \right) + \left( b_3 + b_4 |\cos \phi|^J \right) {}^{10}\log(f_w/C_D) \quad (8.275)$$

and  $p$  and  $q$  are determined using similar equations. In this formula  $\phi$  equals the angle between the wave angle and the current angle, and the coefficients are determined by the model index *modind* and tables 8.2 and 8.3 (related to Soulsby (1997, Table 9, p.91)):

Using the shear stresses given above, the following two Shields parameters are computed:

$$\theta_m = \frac{\tau_m}{\rho g \Delta D_{50}} \text{ and } \theta_w = \frac{\tau_w}{\rho g \Delta D_{50}} \quad (8.276)$$

Furthermore,  $D_*$  is defined as (Soulsby, 1997, p.104):

$$D_* = \left( \frac{g\Delta}{\nu^2} \right)^{1/3} D_{50} \quad (8.277)$$

with which a critical Shields parameter is computed (Soulsby, 1997, eq.77, p.106):

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055 (1 - \exp(-0.02D_*)) \quad (8.278)$$

The sediment transport rates are computed using the following formulations for normalised transport in current direction and normal direction (Soulsby, 1997, eq.129, p.166/167):

$$\Phi_{x1} = 12 (\theta_m - \theta_{cr}) \sqrt{\theta_m + \varepsilon} \quad (8.279)$$

$$\Phi_{x2} = 12 (0.95 + 0.19 \cos(2\phi)) \theta_m \sqrt{\theta_w + \varepsilon} \quad (8.280)$$

$$\Phi_x = \max(\Phi_{x1}, \Phi_{x2}) \quad (8.281)$$

$$\Phi_y = \frac{12 (0.19\theta_m\theta_w^2 \sin(2\phi))}{(\theta_w + \varepsilon)^{1.5} + 1.5 (\theta_m + \varepsilon)^{1.5}} \quad (8.282)$$

where  $\varepsilon$  is a small constant ( $10^{-4}$ ) to prevent numerical complications. From these expression are finally the actual bedload transport rates obtained:

$$S_{b,x} = \frac{\sqrt{g\Delta D_{50}^3}}{U} (\Phi_x u - \Phi_y v) \quad (8.283)$$

$$S_{b,y} = \frac{\sqrt{g\Delta D_{50}^3}}{U} (\Phi_x v - \Phi_y u) \quad (8.284)$$

The transport vector is imposed as bedload transport due to currents. The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)): calibration coefficient  $A_{cal}$ , the model index for the interaction of wave and current forces  $modind$  (integer number 1 to 8) and the  $D_{50}/z_0$  ratio  $\chi$  (about 12).

### 8.5.11 Ashida–Michiue (1974)

The transport rate is given by a generalised version of the Ashida-Michiue formulation:

$$S_{bc} = \alpha \sqrt{\Delta g D_{50}^3} \theta^m \left( 1 - \xi \frac{\theta_c}{\theta} \right)^p \left( 1 - \sqrt{\xi \frac{\theta_c}{\theta}} \right)^q \quad (8.285)$$

where  $\xi$  is the hiding and exposure factor for the sediment fraction considered and:

$$\theta = \left( \frac{q}{C} \right)^2 \frac{1}{\Delta D_{50}} \quad (8.286)$$

in which  $q$  is the magnitude of the flow velocity. The transport rate is imposed as bedload transport due to currents  $S_{bc}$ . The following formula specific parameters have to be specified in the input files of the Transport module (See [section A.3](#)):  $\alpha$ ,  $\theta_c$ ,  $m$ ,  $p$  and  $q$  (Ashida and Michiue recommend  $\alpha=17$ ,  $\theta_c=0.05$ ,  $m=1.5$ ,  $p=1$  and  $q=1$ ).

### 8.5.12 Wilcock–Crowe (2003)

The Wilcock-Crowe transport model is a fractional surface based transport model for calculating bedload transport of mixed sand and gravel sediment. The equations and their development are described in Wilcock and Crowe (2003). The bedload transport rate of each size fraction is given by:

$$S_{bi} = \frac{W_i^* F_i U_*^3}{\Delta g} \quad (8.287)$$

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14 \left(1 - \frac{0.894}{\phi^{0.5}}\right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases} \quad (8.288)$$

$$\phi = \frac{\tau}{\tau_{ri}} \quad (8.289)$$

$$\frac{\tau_{ri}}{\tau_{rm}} = \left(\frac{D_i}{D_m}\right)^b \quad (8.290)$$

$$\tau_{rm} = (0.021 + 0.015 \exp(-20F_s)) (\rho_s - \rho_w) g D_g \quad (8.291)$$

$$b = \frac{0.67}{1 + \exp\left(1.5 - \frac{D_i}{D_g}\right)} \quad (8.292)$$

where:

$D_i$	$D_{50}$ of size fraction $i$
$D_g$	geometric mean grain size of whole grain size distribution
$F_i$	proportion of size fraction $i$ on the bed surface
$F_s$	proportion of sand on the bed surface
$S_{bi}$	bedload transport rate of size fraction $i$
$W_i^*$	dimensionless bedload transport rate of size fraction $i$
$\Delta$	the relative density of the sediment $(\rho_s - \rho_w) / \rho_w$
$\tau_{ri}$	reference shear stress of grains of size $D_i$
$\tau_{rm}$	reference shear stress of grains of size $D_g$

#### Remarks:

- ◇ The Wilcock-Crowe model incorporates its own hiding function so no external formulation should be applied.
- ◇ The roughness height used for the calculation of grain shear stress during the development of the Wilcock-Crowe transport model was  $k_s = 2D_{65}$ .
- ◇ This sediment transport formula does not have any input parameters that can be, or need to be, tuned.

### 8.5.13 Gaeuman et al. (2009) laboratory calibration

The Gaeuman et al. sediment transport model is a modified form of the Wilcock-Crowe model which uses the variance of grain size distribution on the phi scale ( $\sigma_\phi^2$ ) rather than the fraction of sand on the bed surface ( $F_s$ ) as a measure of the bed surface condition for use in the calculation of reference shear stress. The 'laboratory calibration' implementation of the Gaeuman et al. transport model is calibrated to the experimental data used in the derivation of the Wilcock-Crowe transport model. The model, its derivation and calibration is described in Gaeuman et al. (2009).

The formulae for the calculation of  $S_{bi}$ ,  $W_i^*$ ,  $\phi$  and  $\tau_{ri}$  are the same as for the Wilcock-Crowe transport model (Equations 8.287, 8.288, 8.289 and 8.290) but the calculation of  $\tau_{rm}$  and  $b$

differs.

$$\tau_{rm} = \left( \theta_{c0} + \frac{0.015}{1 + \exp(10.1\sigma_\phi^2 - 14.14)} \right) (\rho_s - \rho_w) g D_g \quad (8.293)$$

$$b = \frac{1 - \alpha_0}{1 + \exp\left(1.5 - \frac{D_i}{D_g}\right)} \quad (8.294)$$

$$\sigma_\phi^2 = \sum_{i=1}^n \left( {}^2\log\left(\frac{D_i}{D_g}\right) \right)^2 F_i \quad (8.295)$$

where  $\theta_{c0}$  and  $\alpha_0$  are user specified parameters (See [section A.3](#)). If the values  $\theta_{c0} = 0.021$  and  $\alpha_0 = 0.33$  are specified the original relation calibrated to the Wilcock-Crowe laboratory data is recovered.

**Remark:**

- ◇ The Gaeuman et al. model incorporates its own hiding function so no external formulation should be applied.

#### 8.5.14 Gaeuman et al. (2009) Trinity River calibration

The 'Trinity River calibration' implementation of the Gaeuman et al. transport model is calibrated to observed bedload transport rates in the Trinity River, USA and is described in [Gaeuman et al. \(2009\)](#). It differs from the 'laboratory calibration' implementation in the calculation of  $\tau_{rm}$  and  $b$ .

$$\tau_{rm} = \left( \theta_{c0} + \frac{0.022}{1 + \exp(7.1\sigma_\phi^2 - 11.786)} \right) (\rho_s - \rho_w) g D_g \quad (8.296)$$

$$b = \frac{1 - \alpha_0}{1 + \exp\left(1.9 - \frac{D_i}{3D_g}\right)} \quad (8.297)$$

where  $\theta_{c0}$  and  $\alpha_0$  are user specified parameters (See [section A.3](#)). If the values  $\theta_{c0} = 0.03$  and  $\alpha_0 = 0.3$  are specified the original Gaeuman et al. formulation calibrated to the Trinity River is recovered.

**Remark:**

- ◇ The Gaeuman et al. model incorporates its own hiding function so no external formulation should be applied.

#### 8.5.15 Van Thiel / Van Rijn

The sediment transport formula is based on [Van Thiel de Vries \(2009\)](#), and [Van Rijn \(2007a,b\)](#).

The critical velocity for entrainment is based on the weighted contribution of the critical velocity due to currents  $U_{crc}$  and due to waves  $U_{crw}$ .

$$U_{cr} = \beta_2 U_{crc} + (1 - \beta_2) U_{crw} \quad (8.298)$$

The critical velocity due to currents is based on [Shields \(1936\)](#) and [Maynord \(1978\)](#); [Neill](#)

(1968) for the gravel part.

$$U_{crc} = \begin{cases} 0.19 D_{50}^{0.1} \log 10 \left( \frac{4h}{D_{90}} \right) & \text{for } D_{50} \leq 0.0005 \\ 8.5 D_{50}^{0.6} \log 10 \left( \frac{4h}{D_{90}} \right) & \text{for } D_{50} \leq 0.002 \\ 1.3 \sqrt{\Delta g D_{50}} \left( \frac{h}{D_{50}} \right)^{1/6} & \text{for } D_{50} > 0.002 \end{cases} \quad (8.299)$$

The critical velocity due to waves is based on Komar and Miller (1975):

$$U_{crw} = \begin{cases} 0.24 (\Delta g)^{2/3} (D_{50} T_{rep})^{1/3} & \text{for } D_{50} \leq 0.0005 \\ 0.95 (\Delta g)^{0.57} (D_{50})^{0.43} T_{rep}^{0.14} & \text{for } D_{50} > 0.0005 \end{cases} \quad (8.300)$$

The parameter  $\beta_2$  is a weighting between the flow magnitude  $U_{tot}$  and the turbulence adjusted root-mean-square orbital velocity  $U_{rms,2}$ :

$$\beta_2 = \frac{U_{tot}}{\max(U_{tot} + \sqrt{U_{rms,2}^2}, 0.005)} \quad (8.301)$$

The turbulence adjusted root mean square orbital velocity  $U_{rms,2}$  is defined as

$$U_{rms,2}^2 = U_{rms}^2 + 1.45 k_b, \quad (8.302)$$

where  $U_{rms}$  is defined according to Equation (8.265). The term  $k_b$  accounts for wave-breaking induced turbulence at the bed, and the equation by Roelvink and Stive (1989) is used to account for this:

$$k_b = \frac{k}{\exp(h/H_{rms}) - 1} \quad (8.303)$$

$k$  is the time averaged turbulence variance at the water surface. For wave model 3 and 6 the formulation by Guérin *et al.* (2018) is used, and for wave model 4 the formulation by Battjes (1975); Battjes and Stive (1985) is used.

The velocity asymmetry is determined as function of wave skewness  $S_k$ , wave asymmetry parameter  $A_s$ , root-mean square velocity  $u_{rms}$  and two calibration factor  $f_{Sk}$  and  $f_{As}$ . A higher value for  $U_a$  will simulate a stronger onshore sediment transport component.

$$U_a = (f_{Sk} S_k - f_{As} A_s) U_{rms} \quad (8.304)$$

The method to determine the skewness and asymmetry is either based on Van Thiel de Vries (2009) (waveform=2, default) or on Ruessink *et al.* (2012). The keyword `waveform` sets this.

Subsequently, corrections for hindered erosion and effect of the bed slope on the incipient motion are included.

Under overwash and breaching conditions (high flow velocities and large bed level variations in time), dilatancy might hinder the erosion rates. To activate this the keyword `dilatancy`

can be set to 1. When activated, a correction factor  $f_R$  is computed to account for this (Van Rhee, 2010).

$$f_R = \frac{v_e \rho_{max} - \rho_s}{k_l} \frac{A_R}{1 - \rho_{max} \Delta} \quad (8.305)$$

The permeability  $k_l$  is defined according to the relation of (Bezuijnen *et al.*, 1987):

$$k_l = \frac{g}{160\nu} D_{15}^2 \frac{\rho_s^3}{(1 - \rho_s^2)} \quad (8.306)$$

Similarly a correction factor is introduced for the effect of bed slope on incipient motion:

$$f_b = \frac{\cos(\psi) \sin(\beta) + \sqrt{\cos^2(\beta) \tan^2(\phi_i) - \sin^2(\psi) \sin^2(\beta)}}{\tan(\phi_i)} \quad (8.307)$$

, where  $\psi$  is the difference in angle between the flow direction and the on-slope directed vector,  $\beta$  the bed slope and  $\phi_i$  the angle of repose for the sediment fraction  $i$ .

When dilatancy is activated the above equation is adapted according to (De Vet, 2014):

$$f_b = \frac{\cos(\psi) \sin(\beta) + \sqrt{(f_R^2 + 2f_R \cos(\beta) + \cos^2(\beta)) \tan^2(\phi_i) - \sin^2(\psi) \sin^2(\beta)}}{\tan(\phi_i)} \quad (8.308)$$

Finally, depending on the setting of `bedslpini`, which sets whether or not to include bed slope effects on the threshold of motion, the critical velocity for entrainment is adjusted as follows for bedload transport:

$$U_{cr,b} = \begin{cases} U_{cr} \sqrt{1 + f_R} & \text{for } \text{bedslpini} = 0 \\ U_{cr} \sqrt{1 + f_b^2} & \text{for } \text{bedslpini} = 1, 2 \end{cases} \quad (8.309)$$

For suspended load transport the critical velocity reads:

$$U_{cr,s} = \begin{cases} U_{cr}(1 + \sqrt{f_R}) & \text{for } \text{bedslpini} = 0, 2 \\ U_{cr,b} & \text{for } \text{bedslpini} = 1 \end{cases} \quad (8.310)$$

The velocity used to determine the transport is the average flow magnitude combined with the nearbed wave orbital flow velocity, accounting for turbulence.

$$U_T = \min \left( \sqrt{U_{tot}^2 + 0.64 U_{rms,2}^2}, \frac{S_{max} g D_{50} \Delta}{\max(C_f, 1^{-10})} \right) \quad (8.311)$$

The reference concentrations for bedload and suspended load, are computed as:

$$C_{eq,b} = \min \left( \frac{A_{sb}}{h} (U_T - U_{cr,c})^{1.5}, \frac{c_{max} h}{2} \right) \quad (8.312)$$

$$C_{eq,s} = \frac{1}{h} \min \left( \frac{A_{ss}}{h} (U_T - U_{cr,s})^{2.4}, \frac{c_{max} h}{2} \right) \quad (8.313)$$



where  $c_{max}$  is prescribed through the keyword `cmax` and the bedload factor  $A_{sb}$  and the suspended load factor  $A_{ss}$  are determined as follows:

$$A_{sb} = 0.015h \frac{(D_{50}/h)^{1.2}}{(\Delta g D_{50})^{0.75}} \quad (8.314)$$

$$A_{ss} = 0.012D_{50} \frac{D_*^{-0.6}}{(\Delta g D_{50})^{1.2}} \quad (8.315)$$

The advection-diffusion solver is subsequently used to solve the suspended transport. The bed load transport is computed using

$$S_{b,x} = (U + U_{a,x}) C_{eq,b} \quad (8.316)$$

$$S_{b,y} = (V + U_{a,y}) C_{eq,b} \quad (8.317)$$

in which the velocity asymmetry vector  $U_a$  is oriented in the direction of wave propagation.

#### 8.5.16 Soulsby / Van Rijn, XBeach flavour

Soulsby (1997), Van Rijn (1984c)

#### 8.5.17 Delft3D-ASMITA hybrid

This is not an ordinary transport formula. By using this formula, you switch your modelling concept from the default mode in which the initial bed level develops due to computed sediment transport rates towards an uncertain future state, to the conceptual ASMITA approach in which you define the target bed level and let the model determine how to get towards that target based on sediment availability and transport capacity. You should not use this transport formula together with other transport formulas.

The sediment transport is given by zero bed load

$$S_b^{(\ell)} = 0 \quad (8.318)$$

and an equilibrium concentration

$$c_{eq}^{(\ell)} = c_E \left( \frac{h_e}{h} \right)^n \quad (8.319)$$

where

$c_E$	Global equilibrium concentration [ $\text{kg m}^{-3}$ ] given <code>CEqui</code>
$h_e$	Equilibrium depth [m] relative to $z_{w,ASMITA}$ given <code>HEqui</code> typically spatial varying but always constant in time
$h$	Instantaneous depth [m], computed as $z_{w,ASMITA} - z_b$ . To avoid instabilities when the depth goes to zero, the value of $h$ is limited to be at least equal to $h_e/r_{max}$ where $r_{max}$ is given by <code>MaxHH</code> . This limiter restricts the value of the depth ratio between the brackets to at most the specified value $r_{max}$ .
$n$	Exponent of the concentration formula [-]
$z_b$	Instantaneous bed level [m+REF]
$z_{w,ASMITA}$	ASMITA reference level [m+REF] for evaluating the depth.

The source and sink term  $S^{(\ell)}$  per fraction  $\ell$  in the 2D advection-diffusion Equation (8.2) is given by Equation (8.66) with the relaxation time scale given by Equation (8.67). This term

includes a dimensionless time-scale  $\tilde{T}^{(\ell)}$  which, for normal sediment transport formulas, is given by Galappatti (1983), but here we use a constant value  $\tilde{T}^{(\ell)} = 1$  such that  $T^{(\ell)} = h/w_s^{(\ell)}$ .

The initial sediment concentration should be uniform and equal to the global equilibrium concentration  $c_E$ . The same concentration  $c_E$  should also be specified for all open boundaries and point or lateral discharges.

## 8.6 Morphological updating

The elevation of the bed is dynamically updated at each computational time-step. This is one of the distinct advantages over an online morphological computation as it means that the hydrodynamic flow calculations are always carried out using the latest bed levels.



**Note:** Although the bed level is undated every computational time-step, still the equations for the hydrodynamics (fluid mass and momentum conservation), the suspended sediment (suspended sediment conservation) and the bed updating are decoupled into three separate solve steps: the system is still not treated as a fully coupled system of equations.

At each time-step, the change in the mass of bed material that has occurred as a result of the sediment sink and source terms and transport gradients is calculated. For this we need to understand which source and sink terms, and transport gradients may occur. The distinction between bed load transport and suspended load transport is defined by the interaction with the bed. Bed load frequently interacts with the bed, it represents sliding, rolling and saltating transport of grains. Grains transported as suspended load touch the bed less frequently; they are usually pushed back upward by turbulent motion of the currents. The transition from bed load to suspended load occurs at the reference height  $a$ . Consequently, Equation (8.1) and Equation (8.2) should strictly only be applied for the sediment above the reference height since the sediment transported below the reference height is also included in the bed load term. For this purpose a corrective transport vector  $\vec{S}_c^{(\ell)}$  has been introduced (only in 3D simulations, i.e. when Equation (8.1) is applied). The resulting equation for the depth integrated mass of sediment in the bed is given by

$$\begin{aligned} \frac{1}{\alpha_{MF}} \frac{\partial M_b^{(\ell)}}{\partial t} + \frac{\partial S_{b,c,x}^{(\ell)}}{\partial x} + \frac{\partial S_{b,w,x}^{(\ell)}}{\partial x} + \frac{\partial S_{s,w,x}^{(\ell)}}{\partial x} - \frac{\partial S_{c,x}^{(\ell)}}{\partial x} \\ + \frac{\partial S_{b,c,y}^{(\ell)}}{\partial y} + \frac{\partial S_{b,w,y}^{(\ell)}}{\partial y} + \frac{\partial S_{s,w,y}^{(\ell)}}{\partial y} - \frac{\partial S_{c,y}^{(\ell)}}{\partial y} = -S^{(\ell)} + M_{D\&D}^{(\ell)}, \quad (8.320) \end{aligned}$$

where:

$M_b^{(\ell)}$	depth integrated mass of sediment fraction $(\ell)$ in the bed [ $\text{kg m}^{-2}$ ]
$\alpha_{MF}$	morphological acceleration factor [-]
$S_{b,c,x}^{(\ell)}$ and $S_{b,c,y}^{(\ell)}$	unit bed load transport of fraction $(\ell)$ due to currents [ $\text{kg m}^{-1} \text{s}^{-1}$ ]
$S_{b,w,x}^{(\ell)}$ and $S_{b,w,y}^{(\ell)}$	unit bed load transport of fraction $(\ell)$ due to waves [ $\text{kg m}^{-1} \text{s}^{-1}$ ]
$S_{s,w,x}^{(\ell)}$ and $S_{s,w,y}^{(\ell)}$	unit suspended load transport of fraction $(\ell)$ due to waves [ $\text{kg m}^{-1} \text{s}^{-1}$ ]
$S_{c,x}^{(\ell)}$ and $S_{c,y}^{(\ell)}$	corrective transport of fraction $(\ell)$ compensating the suspended load transport by Equation (8.1) below the reference height [ $\text{kg m}^{-1} \text{s}^{-1}$ ], i.e. defined as

$$\vec{S}_c^{(\ell)} = \int_{z_b}^{z_b+a} c \vec{u} dz \quad (8.321)$$

where  $a$  is the reference height [m]

$S^{(\ell)}$	source and sink term representing the exchange with the bed, i.e. entrainment and deposition [kg/s]
$M_{D\&D}^{(\ell)}$	net dumping (or dredging) rate of sediment fraction ( $\ell$ ) due to dredging and dumping operations [kg s <sup>-1</sup> ]

The unit transport for bed load due to currents ( $\vec{S}_{b,w}^{(\ell)}$ ), bed load due to waves ( $\vec{S}_{s,w}^{(\ell)}$ ) and suspend load due to waves ( $\vec{S}_{s,w}^{(\ell)}$ ) and the source and sink term ( $S^{(\ell)}$ ) depend on the sediment transport formula used for the sediment fraction. The corrective transport compensates for the suspended sediment that was transported below the reference height  $a$ .

The model may keep track of the depth integrated mass of sediment  $M_b^{(\ell)}$ , or resolve the variation in the bed composition  $M_b^{(\ell)}(z)$  over the alluvial deposit (bed stratigraphy).

This change in mass is subsequently translated into a bed level change based on the bed porosity and the densities of the various sediment fractions (optionally, combined into dry bed densities). The bed level change is given by

$$z_b = z_{b,0} + \delta_b(M_b^{(\ell)}, \rho_s^{(\ell)}, p), \quad (8.322)$$

where:

$z_b$	bed level, i.e. top of the alluvial sediment deposit, measured upwards relative to some reference level [m+ RL]
$z_{b,0}$	bed rock level, i.e. bottom of the alluvial sediment deposit, which may vary due to external forcing (e.g. subsidence or uplift due to tectonics) measured upwards relative to some reference level [m + RL]
$\delta_b(, , )$	thickness of the alluvial sediment deposit as function of the sediment mass, sediment density and the porosity [-]
$\rho_s^{(\ell)}$	specific density of the sediment [kg m <sup>-3</sup> ]
$p$	porosity [-], i.e. void or water fraction of the total bed volume, depending on bed composition and degree of consolidation and compaction

Alternatively, the time derivative form of Equation (8.322) may be used

$$\frac{\partial z_b}{\partial t} = \frac{\partial z_{b,0}}{\partial t} + \sum_{\ell} \frac{\partial \delta_b}{\partial M_b^{(\ell)}} \frac{\partial M_b^{(\ell)}}{\partial t} + \frac{\partial \delta_b}{\partial p} \frac{\partial p}{\partial t}. \quad (8.323)$$

**Note:** One obtains the typical Exner equation by ignoring the variability in the bed porosity such that



$$\delta_b(M_b^{(\ell)}, \rho_s^{(\ell)}, p) = \frac{1}{1-p} \sum_{\ell} \frac{M_b^{(\ell)}}{\rho_s^{(\ell)}} \quad (8.324)$$

and inserting this expression into Equation (8.322) and Equation (8.320) while ignoring all terms related to suspended load, wave driven transport, dredging and dumping and external forcing of the bed rock level. Both the bed levels at the cell centres and cell interfaces are updated.

**Remark:**

- ◇ Delft3D-FLOW specific: The bed levels stored at the grid points (if the initial bed levels were specified at that location) are only updated for writing to the communication file and the result files.

A number of additional features have been included in the morphological updating routine in order to increase the flexibility. These are discussed below.

### **Morphological “switch”**

You can specify whether or not to update the bed levels by setting the `BedUpd` (previously called `MorUpd`) flag in the morphology input file to `true` or `false`, respectively. It may be useful to turn bed level updating off if only the initial patterns of erosion and deposition are required, or an investigation of sediment transport patterns for given bed levels is required.

#### **Remark:**

- ◇ The use of `BedUpd` (or `MorUpd`) affects only the bed levels (at  $\zeta$  and velocity points). The mass of sediment available in the bed, i.e. the bed composition, will always be updated *unless* the `CmpUpd` flag set to `false`<sup>2</sup>. If you wish to prevent any change in both the bed composition *and* the bed levels from the initial condition, you must set both flags `BedUpd = false` and `CmpUpd = false`. Alternatively, this may be achieved by either setting the morphological delay interval `MorStt` to a value larger than the simulation period, or by setting the morphological factor `MorFac` to 0. See below for a description of these two user variables.

The model allows you to eventually include both bed composition and bed level updating in a simulation, but not to activate those processes immediately at the start of the simulation. By means of `CmpUpdStt` you can set the start time of the bed composition updating, and with `BedUpdStt`<sup>3</sup> you can set the start time of the bed level updating. The latter time should always be set to a time larger or equal to the former time; by default they are equal. The sediment transport fluxes are by default computed from the very beginning, but their computation can optionally be delayed until the time set by `SedTransStt` which should be earlier than `CmpUpdStt`.

### **Morphological delay**

Frequently, a hydrodynamic simulation will take some time to stabilise after transitioning from the initial conditions to the (dynamic) boundary conditions. It is likely that during this stabilisation period the patterns of erosion and accretion that take place do not accurately reflect the true morphological development and should be ignored. This is made possible by use of `SedTransStt`, `CmpStt` and `MorStt` whereby you can specify a time interval (in `TUnit`<sup>4</sup> after the start time) after which the sediment transport computation, bed composition, and/or morphological bottom updating, respectively, will begin. During the `SedTransStt` time interval, all calculations will proceed as normal, except sediment transport which will not be computed. During the `CmpStt`/`MorStt` time interval all other calculations will proceed, including sediment transport, as normal (sediment will be available for suspension for example) however the effect of the sediment fluxes on the available bottom composition and bed levels will not be taken into account.

### **Morphological time scale factor**

One of the complications inherent in carrying out morphological projections on the basis of hydrodynamic flows is that morphological developments take place on a time scale several times longer than typical flow changes (for example, tidal flows change significantly in a period

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<sup>2</sup>The `CmpUpd` can be set per sediment fraction in the sed-file. If you switch off composition updating for a subset of all sediment fractions, the mass of those sediment fractions in the bed will not be updated. As a consequence, those sediment fractions will not contribute to the bed level updating either.

<sup>3</sup>The old keyword `MorStt` is still supported.

<sup>4</sup>Note that the time unit `TUnit` is by default equal to minutes in Delft3D-FLOW and seconds in D-Flow FM

of hours, whereas the morphology of a coastline will usually take weeks, months, or years to change significantly). One technique for approaching this problem is to use a “morphological time scale factor” whereby the speed of the changes in the morphology is scaled up to a rate that it begins to have a significant impact on the hydrodynamic flows. This can be achieved by specifying a non-unity value for the variable `MorFac` in the morphology input file.

**Remark:**

- ◇ The *Morphological scale factor* can also be time-varying, see [section A.8](#). This feature is not yet supported by the GUI. You have to edit the `<*.mor>` file manually.

The implementation of the morphological time scale factor is achieved by simply multiplying the erosion and deposition fluxes from the bed to the flow and vice-versa by the `MorFac`-factor, at each computational time-step. This allows accelerated bed-level changes to be incorporated dynamically into the hydrodynamic flow calculations.

While the maximum morphological time scale factor that can be included in a morphodynamic model without affecting the accuracy of the model will depend on the particular situation being modelled, and will remain a matter of judgement, tests have shown that the computations remain stable in moderately morphologically active situations even with `MorFac`-factors in excess of 1 000. We also note that setting `MorFac=0` is often a convenient method of preventing both the flow depth and the quantity of sediment available at the bottom from updating, if an investigation of a steady state solution is required.

**Remarks:**

- ◇ Verify that the morphological factor that you use in your simulation is appropriate by varying it (e.g. reducing it by a factor of 2) and verify that such changes do not affect the overall simulation results.
- ◇ The interpretation of the morphological factor differs for coastal and river applications. For coastal applications with tidal motion, the morphological variations during a tidal cycle are often small and the hydrodynamics are not significantly affected by the bed level changes. By increasing the morphological factor to for instance 10, the morphological changes during one simulated tidal cycle are increased by this factor. From a hydrodynamical point of view this increase in morphological development rate is allowed if the hydrodynamics is not significantly influenced. In that case the morphological development after one tidal cycle can be assumed to represent the morphological development that would in real life only have occurred after 10 tidal cycles. In this example the number of hydrodynamic time steps required to simulate a certain period is reduced by a factor of 10 compared to a full 1:1 simulation. This leads to a significant reduction in simulation time. However, one should note that by following this approach the order of events is changed, and possible conflicts may arise in combination with limited sediment availability and bed stratigraphy simulations. In river applications there is no such periodicity as a tidal cycle. For such applications, the morphological factor should be interpreted as a speed-up factor for morphological development without changing the order of events. Effectively, it means that the morphological development is simulated using a, for instance 10 times, larger time step than the hydrodynamics, or phrased more correctly the hydrodynamics is simulated at a 10 times faster rate. This means that in case of time-varying boundary conditions (e.g. river hydrograph) the time-scale of these forcings should be sped up: a 20 day flood peak will be compressed in 2 days. However, one should take care that by speeding up the hydrodynamic forcings one does not substantially change the nature of the overall hydrodynamic and morphological development: a quasi-steady flood period should not become a short, dynamic flash flood. For river applications, changing the morphological factor must be associated with changing all external time-varying forcings. For coastal applications only the overall simulation time should be adjusted. Note that the combination of a river-like flood peak

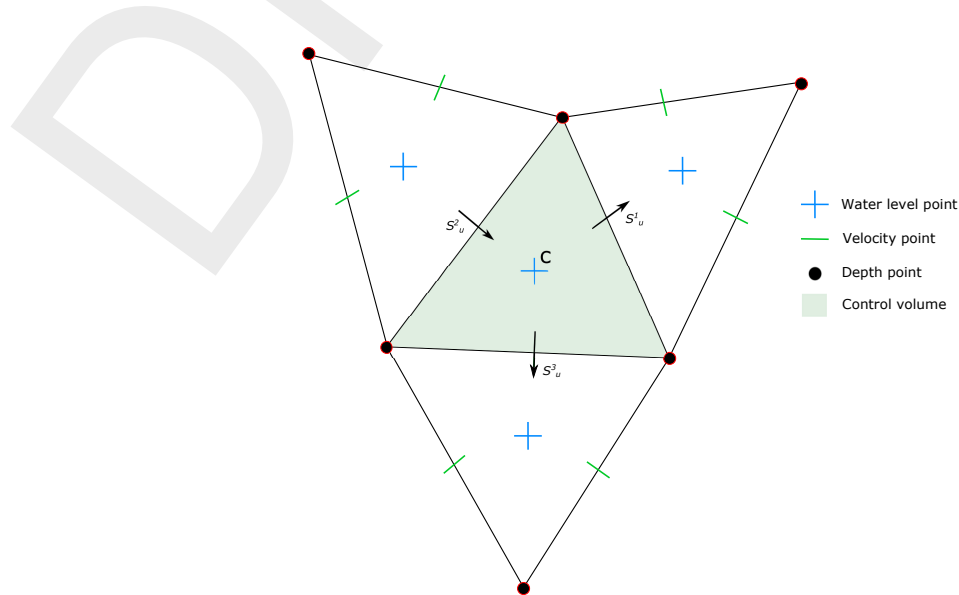
and a tidal motion will cause problems when interpreting morphological factor not equal to 1.

- ◇ The effect of the morphological factor is different for bed and suspended load. At each time step bedload is picked-up from the bed and deposited on the bed: only the transports are increased by the morphological factor used for the time step considered. However, in case of suspended load there is a time-delay between the time of erosion and the time of deposition. The erosion and deposition fluxes are increased by the morphological factor, but the suspended concentrations are not (since that would influence the density effects). It is possible to vary the morphological factor during a simulation to speed up relatively quiet periods more than relatively active periods. Such changes in the morphological factor will not influence the mass balance of a bed or total load simulation since pickup and deposition are combined into one time step. However, in case of suspended load the entrainment and deposition may occur at time-steps governed by different morphological factors. In such cases the entrainment flux that generated a certain suspended sediment concentration will differ from the deposition flux that was caused by the settling of the same suspended sediment. A change in morphological factor during a period of non-zero suspended sediment concentrations, will thus lead to a mass-balance error in the order of the suspended sediment volume times the change in morphological factor. The error may kept to a minimum by appropriately choosing the transition times.

### 8.6.1 Bed level updating including bedload transport

The change in the quantity of bottom sediments caused by the bedload transport is calculated using the expression:

$$\Delta_{SED}^c = \frac{\Delta t f_{MORFAC}}{A^c} \sum_i S_u^i W_u^i \quad (8.325)$$



**Figure 8.6:** Morphological control volume and bedload transport components

where:

$\Delta_{SED}^c$	change in quantity of bottom sediment at location $c$ [kg/m <sup>2</sup> ]
$\Delta t$	computational time-step [s]
$f_{MORFAC}$	user-defined morphological acceleration factor, MORFAC



$A^c$	area of computational cell at location $c$ [m <sup>2</sup> ]
$S_u^i$	computed bedload sediment transport vector in $u$ direction (direction normal to face $i$ ), held at the velocity point [kg/(m s)]
$W_u^i$	width of the face $i$ [m]

This calculation is repeated for all 'sand' and 'bedload' sediment fractions, if more than one is present, and the resulting change in the bottom sediment mass is added to the change due to the suspended sediment sources and sinks and included in the bed composition and bed level updating scheme.

### 8.6.2 Erosion of (temporarily) dry points

In the case of erosion near a dry beach or bank, the standard scheme will not allow erosion of the adjacent cells, even when a steep scour hole would develop right next to the beach. Therefore a scheme has been implemented that allows the (partial) redistribution of an erosion flux from a wet cell to the adjacent dry cells. The distribution is governed by a user-defined factor  $ThetSD$ , which determines the fraction of the erosion to assign (evenly) to the adjacent cells. If  $ThetSD$  equals zero the standard scheme is used, i.e. all erosion occurs at the wet cell. If  $ThetSD$  equals 1 all erosion that would occur in the wet cell is assigned to the adjacent dry cells. The 'wet' and 'dry' cells are in the context of the paragraph above defined as those cells at which the local water depth is larger respectively smaller than the threshold depth  $SedThr$  for computing sediment transport.

A modification to this method may be activated by specifying a parameter  $HMaxTH$  larger than the threshold depth  $SedThr$  for computing sediment transport. In this case, the factor  $ThetSD$  is used as upper limit for the fraction of the erosion to be transferred to adjacent dry cells. The actual factor to be transferred is equal to  $Thet$ , which is computed as:

$$Thet = (h_1 - SedThr) / (HMaxTH - SedThr) \times ThetSD$$

where  $Thet = \min(Thet, ThetSD)$  (8.326)

Here,  $h_1$  is the local water depth. The purpose of this formulation is to allow erosion of parts that are inactive in terms of transport but still wet, while limiting the erosion of the dry beach. If erosion of the dry beach is desired, this option is not recommended, so  $HMaxTH$  should be set less than  $SedThr$ .

#### Remark:

- ◇ The overall erosion flux is redistributed to the adjacent cells. Depending on the availability of individual sediment fractions at the central 'wet' cell and the surrounding 'dry' cells, the erosion from the adjacent cells will replenish the eroded cell with different sediment fractions than those that were eroded.

### 8.6.3 Dune front slumping

**Note:** This feature is only available in D-Flow FM.



During severe storms, when infragravity wave runup collides with and partly inundates a dune, dune face slumping can occur, and sediment is brought from the dry dune into the wet profile, where it is transported further seaward by undertow and infragravity backwash. This process is implemented in a similar way as in the XBeach model (Roelvink *et al.*, 2009), and requires the D-Flow FM surfbeat wave module (Reyns *et al.*, 2023) to model the infragravity-related hydrodynamics properly. During the morphological update, the slope magnitude between every pair of adjacent cells, calculated at the corresponding flow link position, is compared to

a critical slope (`wetslope`, `dryslope`) depending on the local depth relative to a threshold (`hswitch`). When the critical slope is exceeded, a bedload flux is constructed to bring down the slope magnitude to the appropriate critical slope value. The resulting transport flux is not applied immediately, but relaxed using the `avaltime` relaxation time. If necessary to stabilize the morphological development, the maximum allowed bed level change in one time step due to avalanching can be limited by using `DzMaxDune`.



#### Swash slope nudging

**Note:** This feature is only available in D-Flow FM.

In order to improve the modelling of the post-storm recovery of the intertidal part of a beach, [Roelvink \*et al.\* \(2019\)](#) describe the so-called bermslope concept, where the observed slope of the intertidal beach is used to adjust the modelled sediment transports to nudge the computed slope to the data. This process can be switched on by setting the keyword `bermslopetransport` in the `<*.mor>` file to `true`. In computational cells where the water depth is smaller than threshold depth `bermslopedepth` and the swash zone starts (defined by `bermslopedepth` or a limit wave height over water depth ratio `bermslopegamma`), the swash behaviour model carries out a correction on the computed transports in order to nudge the beach slope close the water line to the equilibrium slope `bermslope` as follows:

$$S_{u,corrected}^i = S_u^i - \text{bermslopefac} |S_u^i| \left( \frac{\partial z_b}{\partial s} - \text{bermslope} \right) \quad (8.327)$$

where:

$S_{u,corrected}^i$	Corrected sediment transport in cell $i$ in direction of velocity $\vec{u}$ [kg/m/s]
$S_u^i$	Sediment transport in cell $i$ in direction of velocity $\vec{u}$ [kg/m/s]
$z_b$	Bed level [m]
$s$	Space coordinate in direction of velocity $\vec{u}$ [m]
$\vec{u}$	Velocity vector in flow link direction [m/s]
<code>bermslopefac</code>	Calibration factor for bermslope effect [-]

Guidance on choosing an appropriate swash slope `bermslope` in function of the beach sediment characteristics is provided in [Roelvink \*et al.\* \(2019\)](#). The choice whether to include bedload or suspended load corrections (or both) can be set using the `bermslopebed` and `bermslopesus` keywords ([Section A.2](#)).

#### 8.6.5 Dredging and dumping

If the bed levels are updated, you may also include some dredging and dumping activities at the end of each half time step. This feature can also be used for sand mining (only dredging, no associated dumping within the model domain) and sediment nourishment (only dumping, no associated dredging within the model domain). Dredging and dumping is performed at this stage in the following order:

- ◇ For each dredge area: if the bed level exceeds a threshold level (or the water depth drops below a certain level) then the bed level is lowered based on the dredging option and the corresponding volume of sediment is removed. If the dredging capacity is less than the volume to be dredged, the sequence of dredging (e.g. top first or uniform) determines which grid cells are dredging at the current point in time.



- ◇ The volume of dredged material is summed over all cells in a dredge area and distributed over the dump areas, using the link percentages or the link order (up to the dump capacity). In simulations with multiple sediment fractions the sediment composition is tracked.
- ◇ For each dump area: the bed level is raised and the bed composition is adjusted based on the volume and characteristics of material to be dumped. The sediment may be distributed equally or non-uniformly (e.g. deepest points first) over the grid cells in the dump area.

**Remark:**

- ◇ Dredging and dumping may also be performed during initialization, before the first time-step.

**Warning:**

- ◇ Dredging large amounts of material may harm the stability of the calculation.

The dredging and dumping feature allows you to specify dredging and dumping areas as  $x,y$  polygons. Within each dredging polygon the bed levels are lowered to a user-defined depth; by default grid cells are considered to lie within a polygon if their centre lies within the polygon. It is possible to distribute the dredged material over multiple dumping locations. You may also decide to not dump the sediment back into the model (feature referred to as sand mining); this can be implemented by defining a dump polygon outside the grid, or by not specifying any dump polygon at all. This option cannot be combined with the option to dredge only as much as dump capacity is available. For sediment nourishment one should use a `[nourishment]` block specifying the amount (and, if applicable, the composition) of the nourished sediment. The dredging and dumping activities should be specified in a `<*.dad>` file; for a description of this attribute file see [section A.10](#). The master input file of D-Flow FM should contain a keyword `Fildad` referring to the file used. The `<*.dad>` file refers to the file containing the polygons.

### 8.6.6 Bed composition models and sediment availability

The morphology module currently implements two bed composition models:

- ◇ A uniformly mixed bed (one sediment layer). There is no bookkeeping of the order in which sediments are deposited and all sediments are available for erosion.
- ◇ A layered bed stratigraphy (multiple sediment layers). A user-defined number of bed composition bookkeeping layers may be included to keep track of sediment deposits. When sediments are deposited, they are initially added to the top-most layer. After mixing in the top layer, sediments are pushed towards the bookkeeping layers beneath it. The bookkeeping layers are filled up to a user-defined maximum thickness, if this threshold is exceeded a new layer is created. If the creation of a new layer would exceed the maximum number of layers specified by you, layers at the bottom of the stratigraphy stack will be merged. Only sediments in the top-most layer are available for erosion. After erosion, the top-most layer is replenished from below.

The default bed composition model is the uniformly mixed one. Currently only the default bed composition model is supported by the user interface. See [section A.2](#) on how to select the other bed composition model.

At input you must specify the amount of sediment available at the bed as the total (dry) mass of all sediment fractions in  $[\text{kg}/\text{m}^2]$ . This may be a constant value for the entire model or, alternatively, a space-varying initial sediment file (values to be specified at cell centres). The initial bed composition is assumed to be uniformly mixed.<sup>5</sup> The thickness of the total sediment

<sup>5</sup>The uniformly mixed bed can be used as input for both bed composition models. If you have more detailed

layer is calculated from the sediment mass by dividing by the user-defined dry bed density  $CDryB$ . Currently,  $CDryB$  is constant in time and space for each individual sediment fraction. The top of these sediment deposits will coincide with the initial bed level. Below the bottom of these deposits the model assumes a non-erodible bed (sometimes referred to as a fixed layer).

When the model almost runs out of sediment at a particular location, the sediment flux terms will be reduced. The reduction starts when the available sediment thickness drops below a user-defined threshold  $Thresh$ . The flux terms affected are slightly different for cohesive and non-cohesive sediments, as described below. Unfortunately, the reduction factor cannot prevent an erosion flux that is larger than the amount of sediment actually available (in the top layer). The cleanest solution of this problem would be to reduce the sediment erosion flux and repeat the time step, but this may result in cascading effects trickling into neighbouring cells and hence it may result in a significant reduction in the computational speed. We've implemented an alternative, pragmatic approach in which the erosional flux is not affected, but we keep track of the mass shortage per sediment fraction: the mass shortage has to be compensated by deposition of that particular sediment fraction (or replenishment from lower layers during erosion of other sediment fractions) before that the sediment fraction can have a non-zero mass again (at that particular grid cell). This tracking of the mass shortage is by default switched on for the layered bed, but is optional for the uniformly mixed bed ( $TrackMassShortage$  in the **Numerics** block of the mor-file).

### ***Cohesive sediment fractions***

In the case of cohesive sediment, the erosive sediment source term is reduced proportionally to the ratio of available sediment thickness over  $Thresh$ . The deposition term is never reduced.

### ***Non-cohesive sediment fractions***

In the case of non-cohesive sediments all bedload transport rates out of a grid cell are reduced by the upwind ratio of available sediment thickness over  $Thresh$ . The source and sink terms of the advection-diffusion equation are not reduced unless the erosive sediment source term is predicted to be larger than the deposition (sink) term, in that case both terms are reduced by the ratio of available sediment thickness over  $Thresh$  as shown by the following equations:

$$Source_{total} = f_r Source_{total}, \quad (8.328)$$

$$Sink_{total} = f_r Sink_{total}, \quad (8.329)$$

where  $f_r$  is a reduction factor determined by:

$$f_r = \min \left( \frac{\Delta_{sed}}{Thresh}, 1 \right), \quad (8.330)$$

where  $\Delta_{sed}$  is the thickness of sediment at the bed.

The likelihood of erosive conditions occurring is assessed by calculating the total sediment source and sink terms using the concentration from the previous time-step to evaluate the implicit sink term. If the sink term is greater than the source term, then deposition is expected, and  $f_r$  is set to 1.0 so that deposition close to the fixed layer is not hindered.

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information on the bed stratigraphy, you may use the bed stratigraphy model and specify an initial layering of the bed composition by means of the `IniComp` keyword (see [section A.2](#)) and associated initial bed composition file (see [section A.9](#)). In that case the bed composition given in the `<*.sed>` file will overruled, you have to specify dummy values though.

## 8.7 Specific implementation aspects

### ***Negative water depth check***

In rare situations (with high morphological acceleration factors) it is possible that, in one time-step, the bed accretes more than the water depth. If this occurs the water depth will become negative (water surface level is below the bed level). This situation is checked for and, if it occurs, the water surface level for the cell is set equal to the new bed level. The cell will then be set dry.

### ***Threshold depth for sediment calculations introduced***

If the water depth in a cell is less than  $SedThr$ , specified in the morphology input file, then the sediment source and sink terms for the suspended sediment fractions ('sand' and 'mud') will be set to zero (such that neither erosion nor resuspension will occur there). Note that the advection diffusion equation may bring suspended sediment into such cells but it will not interact with the bed; the only way for this sediment to leave the water column is by an increase in water depth (such that interaction is allowed) or by advective/diffusive transport out of the shallow cell. Furthermore, the bedload transport into (and out of) these cells for 'sand' and 'bedload' sediment fractions will be set to zero (bed load transport for 'mud' fractions is zero always). This restriction has been included in order to prevent numerical problems during the computation of the reference concentration, e.g. to prevent sudden bursts of sediment from occurring when computational cells are flooded.

#### **Remark:**

- ◇ In areas with very shallow water depths and sediment sources and sinks, you must ensure that the user-defined threshold depth for drying and flooding is not set too large.

### ***Calculation of bed shear in wave and current situations altered***

The calculation of the bed shear velocity  $u_*$  has been simplified in situations with waves and currents. The bed shear is always calculated using the velocities computed in the bottom computational layer, rather than using the computational layer closest to the top of the sediment mixing layer. The reference velocity in the bottom computational layer is adjusted to the top of the sediment mixing layer using the apparent bed roughness  $k_a$  before being used to compute the bed shear velocity using the physical bed roughness  $k_s$ .

### ***Depth at grid cell faces (velocity points)***

During a morphological simulation the depth stored at the  $U$  and  $V$  velocity points must be updated to reflect the bed level changes calculated in the water level points. This *used to be* performed by setting the new depth for the velocity point by copying the new depth held at the water level point, using a simple upwind numerical scheme. As this may introduce instabilities in the flow computation, especially near drying and flooding and in tidal simulations, this method has been replaced by setting the depth at  $U$  and  $V$  points equal to the *minimum* of the adjacent depths in water level points. This change significantly improves the smoothness of flooding dry cells.

#### **Remarks:**

- ◇ The setting of depths at velocity points as the minimum of the adjacent water level points only comes into effect if sediment is present and the user-defined flag `MORUPD` is `.true.` (i.e. bed level changes are expected to occur at some point during the simulation period). If this condition is not met then the depths at the velocity points do

not need to be updated during the course of the simulation.

- ◇ The program still requires the depth at velocity points to be set to MOR for morphological simulations. This anticipated that this restriction is lifted in a coming release.
- ◇ Since the MOR and MIN procedures for computing the depth at cell interfaces are equivalent, we advise you to use the MIN procedure during the calibration of a hydronamic model that will later on be converted into a morphological model.

DRAFT

## A File descriptions

### A.1 Sediment input file

The sediment input file contains the characteristics of all sediment fractions. In the record description the name of the quantities are given to simplify their reference in the formulas given in [chapter 8](#).

#### Remarks:

- ◇ The `<*.sed>` file can be formatted in a number of ways. The computational engines read all formats. The preferred format is the keyword based file described in [Table A.1](#). The Delft3D-FLOW user interface reads all formats, but writes only the preferred format. The D-Flow FM user interface reads and writes only the preferred format.
- ◇ The value of a number of keywords can be either 1 real or 1 string; the former case specifies a uniform value throughout the domain, whereas the latter case specifies a file name which may contain spatially varying values. When used with Delft3D-FLOW, the file format should be a QUICKIN file (dep-file like) with data specified in cell centres. When used with D-Flow FM, the file should have a file extension starting with “.xy” to indicate that it is a samples file.

**Table A.1:** Sediment input file with keywords

Keyword	Record description
<b>SedimentFileInformation</b>	
FileCreatedBy	contains version number of user interface
FileCreationDate	creation date and time of the <code>&lt;*.sed&gt;</code> file
FileVersion	2.00
<b>SedimentOverall</b>	
Cref	reference density (CSOIL) for hindered settling calculations (not active when $\geq 1 \cdot 10^6$ ) [kg/m <sup>3</sup> ] (1 real)
FlocModel	name of the flocculation model concept; must be <ul style="list-style-type: none"><li>◇ none (no flocculation dynamics between clay fractions),</li><li>◇ manning_dyer (two interacting floc sizes),</li><li>◇ chassagne_safar (two interacting floc sizes) or</li><li>◇ verney_etal (multiple interacting floc sizes).</li></ul> (1 string)
IopSus	backward compatibility option; specify IopSus via transport formula if needed
MudCnt	fraction of non-simulated mud in the bed; this keyword is only used if <i>none</i> of the sediment fractions is of type “mud” (1 real or 1 string; default 0)
MudTPS	backward compatibility option equivalent to SchmidtNumberMud.

continued on next page

Table A.1 — continued from previous page

Keyword	Record description
SchmidtNumberMud	turbulent Schmidt number [-] used for all cohesive sediment fractions. This value may be overruled per sediment fraction by means of the fraction <code>SchmidtNumber</code> . (1 real; default 0.7) Before the introduction of this keyword, D-Flow FM always used 1.0 irrespective of the value specified for <code>MudTPS</code> .
SchmidtNumberSand	turbulent Schmidt number [-] used for all non-cohesive sediment fractions. This value may be overruled per sediment fraction by means of the fraction <code>SchmidtNumber</code> . (1 real; default 1.0)
NFlocSizes	number of floc sizes to be used in case the <code>verney_etal</code> flocculation concept is selected. The number is equal to 2 for <code>manning_dyer</code> or <code>chassagne_safar</code> . (1 positive integer)
TBreakUp	relaxation time scale [s] towards the equilibrium distribution of clay mass over the floc sizes if the macrofloc fraction decreases (break-up dominant over flocculation). The default value is equal to the specified <code>TFloc</code> value. (1 positive float)
TFloc	relaxation time scale [s] towards the equilibrium distribution of clay mass over the floc sizes if the macrofloc fraction increases (flocculation dominant over break-up). The default value is 0 s such that equilibrium dynamics is applied. (1 positive float)
<b>Sediment</b>	
Name	name of sediment fraction (1 string); must correspond to <code>NamC</code> entry in <code>mdf</code> -file for Delft3D-FLOW and <code>SedTyp</code> equal "sand" or "mud"
SedTyp	<p>type of sediment; must be</p> <ul style="list-style-type: none"> <li>◇ clay,</li> <li>◇ silt,</li> <li>◇ sand or</li> <li>◇ gravel.</li> </ul> <p>If the old option <code>mud</code> is used, then it will be converted to <code>clay</code>. For each clay floc size a separate <code>[Sediment]</code> block needs to be specified. If the old option <code>bedload</code> is used, then it will be converted to <code>sand</code> with <code>TotalLoad = yes</code>. (1 string)</p>

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Table A.1 — continued from previous page

Keyword	Record description
TotalLoad	logical flag indicating the mode of sediment transport; must be <code>yes</code> (transport given by algebraic total/bed load expressions only) or <code>no</code> (transport includes a suspended load using the advection-diffusion solver). The default value is <code>no</code> . This parameter cannot be set to <code>yes</code> for sediment types <code>clay</code> and <code>silt</code> . (1 logical)
ClayLabel	name of the clay population to which this fraction belongs. This keyword is only read if <code>SedType = clay</code> and it is only required if the model includes multiple clay populations. (1 string)
FlocSize	relative size index of fraction in the hierarchy of a clay population sharing the same <code>ClayLabel</code> : 1 indicates the smallest floc size and $N$ indicates the largest floc size. If the <code>FlocModel</code> is <code>manning_dyer</code> or <code>chassagne_safar</code> the population includes two floc sizes and hence <code>FlocSize</code> will be either 1 (for the microflocs) or 2 (for the macroflocs). (1 positive integer)
RhoSol	specific density of sediment fraction [ $\text{kg/m}^3$ ] (1 real)
SedDxx	$xx$ percentile sediment diameter (for sand or bedload) where $xx$ can take on values from 01 to 99 [m] (1 real)
SedMinDia	minimum sediment diameter (for sand or bedload) [m] (1 real)
SedDia	median sediment diameter (for sand or bedload) equivalent to <code>SedD50</code> [m]: (1 real or 1 string)
SedSg	geometric standard deviation of sediment diameter (for sand or bedload) [m] (1 real)
SedMaxDia	maximum sediment diameter (for sand or bedload) [m] (1 real)
FacDSS	factor for determining suspended sediment diameter $D_{\text{sus}} = \text{FACDSS} * \text{SEDDIA}$ (for sand) [-] (1 real)
CmpUpd	update bed composition for this fraction during flow run (1 logical: false or true; default true) This flag is only used if <code>CmpUpd</code> in the morphology input file is true. If a fraction is excluded from bed composition updating, it is also doesn't influence the bed level anymore.

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Table A.1 — continued from previous page

Keyword	Record description
SettleFrm	<p>name of the settling velocity formula to be used for this fraction; must be</p> <ul style="list-style-type: none"> <li>◇ function_of_conditions,</li> <li>◇ function_of_diameter,</li> <li>◇ manning_dyer,</li> <li>◇ chassagne_safar or</li> <li>◇ blank.</li> </ul> <p>The default value varies depending on other settings: for sand or gravel fractions the default formula is function_of_diameter and for silt fractions the default formula is function_of_conditions. For clay fractions the default formula is function_of_conditions if FlocModel = none and it's automatically switched to the appropriate settling formula for the selected FlocSize index if FlocModel = manning_dyer or chassagne_safar. Note: selecting the option manning_dyer or chassagne_safar for SettleFrm implies using the single fraction approach using macro- and microflocs in dynamic equilibrium (flocculation approach 3a). (1 string)</p>
SalMax	salinity for saline settling velocity (for default mud settling equation) [ppt] (1 real)
WS0	settling velocity fresh water (for default mud settling equation) [m/s] (1 real)
WSM	settling velocity saline water (for default mud settling equation) [m/s] (1 real)
TCoefWS	Dimensionless coefficient $\alpha_T$ for temperature dependency in Equation (8.12). Default 1 (no temperature dependency). (1 positive float)
CFlocCr	Critical concentration $c_{cr,fl}$ for flocculation in Equation (8.12). Default $0.1 \text{ kg m}^{-3}$ . (1 positive float)
CPowWS	Dimensionless coefficient $n$ for concentration dependency in Equation (8.12). Default 0 (no concentration dependency). (1 positive float)
SettleLib	name of the shared object (.dll on Windows, or .so on Linux) without file extension in which the user-defined settling velocity routine is located (1 string). Only to be specified in combination with SettleFunction.
SettleFunction	name of the user-defined subroutine which provides the settling velocity (1 string). Only to be specified in combination with SettleLib. See section A.6 for a description of the subroutine interface.

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Table A.1 — continued from previous page

Keyword	Record description
SettleInput	optional file name to be passed to SettleFunction (1 string). Only to be specified in combination with SettleFunction.
SchmidtNumber	turbulent Schmidt number [-]. The default value; depends on the SedTyp and the values of SchmidtNumberMud and SchmidtNumberSand. (1 real)
CDryB	dry bed density of sediment fraction [kg/m <sup>3</sup> ] (1 real)
SdBUni or IniSedThick	initial sediment mass at bed per unit area [kg/m <sup>2</sup> ] initial sediment layer thickness at bed [m] (1 real or 1 string)
TraFrm	Name of file containing the sediment transport formula settings (1 string) or sediment transport formula number <b>IFORM</b> (1 integer). See Section A.3. This formula overrules the default formula (-1 for sand/bedload, -3 for mud).
*	If TraFrm specifies the number of the sediment transport formula <b>IFORM</b> then the keywords associated with the sediment transport formula should be listed in this <b>Sediment</b> block. See Section A.3 for a listing of the transport formula specific keywords.
The Sediment block can be repeated for other fractions	

**Remarks:**

- ◇ The SedDia parameter may only be specified as a file if the simulation includes only one sediment fraction.
- ◇ There are a couple of options to specify the characteristic diameter(s) for sand or bedload fractions. Table A.2 gives an overview of the various options, the associated sediment distribution types and the implicit assumptions.
- ◇ Note that the explicit temperature and salinity dependency of the settling velocity is largely lost when switching on one of the more 'advanced' flocculation models. The settling formulas of `manning_dyer` do not depend on these quantities. The formulas of `chassagne_safar` depend on these quantities indirectly via the water density  $\rho_w$ .
- ◇ When the morphology module is used in conjunction with Delft3D-FLOW, all spatial data files should be QUICKIN files with data defined in cell centres. When the morphology module is combined with D-Flow FM, the sample files format should be used and the file extension should start with ".xy".

**Table A.2:** Options for sediment diameter characteristics

Specified quantities	Assumptions
SedDia (uniform value) or SedD50 (uniform value)	Piecewise log-uniform distribution SedD10 = 0.75 SedD50 SedD90 = 1.5 SedD50
SedDia (filename) or SedD50 (filename)	Lognormal distribution (spatially varying grain size) SedSg = 1.34
SedDia (filename) or SedD50 (filename), SedSg	Lognormal distribution (spatially varying grain size)
SedDxx (any xx), SedSg	Lognormal distribution
Two SedDxx values	Lognormal distribution SedSg computed from xx and SedDxx
SedMinDia, SedMaxDia	Loguniform distribution
SedMinDia or SedMaxDia, One SedDxx value	Loguniform distribution
More than two SedDxx, SedMinDia, SedMaxDia values	Piecewise loguniform distribution
Other combinations	not allowed

**Example of a version 2 file, with keywords:**

```
[SedimentFileInformation]
  FileCreatedBy   = Delft3D-Flow-GUI, Version: 3.39.14.03
  FileCreationDate = Thu Dec 08 2005, 14:47:46
  FileVersion     = 02.00
[SedimentOverall]
  IopSus          = 0                               Suspended sediment size is Y/N
                                                       calculated dependent on d50
  Cref            = 1.60e+03                        [kg/m3] CSoil Reference density for hindered
                                                       settling
[Sediment]
  Name            = #Sediment sand#                Name of the sediment fraction
  SedTyp          = sand                            Must be "sand", "mud" or "bedload"
  RhoSol          = 2.6500000e+003 [kg/m3]           Specific density
  SedDia          = 2.0000000e-004 [m]               Median sediment diameter (D50)
  CDryB          = 1.6000000e+003 [kg/m3]           Dry bed density
  IniSedThick     = 0.50e+000 [m]                   Initial sediment layer thickness at bed
                                                       (uniform value or file name)
  FacDSS          = 1.0e+0 [-]                      FacDss*SedDia = Initial suspended
                                                       sediment diameter.
[Sediment]
  Name            = #Sediment mud#                  Name of the sediment fraction
  SedTyp          = mud                             Must be "sand", "mud" or "bedload"
  RhoSol          = 2.6500000e+003 [kg/m3]           Specific density
  SalMax          = 0.0000000e+000 [ppt]             Salinity for saline settling velocity
  WS0             = 2.5000001e-004 [m/s]             Settling velocity fresh water
  WSM             = 2.5000001e-004 [m/s]             Settling velocity saline water
```

TcrSed	= 1.0000000e+003	[N/m <sup>2</sup> ]	Critical stress for sedimentation
TcrEro	= 5.0000000e-001	[N/m <sup>2</sup> ]	Critical stress for erosion
EroPar	= 9.9999997e-005	[kg/m <sup>2</sup> s]	Erosion parameter
CDryB	= 5.0000000e+002	[kg/m <sup>3</sup> ]	Dry bed density
IniSedThick	= 0.05e+000	[m]	Initial sediment layer thickness at bed (uniform value or file name)
FacDSS	= 1.00e+0	[-]	FacDss*SedDia = Initial suspended sediment diameter

**Table A.3:** Sediment input file without keywords. This format is only included for backward compatibility; please use the format described in [Table A.1](#) instead.

Record	Record description
1	VERSION: version number (in the present Delft3D Release, this line should read “* Version 01”)
2	LSED: number of sediment fractions CSOIL: reference density for hindered settling calculations (not active when $\geq 1 \cdot 10^6$ ) [kg/m <sup>3</sup> ] IOPSUS: option for determining suspended sediment diameter (see <a href="#">section 8.3.1</a> ) (1 integer, 1 real, 1 integer)
3	SEDTP: type of sediment: “sand” or “mud” (1 string)
4	RHOSOL: specific density of sediment fraction [kg/m <sup>3</sup> ] (1 real)
5	SEDDIA: median sediment diameter (for sand) [m] (1 real)
6	SALMAX: salinity for saline settling velocity (for mud) [ppt] (1 real)
7	WS0: settling velocity fresh water (for mud) [m/s] (1 real)
8	WSM: settling velocity saline water (for mud) [m/s] (1 real)
9	TCDUNI: critical stress for sedimentation (uniform value) [N/m <sup>2</sup> ] (1 real) or FILTCD: file with spatially varying values of TCDUNI <*.tcd> at cell centres (1 string)
10	TCEUNI: critical stress for erosion (uniform value) [N/m <sup>2</sup> ] (1 real) or FILTCE: file with spatially varying values of TCEUNI <*.tce> at cell centres (1 string)
11	EROUNI: erosion parameter (uniform value) [kg/m <sup>2</sup> s] (1 real) or FILERO: file with spatially varying values of EROUNI <*.ero> at cell centres (1 string)
12	CDRYB: dry bed density [kg/m <sup>3</sup> ] (1 real)
13	SDBUNI: initial sediment mass at bed per unit area [kg/m <sup>2</sup> ] (1 real) or FILSDB: filename with non-uniform values of SDBUNI <*.sdb> at cell centres (1 string)

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Table A.3 — continued from previous page

Record	Record description
14	FACDSS: factor for determining suspended sediment diameter $D_{sus} = FACDSS * SEDDIA$ (for sand) [-] (1 real)
15 to 27	repeat records 3 to 14 for a second sediment fraction; repeat this block as many times as there are sediment fractions (max. LSED)

**Remarks:**

- ◇ If no version number is specified, the program will read records 2 to 13 from the input file, and set  $FACDSS = 1$ . This has been done to ensure backward compatibility.
- ◇ The filenames for non-uniform parameters have a mandatory extension as indicated in [Table A.3](#).
- ◇ Records 6–11 only have meaning for mud fractions (but have to be included for sand as well).
- ◇ Record 5 only has meaning for sand fractions (but has to be included in case of mud).

**Example of a version 1 file, without keywords:**

This example concerns the transport of two sediment fractions one sand (with a  $D_{50} = 140$  micron) and one mud (with a spatially-varying critical stress for erosion, defined in the file <critstr.tce>). Comments are printed between brackets.

```

* Version 01
2 1600. 2 {LSED : no. of sediment, CSOIL, IOPSUS }
sand {SED TYP : type of sediment}
2650.0 {RHOSOL : density sediment [kg/m3]}
0.00014 {SEDDIA : median sediment diameter [m]}
0.0000 {SALMAX : salinity saline water [ppt]}
0.0000 {WS0 : settling velocity fresh water [m/s]}
0.0000 {WSM : settling velocity saline water [m/s]}
0.0000 {TCDUNI : critical stress for sedimentation [N/m2]}
0.0000 {TCEUNI : critical stress for erosion [N/m2]}
0.0000 {EROUNI : Erosion parameter [kg/m2/s]}
1600.0 {CDRYB : dry bed density [kg/m3]}
800.0 {SDBUNI : Uniform value of init. mass on bed [kg/m2]}
0.8 {FACDSS : factor for suspended sediment diameter [-]}
mud {SED TYP : type of sediment}
2650.0 {RHOSOL : density sediment [kg/m3]}
0.0000 {SEDDIA : median sediment diameter [m]}
10.000 {SALMAX : salinity saline water [ppt]}
0.0005 {WS0 : settling velocity fresh water [m/s]}
0.0020 {WSM : settling velocity saline water [m/s]}
0.1000 {TCDUNI : critical stress for sedimentation [N/m2]}
critstr.tce
0.0001 {EROUNI : Erosion parameter [kg/m2/s]}
300.0 {CDRYB : dry bed density [kg/m3]}
800.0 {SDBUNI : Uniform value of init. mass on bed [kg/m2]}
1.0 {FACDSS : factor for suspended sediment diameter [-]}

```

**Remark:**

- ◇ Additional comments in the input file are not mandatory.

**Restrictions:**

- ◇ Records specifying an attribute file name should not contain additional comment text.
- ◇ The values of the parameters are not checked against their domains.

**Attribute files in the sediment input file**

In the sediment input file a number of quantities can be specified to vary spatially; the values are then specified by an attribute file. The file extensions are

**Table A.4:** Recommended file names for sediment attribute files

Keyword	Delft3D-FLOW	D-Flow FM
MudCnt	*.mdc	*.xymdc
SedDia	*.d50	*.xyd50
SdBUni or IniSedThick	*.sdb	*.xysdb

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Keyword	Delft3D-FLOW	D-Flow FM
TcrDep	*.tcd	*.xytcd
TcrEro	*.tce	*.xytce
EroPar	*.ero	*.xyero

These (ASCII) files have the same format as the QUICKIN depth file for Delft3D-FLOW and as sample files for D-Flow FM.

## A.2 Morphology input file

The morphological input file contains additional information necessary for a morphodynamic run. Like the <\*.sed> file there is the (old) version without keywords and a newer version with keywords. All user interfaces only write the newer keyword-based version, but the Delft3D-FLOW user interface also accepts the old file without keywords — the D-Flow FM user interface doesn't.

Table A.5: Morphological input file with keywords

Keyword	Record description
<b>MorphologyFileInformation</b>	
FileCreatedBy	contains version number of the user interface
FileCreationDate	creation date and time of the <*.mor> file
FileVersion	version number
<b>Morphology</b>	
MorFac	morphological scale factor constant (1 real) or name of file with time-dependent values (1 string)
MorStt	time interval in <code>Tunit</code> after the start of the simulation after which morphological (both bed level and bed composition) changes will be calculated; the keywords <code>BedUpdStt</code> and <code>CmpUpdStt</code> give more control and overrule the <code>MorStt</code> value if specified (1 real)
BedUpdStt	time interval in <code>Tunit</code> after the start of the simulation after which bed level updates will be calculated. If specified, this keyword overrules <code>MorStt</code> . The value specified for <code>BedUpdStt</code> should be larger than the value specified for <code>CmpUpdStt</code> . (1 real)

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Keyword	Record description
CmpUpdStt	time interval in <code>Tunit</code> after the start of the simulation after which bed composition changes will be calculated. If specified, this keyword overrules <code>MorStt</code> . (1 real)
SedTransStt	time interval in <code>Tunit</code> after the start of the simulation after which sediment transport will be calculated; The value specified for <code>SedTransStt</code> should be smaller than the value specified for the keywords <code>MorStt</code> , <code>BedUpdStt</code> and <code>CmpUpdStt</code> .
Thresh	threshold sediment thickness for reducing sediment exchange [m] (1 real)
MorUpd	backward compatibility option equivalent to <code>BedUpd</code> .
BedUpd	update bed level during simulation (1 logical: false or true; default true)
CmpUpd	update bed composition during simulation (1 logical: false or true; default true) If this flag is true, the updating may still be switched off for individual fractions by means of the <code>CmpUpd</code> flag in the sediment input file.
NeglectEntrainment	compute bed level changes from suspended sediment transport rates instead of from the entrainment and deposition terms; neglect the entrainment of suspended sediment in the mass balance (1 logical: false or true; default false)
EqmBc	backward compatibility option equivalent to <code>NeuBcSand</code>
NeuBcSand	zero-gradient Neumann boundary condition for non-cohesive suspended sediment concentrations at inflow boundaries only used by Delft3D-FLOW (1 logical: false or true; default false)
NeuBcMud	zero-gradient Neumann boundary condition for cohesive suspended sediment concentrations at inflow boundaries only used by Delft3D-FLOW (1 logical: false or true; default false)
DensIn	include effect of sediment on density gradient (1 logical: false or true; default true)
AksFac, RWave	backward compatibility option; specify <code>AksFac</code> and <code>RWave</code> via transport formula if needed
Sus	current-related suspended sediment transport factor [-] (1 real; default 1.0)

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Keyword	Record description
Bed	current-related bedload transport factor [-] (1 real; default 1.0)
SusW	wave-related suspended sediment transport factor [-] (1 real; default 1.0)
BedW	wave-related bedload sediment transport factor [-] (1 real; default 1.0)
SedThr	minimum water depth for sediment calculations [m] (1 real; default 0.5)
ThetSD	global / maximum dry cell erosion factor [-] (1 real; default 0.0)
HMaxTH	maximum depth for variable THETSD [m] (1 real; default 1.0)
FWFac	tuning parameter for wave streaming in Delft3D-FLOW [-] (1 real; default 1.0)
Bermslope	switch for swash slope nudging; only applies to D-Flow FM (1 logical; default false)
Bermslopefac	calibration factor for swash slope nudging (1 real; default 1.0)
Bermslopegamma	in case of a wave model ( $Wavemodelnr > 0$ ), the wave height to depth ratio above which swash slope nudging is applied [-] (1 real; default 1.0)
Bermslopedepth	maximum water depth for applying swash slope nudging [m] (1 real; default 0.5)
Bermslopesus	apply swash slope nudging using suspended transport contributions (1 logical; default true)
Bermslopebed	apply swash slope nudging using bedload transport contributions (1 logical; default true)
DuneAvalan	switch for dune front avalanching; only applies to D-Flow FM (1 logical; default false)
WetSlope	underwater slope used to nudge bed slope to [-]; if <code>Duneavalan</code> is false, this keyword can be used to nudge slopes to a certain value, in Delft3D-FLOW and D-Flow FM (1 real; default 10.0)
DrySlope	subaerial slope used to nudge bed slope to [-] (1 real; default 1.0)
Hswitch	depth to switch from <code>Wetslope</code> to <code>Dryslope</code> to nudge bed slope to (1 real; default 0.1)
DzMaxDune	maximum bed level change by avalanching per timestep [m] (1 real; default 100.0)

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Keyword	Record description
AvalTime	relaxation time for dune avalanching [s] (1 real; default 86400.0)
EpsPar, IopKCW, RDC, RDW	backward compatibility option; specify EpsPar, IopKCW, RDC and RDW via transport formula if needed
UpdInf	update bed levels at inflow boundaries (1 logical: false or true; default false)
Multi	"Mormerge": run multiple morphological simulations in parallel and continuously merge the morphological developments (1 logical: false or true; default false). See <a href="https://svn.oss.deltares.nl/repos/delft3d/trunk/examples/05_mormerge">https://svn.oss.deltares.nl/repos/delft3d/trunk/examples/05_mormerge</a>
DzMax	maximum bed level change per time step expressed as percentage of water depth [m] (1 real; default 0.05)
CaMax	maximum equilibrium sediment concentration in Van Rijn formula (1 real)
OldMudFrac	if true, do not include the fractional reduction factor in the mud entrainment term (1 logical: false or true; default false)
IHidExp	hiding and exposure formulation number (1 integer in the range 1 to 5; default 1). If the simulation includes a mud fraction, only 1 is allowed. 1 no hiding and exposure 2 Egiazaroff formulation 3 Ashida & Michiue formulation 4 Parker et al. formulation 5 Wu, Wang & Jia formulation
ASKLHE	hiding and exposure parameter for formulation 4 (1 real)
MWWJHE	hiding and exposure parameter for formulation 5 (1 real)
Espir	effect of spiral flow on bedload transport (1 real; default 0.0)

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Keyword	Record description
ISlope	bed slope formulation (1 integer in the range 1 to 4; default 2) 1 no bed slope 2 Bagnold formulation 3 Koch & Flokstra formulation 4 Parker & Andrews formulation
AlfaBs	longitudinal bed gradient factor for bedload transport (1 real; default 1.0) used by all formulations except formulation 1
AlfaBn	transverse bed gradient factor for bedload transport for formulation 2 (1 real; default 1.5)
Ashld	multiplicative factor $A_{sh}$ for bed slope formulation 3 (1 real; default 0.85)
Bshld	power $B_{sh}$ for bed slope formulation 3 (1 real; default 0.5)
Cshld	power $C_{sh}$ for bed slope formulation 3 (1 real; default 0)
Dshld	power $D_{sh}$ for bed slope formulation 3 (1 real; default 0)
CoulFri	Coulomb friction for bed slope formulation 4 (1 real)
FlFdRat	Lift/drag force ratio for bed slope formulation 4 (1 real)
ThetaCr	Critical shear stress for bed slope formulation 4 (1 real)
BcFil	file containing morphological boundary conditions (1 string)
<b>Boundary</b>	
Name	name of boundary as specified in BND file (1 string)

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Keyword	Record description
IBedCond	bedload or bed level boundary condition (1 integer in the range 0 to 5) 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	bed composition boundary condition (1 integer in the range 0 to 3) 0 no bed composition constraint 1 composition constant 2 mass fractions specified as function of time 3 volume fractions specified as function of time
the Boundary block can be repeated for other boundaries	
<b>Numerics</b>	
UpwindBedload	use upwind bedload (true, default) or central bedload (false)
LaterallyAveragedBedload	smoothed bedload transport rates (1 logical: false or true). Default false.
MaximumWaterdepth	use locally maximum water depth to compute characteristic velocity for sediment transport at cell centre (1 logical: false or true). Default false.
MaximumWaterdepthFraction	fraction of the flow depth at links used in finding the maximum water depth (1 real in the range 0 to 1, default is 1). Only used if MaximumWaterdepth=true.
TrackMassShortage	determine whether the code keeps track of sediment fraction for which the erosional flux exceeded the available mass (1 logical: false or true). The default setting is false for IUnderLyr = 1, and true otherwise.

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Keyword	Record description
<b>Output</b> All keywords in this block determine whether the named quantity is to be written to the map-file. Unless indicated otherwise, the value should be 1 logical. For logical flags the default is false unless specified otherwise in the description below. The logical defaults can be changed to all true or all false by means of the keyword <code>Default</code> .	
<code>Default</code>	set the default to be used for <i>all</i> logical keywords in this block. If specified, the value specified for this keyword overrules the keyword-specific default value specified here in this table.
<code>VelocAtZeta</code>	characteristic velocity vector at cell centres
<code>VelocMagAtZeta</code>	velocity magnitude at cell centres
<code>VelocZAtZeta</code>	height of characteristic velocity at cell centres
<code>ShearVeloc</code>	shear velocity $u_*$
<code>BedTranspAtFlux</code>	bedload transport (due to currents and waves) plus suspended transport due to waves at staggered cell faces. Default true.
<code>BedTranspDueToCurrentsAtZeta</code>	bedload transport due to currents at cell centres
<code>BedTranspDueToCurrentsAtFlux</code>	bedload transport due to currents at staggered cell faces
<code>BedTranspDueToWavesAtZeta</code>	bedload transport due to waves at cell centres
<code>BedTranspDueToWavesAtFlux</code>	bedload transport due to waves at staggered cell faces
<code>SuspTranspAtFlux</code>	depth integrated suspended load transport minus near bed corrective transport at staggered cell faces. Default true.
<code>SuspTranspDueToWavesAtZeta</code>	suspended load transport due to waves at cell centres
<code>SuspTranspDueToWavesAtFlux</code>	suspended load transport due to waves at staggered cell faces
<code>NearBedTranspCorrAtFlux</code>	near bed corrective transport at staggered cell faces
<code>EquilibriumConcentration</code>	equilibrium concentration at which entrainment equals deposition. Only for 2D simulations. Default true.
<code>NearBedRefConcentration</code>	near bed reference concentration. Default true.
<code>SettlingVelocity</code>	settling velocity. Default true.

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Keyword	Record description
Seddif	vertical sediment diffusivity. Default false.
SourceSinkTerms	source and sink terms
Bedslope	bed slope vector
Taurat	shear stress ratio
Bedforms	bed form roughnesses
Dm	arithmetic mean sediment diameter
Dg	geometric mean sediment diameter
Frac	sediment fraction in top layer
MudFrac	mud fraction in top layer
FixFac	non-erodible layer reduction factor
HidExp	hiding and exposure factor
Percentiles	percentiles of characteristic sediment diameter to be written to the map-file (default: 10, 50 and 90)
CumNetSedimentationFlux	accumulated net sedimentation over the period between two map-file output times
BedLayerSedimentMass	mass of each sediment fraction per unit area per bed layer. Default: true.
BedLayerDepth	depth of bed layer interfaces. Default: true.
BedLayerVolumeFractions	volume fraction of each sediment fraction per bed layer. Default: true.
BedLayerPorosity	porosity per bed layer. Only if IPorosity>0. Default: true.
StatWaterDepth	The value lists the statistics to be computed and stored for the water depth over the period between two output times (1 string). The program will check whether the following substrings occur in the value string: min, max, mean, and std for minimum, maximum, mean, and standard deviation respectively. Default: none.

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Keyword	Record description
StatVelocity	The value lists the statistics to be computed and stored for the depth averaged velocity over the period between two output times (1 string). The program will check whether the following substrings occur in the value string: min, max, mean, and std for minimum, maximum, mean, and standard deviation respectively. Default: none.
StatBedload	The value lists the statistics to be computed and stored for the total bed load (accumulated over all sediment fractions) over the period between two output times (1 string). The program will check whether the following substrings occur in the value string: min, max, mean, and std for minimum, maximum, mean, and standard deviation respectively. Default: none.
StatSusplod	The value lists the statistics to be computed and stored for the total suspended load (accumulated over all sediment fractions) over the period between two output times (1 string). The program will check whether the following substrings occur in the value string: min, max, mean, and std for minimum, maximum, mean, and standard deviation respectively. Default: none.
TranspType	sediment transport unit (1 integer in the range 0 to 2; default 2): 0     kg/(s m) 1     m <sup>3</sup> bed material/(s m) 2     m <sup>3</sup> stone/(s m)
AverageAtEachOutputTime	cumulative average of sediment transport rates at each map output time step instead of only at end of simulation
<b>Underlayer</b>	
IUnderLyr	stratigraphy schematisation model (1 integer, either 1 or 2; default 1) 1     one well mixed layer 2     multiple layers
MxNULyr	maximum number of underlayers (excluding transport and base layers) in case IUnderLyr=2 (1 integer)

continued on next page

Table A.5 — continued from previous page

Keyword	Record description
TTLForm	transport layer thickness formulation in case IUnderLyr=2 (1 integer in the range 1 to 3; default 1) 1 constant user-defined 2 proportional to water depth 3 proportional to bedform height
ThTrLyr	thickness of transport layer [m] in case of TTLForm=1 uniform or (1 real) or file name (1 string)
TTLAlpha	proportionality constant in case of TTLForm=2 or 3 (1 real; default 0.1)
TTLMin	minimum thickness [m] in case of TTLForm=2 or 3 (1 real; default 0)
ThUnLyr	characteristic maximum thickness [m] of stratigraphy layers in case IUnderLyr=2 (1 real)
UpdBaseLyr	update option for composition and thickness of base layer (1 integer in the range 1 to 4) 1 composition and thickness computed 2 composition constant, thickness computed 3 composition copied from layer above, thickness computed 4 composition and thickness constant
IniComp	file containing initial bed composition (1 string) usage of this keyword overrules the IniSedThick (or older SdBUni) values given in the sed file (see <a href="#">section A.9</a> )

For these boundary conditions you need to specify the imposed time-series in the file referred to using the BcFil keyword. File format described in [section A.7](#).

**Example of a version 2 file, with keywords:**

```
[MorphologyFileInformation]
FileCreatedBy   = Delft3D-FLOW-GUI, Version: 3.39.14.03
FileCreationDate = Thu Dec 08 2005, 14:47:50
FileVersion     = 02.00
[Morphology]
EpsPar          = false           Only for waves in combination with k-eps
IopKCW          = 1              Flag for determining Rc and Rw
RDC             = 0.01           [m] Current related roughness (IopKCW = 0)
RDW            = 0.02           [m] Wave related roughness (IopKCW = 0)
MorFac          = 1.0000000e+000 [-] Morphological scale factor
MorStt          = 7.20e+02       [min] Spin-up interval from TStart till start of morph changes
Thresh          = 5.0e-002       [m] Threshold sed thickness for reducing sed exchange
MorUpd          = true           Update bathymetry during simulation
```

```

EqmBc      = true           Equilibrium concentration at inflow
                             boundaries
DensIn      = false         Include effect of sediment on density
                             gradient
AksFac      = 1.00000e+000   [-] Van Rijn's reference height = AKSFAC * KS
RWave       = 2.0e+0        [-] Wave related roughness = RWAVE * estimated
                             ripple height. Van Rijn Recommends range 1-3
AlfaBs      = 1.00e+00      [-] Longitudinal bed gradient factor for bedload transport
AlfaBn      = 1.50e+0       [-] Transverse bed gradient factor for bedload transport
Sus         = 1.0e+0        [-] Multipl fac for suspended sed reference concentration
Bed         = 1.0e+00       [-] Multipl factor for bedload transport vector magnitude
SusW        = 1.0e+000      [-] Wave-related suspended sed. transport factor
BedW        = 1.00e+000     [-] Wave-related bedload sed. transport factor
SedThr      = 1.00e-001     [m] Minimum threshold depth for sediment computations
ThetSD      = 0.00e+000     [-] Fraction of erosion to assign to adjacent dry cells
HMaxTH      = 1.50e+00      [m] Max depth for var THETSD. Set < SEDTHR to use global
                             value only
FWFac       = 1.0e+00       [-] Only for waves in combination with k-eps model

```

**Table A.6:** Morphological input file without keywords. This format is only included for backward compatibility; please use the format described in [Table A.5](#) instead.

Record	Record description
1	VERSION: version number (in the present Delft3D Release, this line should read “* Version 01”)
2	MORFAC: morphological scale factor (1 real)
3	MORSTT: time interval in minutes after the start of the simulation after which morphological changes will be calculated (1 real)
4	THRESH: threshold sediment thickness for reducing sediment exchange [m] (1 real)
5	MORUPD: update bathymetry during simulation (1 logical: .false. or .true.)
6	EQMBC: equilibrium sediment concentration profile at inflow boundaries (1 logical: .false. or .true.)
7	DENSIN: include effect of sediment on density gradient (1 logical: .false. or .true.)
8	AKSFAC: Van Rijn's reference height = AKSFAC * KS (1 real)
9	RWAVE: multiplication factor estimated ripple height; wave related roughness = RWAVE * estimated ripple height (1 real ) NOTE: estimated ripple height now fixed at 0.025 m.
10	ALFABS: longitudinal bed gradient factor for bedload transport (1 real)
11	ALFABN: transverse bed gradient factor for bedload transport (1 real)
12	SUS: current-related suspended sediment transport factor (1 real)
13	BED: current-related bedload transport factor (1 real)

continued on next page



Table A.6 — continued from previous page

Record	Record description
14	SUSW: wave-related suspended sediment transport factor (1 real)
15	BEDW: wave-related bedload sediment transport factor (1 real)
16	SEDTHR: minimum depth for sediment calculations (1 real)
17	THETSD: global / maximum dry cell erosion factor (1 real)
18	HMAXTH: maximum depth for variable THETSD (1 real)
19	FWFAC: tuning parameter for wave streaming (1 real)
20	EPSPAR: Van Rijn's parabolic mixing coefficient (1 logical)
21	IOPKCW: option for ks and kw, RC: current related roughness ks, RW: wave related roughness kw

**Example version 1 file with no keywords:**

This example concerns a morphological simulation in which the bed-level updating commences 6250 minutes after the start of the simulation. Comments are printed between brackets.

```

* Version 01
180.      {MORFAC : morphological scale factor}
6250.     {MORSTT : time interval in min after start, for bed updating}
0.2       {THRESH : threshold sed. thickness for reducing sed. exchange}
.true.    {MORUPD : update bathymetry during simulation}
.true.    {EQMBC : equilibrium concentration at inflow boundaries}
.true.    {DENSIN : include effect of sediment on density gradient}
1.0       {AKSFAC : Van Rijn's reference height = AKSFAC * KS}
2.0       {RWAVE : multiplication factor estimated ripple height}
1.0       {ALFABS : long. bed gradient factor for bedload transport}
1.5       {ALFABN : tran. bed gradient factor for bedload transport}
1.0       {SUS : multiplication factor sus. sed. ref. concentration}
1.0       {BED : multiplication factor bedload transp. vector magn.}
1.0       {SUSW : wave-related suspended sediment transport factor}
1.0       {BEDW : wave-related bedload sediment transport factor}
0.25      {SEDTHR : minimum depth for sediment calculations}
1.0       {THETSD : global / maximum dry cell erosion factor}
0.01      {HMAXTH : maximum depth for variable THETSD}
0.1       {FWFAC : tuning parameter for wave streaming}
.false.   {EPSPAR : Van Rijn's parabolic-linear mixing distribution}
1 0.01 0.02 {IOPKCW, RDC, RDW : parameters for determining morphological roughness}

```

**Remarks:**

- ◇ If no version number is specified, the program will read records 2 to 19 from the input file,

and set `EPSPAR = FALSE` and `IOPKCW = 1`. This has been done to ensure backward compatibility.

- ◇ If `EPSPAR` is set to `TRUE`, Van Rijn's parametric mixing distribution is also used if the  $k$ - $\varepsilon$  model is selected in `FLOW`. If it is set to `FALSE`, the mixing is set equal to the  $\varepsilon$  of the  $k$ - $\varepsilon$  model.
- ◇ `IOPKCW` is a switch to determine  $k_s$  and  $k_w$ :

`IOPKCW = 0` :  $k_s = RDC$  and  $k_w = RDW$

`IOPKCW = 1` :  $k_s$  is taken from current-related effective roughness height as determined in the `FLOW` (spatially varying) and  $k_w = RWAVE \cdot \Delta_r$  (see [section 8.3.3](#)).

- ◇ The file for specifying bedload, bed level and/or bed composition boundary conditions is described in [section A.7](#).

#### Restriction:

- ◇ The values of the parameters are not checked against their domains.

#### Output enhancements:

The following parameters or (time dependent) data have been added to the result files:

Result file	Data
History file	Sediment concentrations, bedload transport, suspended transport, cumulative bedload and suspended transports in monitoring points and integrated over cross-sections, near-bed reference concentrations
Map file	Sediment concentrations per layer, bedload and suspended transport, instantaneous and averaged, time-varying bathymetry, available sediment per fraction, cumulative erosion/sedimentation, near-bed reference concentrations, as well as any additional quantity selected in the output block of the morphology input file (as indicated in <a href="#">Table A.5</a> )

#### Remarks:

- ◇ Use the MATLAB interface or Delft3D-QUICKPLOT to plot all these parameters.
- ◇ Use the parameter `DensIn` to switch on or off the effect of the sediment concentration on the density and thereby its influence on the turbulence.

### A.3 Sediment transport input file

By default, the formulations of [Van Rijn \*et al.\* \(2000\)](#) are applied for the suspended and bedload transport of non-cohesive sediment (`IFORM = -1`), while the formulations of Partheniades and Krone are used for cohesive sediment (`IFORM = -3`). These are just two of the sediment transport formulae implemented; [Table A.7](#) gives an overview of all transport formulae available. You can also supply a library with your own favourite sediment transport formula and use one of those, but more about that in [Section A.4](#). Let's focus now on the set of predefined formulations.

**Table A.7:** List of transport formulae implemented

Formula	Bedload	Affected by Waves	IFORM
<b>for cohesive fractions</b>			
8.2.11, Partheniades-Krone	Suspended	Yes	-3
A.5, User defined transport routine for mud fractions	Suspended	Yes	—
<b>for non-cohesive fractions</b>			
8.5.1, Van Rijn (2007)	Bedload + suspended	Yes	-2
8.5.2, SANTOSS	Bedload + suspended	Yes	-4
8.5.3, Van Rijn (1993)	Bedload + suspended	Yes	-1
8.5.4, Engelund-Hansen (1967)	Total transport	No	1
8.5.5, Meyer-Peter-Muller (1948)	Total transport	No	2
8.5.6, General formula	Total transport	No	4
8.5.7, Bijker (1971)	Bedload + suspended	Yes	5
8.5.8, Van Rijn (1984)	Bedload + suspended	No	7
8.5.9, Soulsby/Van Rijn	Bedload + suspended	Yes	11
8.5.10, Soulsby	Bedload + suspended	Yes	12
8.5.11, Ashida-Michiue (1974)	Total transport	Yes	14
8.5.12, Wilcock-Crowe (2003)	Bedload	No	16
8.5.13, Gaeuman et al. (2009) laboratory calibration	Bedload	No	17
8.5.14, Gaeuman et al. (2009) Trinity River calibration	Bedload	No	18
8.5.15, Van Thiel / Van Rijn	Bedload + suspended	Yes	19
8.5.16, Soulsby / Van Rijn, XBeach flavour	Bedload + suspended	Yes	20
8.5.17, Delft3D-ASMITA hybrid	Suspended	No	22
A.4, User defined transport routine for sand or bedload fractions	Bedload + suspended	Yes	—

If you want to use one of these formulae, you have to specify the **IFORM** number listed in Table A.7 as value for the keyword `TraFrm` in the **Sediment** block of the sediment transport input file (see Table A.1) and specify the keywords relevant for the selected transport formula. The following table lists the parameters to be specified in the sediment transport input file for each separate transport formula.

**Table A.8:** Transport formula parameters

Keyword	Parameter	Unit
8.2.11, Partheniades-Krone		

Keyword	Parameter	Unit
EroPar	erosion parameter	kg/m <sup>2</sup> s
TcrSed	critical shear stress for sedimentation	N/m <sup>2</sup>
TcrEro	critical shear stress for erosion of bed	N/m <sup>2</sup>
TcrFluff	critical shear stress for erosion of fluff layer [default: 0]	N/m <sup>2</sup>
ParFluff0	maximum erosion flux from fluff layer [default: 0]	s/m
ParFluff1	erosion parameter for fluff layer [default: 0]	m s/kg
DepEff	reduction factor for deposition/sedimentation rate (value between 0 = no sedimentation and 1 = reference sedimentation, or equal to -1 = reduction based on critical shear stress for sedimentation) [default: -1]	-
PowerN	power for the relative critical shear stress for erosion term [default: 1]	-

#### A.5, User defined transport routine for mud fractions

	none	-
--	------	---

##### 8.5.1, Van Rijn (2007)

IopSus	option for determining suspended sediment diameter (see <a href="#">section 8.3.1</a> ) [default: 0]	integer
Pangle	phase lead for bed shear stress of Nielsen (1992) [default: 0]	deg
Fpco	phase lag effects in wave-induced suspended transport [default: 1]	-
Subiw	wave period subdivision [Default: 51]	integer
EpsPar	only for waves in combination with k-epsilon turbulence model; Van Rijn's parabolic mixing coefficient [default: 0]	logical
GamTcr	power of the grain size ratio in the critical shear stress expression [default: 1.5]	-
SalMax	salinity for saline settling velocity [default: 0]	ppt
BetaM	exponent used for effect of mud fraction on critical shear stress [default: 3]	-
Wform	wave form used: 1: Isobe and Horikawa (1982), 2: Boechat Albernaz <i>et al.</i> (2019) [default: 1]	-

##### 8.5.2, SANTOSS

IopSus	option for determining suspended sediment diameter (see <a href="#">section 8.3.1</a> ) [default: 0]	integer
Pangle	phase lead for bed shear stress of Nielsen (1992) [default: 0]	deg
Fpco	phase lag effects in wave-induced suspended transport [default: 1]	-
Subiw	wave period subdivision [Default: 51]	integer

Keyword	Parameter	Unit
EpsPar	only for waves in combination with k-epsilon turbulence model; Van Rijn's parabolic mixing coefficient [default: 0]	logical
GamTcr	power of the grain size ratio in the critical shear stress expression [default: 1.5]	-
SalMax	salinity for saline settling velocity [default: 0]	ppt
BetaM	exponent used for effect of mud fraction on critical shear stress [default: 3]	-
Wform	wave form used: 1: Isobe and Horikawa (1982), 2: Boechat Albernaz <i>et al.</i> (2019) [default: 1]	-
SW_effects	switch to turn on surface wave effects, [1 is true, default is 1]	logical
AS_effects	switch to turn on wave asymmetry effects, [1 is true, default is 1]	logical
PL_effects	switch to turn on phase lag effects, [1 is true, default is 1]	logical
SL_effects	switch to turn on slope effect effects on critical shear stress, [1 is true, default is 1]	logical

#### 8.5.3, Van Rijn (1993)

IopSus	option for determining suspended sediment diameter (see <a href="#">section 8.3.1</a> ) [default: 0]	integer
AksFac	Van Rijn's reference height = AKSFAC * $k_s$ [default: 1]	-
RWave	multiplication factor estimated ripple height; wave related roughness = RWAVE * estimated ripple height. NOTE: estimated ripple height now fixed at 0.025 m. [default: 2]	-
RDC	current related roughness $k_s$ [default: 0.01]	m
RDW	wave related roughness $k_w$ [default: 0.02]	m
IopKCW	option for $k_s$ and $k_w$ [default: 1 (true)]	logical
EpsPar	Only for waves in combination with k-epsilon turbulence model; Van Rijn's parabolic mixing coefficient [default: 0 (false)]	logical
BetaM	exponent used for effect of mud fraction on critical shear stress [default: 3]	-

#### 8.5.4, Engelund-Hansen (1967)

ACal	calibration coefficient $\alpha$	-
RouKs	bed roughness height $r_k$ (dummy)	m
SusFac	suspended sediment fraction [default: 0]	-

#### 8.5.5, Meyer-Peter-Muller (1948)

ACal	calibration coefficient $\alpha$	-
------	----------------------------------	---

#### 8.5.6, General formula

Keyword	Parameter	Unit
ACal	calibration coefficient $\alpha$	-
PowerB	power $b$	-
PowerC	power $c$	-
RipFac	ripple factor or efficiency factor $\mu$	-
ThetaC	critical Shields' mobility parameter $\theta_c$	-

#### 8.5.7, Bijker (1971)

CalBs	calibration coefficient $b$ for shallow water $BS$	-
CalBd	calibration coefficient $b$ for deep water $BD$	-
CritCs	shallow water ( $h_w/h$ ) criterion $C_s$	-
CritCd	deep water ( $h_w/h$ ) criterion $C_d$	-
—*	dummy parameter	NA
RouKs	bed roughness height $r_c$ (used if specified value > 0; otherwise derived from the model roughness) [default: -999]	m
WSettle	settling velocity $w$ (used if specified value > 0; otherwise the sediment settling velocity is used) [default: -999]	m/s
Porosity	porosity $\varepsilon$ (used if specified value > 0; otherwise the local bed porosity is used) [default: -999]	-
TWave	wave period $T_{user}$ (used if computed wave period < $10^{-6}$ and $T_{user} > 10^{-6}$ ) [default: -999]	s
FacA	factor for wave asymmetry $FacA$ [default: 0]	-
FacU	factor for averaged flow $FacU$ (currently not used) [default: 0]	-
EpsSL	slope calibration coefficient $\varepsilon_{sl}$ [default: 0]	-

#### 8.5.8, Van Rijn (1984)

ACal	calibration coefficient $\alpha_1$	-
—*	dummy parameter	NA
Aks	reference height $\xi_c$	m
WSettle	settling velocity $w_s$	m/s

#### 8.5.9, Soulsby/Van Rijn

ACal	calibration coefficient $A_{cal}$	-
RatioD90D50	$D_{90}/D_{50}$ ratio	-
RouZ0	$z_0$ roughness height	m

#### 8.5.10, Soulsby

ACal	calibration coefficient $A_{cal}$	-
ModInd	model index modind	-
RatioD50Z0	$D_{50}/z_0$ ratio $\chi$	-

Keyword	Parameter	Unit
–, Wang/Fredsoe		
VicMol	kinematic (molecular) viscosity coefficient $\nu_{mol}$	m <sup>2</sup> /s
ACal	calibration coefficient $A_{cal}$	-
8.5.11, Ashida–Michiue (1974)		
ACal	calibration coefficient $\alpha$	-
ThetaC	critical Shields' mobility parameter $\theta_c$	-
PowerM	power $m$	-
PowerP	power $p$	-
PowerQ	power $q$	-
8.5.12, Wilcock–Crowe (2003)		
ACal	calibration coefficient	-
8.5.13, Gaeuman et al. (2009) laboratory calibration		
ThetaC0	calibration coefficient $\theta_{c0}$	-
Alpha0	calibration coefficient $\alpha_0$	-
8.5.14, Gaeuman et al. (2009) Trinity River calibration		
ThetaC0	calibration coefficient $\theta_{c0}$	-
Alpha0	calibration coefficient $\alpha_0$	-
8.5.15, Van Thiel / Van Rijn		
facua	Multiplication factor for sediment advection velocity [not used] $f_{ua}$ [default: 0.1]	-
facAs	Multiplication factor for wave asymmetry $f_{As}$ [default: 0.1]	-
facSk	Multiplication factor for wave skewness $f_{Sk}$ [default: 0.1]	-
waveform	1=Ruessink <i>et al.</i> (2012), 2=Van Thiel de Vries (2009) [default: 2]	-
sws	Setting for asymmetry 0=not included, 1=included [default: 1]	-
lws	Setting for asymmetry [not used] 0=not included, 1=included [default: 0]	-
dilatancy	Hindered erosion by dilatancy. 0=not included, 1=included [default: 0]	-
rheeA	Weighting parameter for hindered erosion by dilatancy (0.75 for a single particle, 1.7 for a continuum) $A_R$ [default: 0.75]	-
pormax	Porosity in the sheared zone $\rho_{max}$ [default: 0.5]	kg/m <sup>3</sup>
bedslpini	Include bed slope effect on critical velocity. 0=no, 1=suspended + bedload; 2=bedload only [default: 0]	-

Keyword	Parameter	Unit
smax	Multiplication factor for maximum suspension at (inundation) overwash conditions $S_{max}$ [default: -1.0]	-
reposeangle	Angle of internal friction $\phi$ [default: 30.0]	°
cmax	Maximum allowed sediment concentration $C_{max}$ [default: 0.1]	m <sup>3</sup> /m <sup>3</sup>

#### 8.5.16, Soulsby / Van Rijn, XBeach flavour

facua	Multiplication factor for sediment advection velocity [not used] $f_{ua}$ [default: 0.1]	-
facAs	Multiplication factor for wave asymmetry $f_{As}$ [default: 0.1]	-
facSk	Multiplication factor for wave skewness $f_{Sk}$ [default: 0.1]	-
waveform	1=Ruessink <i>et al.</i> (2012), 2=Van Thiel de Vries (2009) [default: 2]	-
sws	Setting for asymmetry 0=not included, 1=included [default: 1]	-
lws	Setting for asymmetry [not used] 0=not included, 1=included [default: 0]	-
dilatancy	Hindered erosion by dilatancy. 0=not included, 1=included [default: 0]	-
rheeA	Weighting parameter for hindered erosion by dilatancy (0.75 for a single particle, 1.7 for a continuum) $A_R$ [default: 0.75]	-
pormax	Porosity in the sheared zone $\rho_{max}$ [default: 0.5]	kg/m <sup>3</sup>
bedslpini	Include bed slope effect on critical velocity. 0=no, 1=suspended + bedload; 2=bedload only [default: 0]	-
smax	Multiplication factor for maximum suspension at (inundation) overwash conditions $S_{max}$ [default: -1.0]	-
reposeangle	Angle of internal friction $\phi$ [default: 30.0]	°
cmax	Maximum allowed sediment concentration $C_{max}$ [default: 0.1]	m <sup>3</sup> /m <sup>3</sup>
z0	Roughness height $z_0$ [default: 0.006]	m

#### 8.5.17, Delft3D-ASMITA hybrid

CEqui	Global equilibrium concentration given $c_E$	kg m <sup>-3</sup>
HEqui	Equilibrium depth $h_e$ relative to $z_{w,ASMITA}$	m
N	Exponent $n$ of the concentration formula [default: 3]	-
MaxHH	Limiter $r_{max}$ for the depth ratio [default: 10]	-
RefLevel	ASMITA reference level $z_{w,ASMITA}$ [default: 0]	m+REF

#### A.4, User defined transport routine for sand or bedload fractions

	none	-
--	------	---

–\* Dummy parameters are only relevant for old files not using keywords.



The value of any parameter can be a number (uniform value) or a file name (either a spatially varying value, or a time varying value). This is an example of a sediment file (see Section A.1) with keywords to be used with the Bijker formulation. All parameters are constant except for the bed porosity which is specified to be spatially varying; the values are read from the file <poros.par>.

```
[SedimentFileInformation]
  FileCreatedBy = Delft3D-FLOW-GUI, Version: 3.39.14.03
  FileCreationDate = Thu Dec 08 2005, 14:47:46
  FileVersion = 02.00
[Sediment]
  Name           = #Sediment sand#           Name of the sediment fraction
  SedTyp          = sand                     Must be "sand", "mud" or "bedload"
  RhoSol          = 2.6500000e+003 [kg/m3]    Specific density
  SedDia          = 2.0000000e-004 [m]        Median sediment diameter (D50)
  CDryB           = 1.6000000e+003 [kg/m3]    Dry bed density
  IniSedThick     = 0.50e+000 [m]            Initial sediment layer thickness at bed
                                           (uniform value or file name)
  FacDSS          = 1.0 [-]                 FacDss*SedDia = Initial suspended
                                           sediment diameter.
  TraFrm          = 5                       Transport formula number
                                           5 represents Bijker (1971)
  CalBs           = 5 [-]                  Calibration coefficient b
                                           for shallow water BS
  CalBd           = 2 [-]                  Calibration coefficient b
                                           for deep water BD
  CritCs          = .4 [-]                 Shallow water (hw=h) criterion Cs
  CritCd          = .05 [-]                 Deep water (hw=h) criterion Cd
  RouKs           = .05 [m]                Bed roughness height rc
  WSettle         = .016 [m/s]              Settling velocity w
  Porosity        = #poros.par# [-]         Bed porosity
  TWave           = 7.0 [s]                Wave period (only used if the computed
                                           wave period < 10E-6)
```

### Backward compatibility

The kernel also supports old files in which the value of TraFrm is not the integer of the sediment transport formula, but the name of a sediment transport input file <\*.tra>. This option is not supported by the user interface. These sediment transport input files exist in two flavours: keyword based and not keyword based.

#### Remark:

- ◇ The user-defined transport formula requires a keyword based transport input file as described below.

### Keyword based transport formula files

The format of the keyword based transport input file is given in Table A.9. This file may select one of the implemented transport formulae by means of the transport formula number **IFORM** or it may point to a shared library (on Windows commonly referred to as a DLL) and the subroutine in that library that should be called to determine the transport rates by means of a user-defined transport formula. Two examples are given below: one for the built-in Bijker formula and one for a user-defined transport formula.

#### Remarks:

- ◇ The user-specified library may contain one or more sediment transport formulae.
- ◇ The interface of the user-specified transport formula subroutine depends on the type of sediment ("sand", "bedload" or "mud") for which the formula is to be used. For sand fractions the routine should return sbc\_total, sbc, sbcu, sbcv, equi\_conc, cesus,

ssus, sbwu, sbwv, sswu, sswv and t\_relax. Even though bedload fractions don't have a suspended load component, the subroutine for such sediment fractions should return the same list of quantities as for the case of sand fractions. For mud fractions the routine should return source and sink. The meaning of these output arguments is described in the Sections A.4 and A.5 for sand and mud fractions, respectively.

Below, you find an example of a keyword based sediment transport input file using the Bijker formulation. The example uses uniform values for all parameters except for the bed porosity which is read from a file <poros.par>.

```
[TransportFormulaFileInformation]
  FileCreationDate = Thu Dec 08 2005, 14:47:50
  FileVersion      = 01.00
[TransportFormula]
  Number          = 5
  CalBs           = 5
  CalBd           = 2
  CritCs          = .4
  CritCd          = .05
  RouKs           = .05
  WSettle         = .016
  Porosity        = #poros.par#
  TWave           = 7.0
```

The second example concerns the use of user-defined subroutine EngHan that implements the Engelund Hansen transport formula; the subroutine is located in a library <MyTransportLibrary.dll> or <MyTransportLibrary.so> depending on the operating system. The DLL points to the appropriate library file (which should be located in the work directory or somewhere on the Windows search path). The Function points to the appropriate subroutine in the library file.

```
[TransportFormulaFileInformation]
  FileCreationDate = Thu Dec 08 2005, 14:47:50
  FileVersion      = 01.00
[TransportFormula]
  Name             = My Engelund Hansen implementation
  DLL              = MyTransportLibrary
  Function          = EngHan
```

### ***Transport formula files without keywords***

The formatting of these files is as follows:

- ◇ The file without keywords may start with an arbitrary number of lines not containing the text IFORM.
- ◇ Then a line starting with sediment transport formula number **IFORM** and containing text IFORM.
- ◇ Then an arbitrary number of lines starting with an asterisk (\*) may follow.
- ◇ Then a line starting with the number sign (#) followed by a transport formula number optionally followed by text identifying the transport formula for the user. The next lines should contain the parameter values of the transport formula coefficients: one parameter value per line optionally followed by text identifying the parameter. There may be an arbitrary number of blocks starting with # in the file, but exactly one should correspond to the transport formula number IFORM specified above.

An example file for transport formula 5 referred to as "Bijker (1971)" is provided below. This file format only supports the specification of uniform values (spatially varying parameters are

**Table A.9:** Sediment transport formula input file with keywords

Keyword	Record description
<b>TransportFormulaFileInformation</b>	
FileCreatedBy	contains version number of user interface
FileCreationDate	creation date and time of the <*.tra> file
FileVersion	version number, currently 01.00
<b>TransportFormula</b>	
Number	sediment transport formula number <b>IFORM</b> (1 integer). Only used for the transport formulae listed in Table A.7.
*	If <b>TraFrm</b> specifies the number of the sediment transport formula <b>IFORM</b> then the keywords associated with the sediment transport formula should also be listed in this block. See Table A.8 for a listing of the transport formula specific keywords.
Name	name of transport formula (string). Only used for user defined transport formulae.
DLL	library name without <.dll> or <.so> extension (string). Only used for user defined transport formulae.
Function	function name within library to call. Only used for user defined transport formulae.
InputFile	optional file name to be passed to library. Only used for user defined transport formulae.

only supported in the newer keyword based input files). Dummy parameters listed in Table A.8 must be included.

#### Remarks:

- ◇ [Van Rijn \(1993\)](#) does not require any additional parameters. Only the transport formula number (-1) followed by the string `IFORM` is required.
- ◇ The keyword `IFORM` must be present in the same line as the formula number **IFORM**.
- ◇ The file should not contain tabs.

```

5          Number of transport formula  IFORM
*-----
#5          BIJKER with wave effect
5          -Par 1- Coefficient shallow water    BS
2          -Par 2- Coefficient deep water       BD
.4          -Par 3- Shallow water limit         CRITS
.05         -Par 4- Deep water limit            CRITD
.000300     -Par 5- Dummy D90 grain size        D90
.05         -Par 6- Bottom roughness height     RK
.016        -Par 7- Particle fall velocity      W
.4          -Par 8- Porosity                   POR
7.0         -Par 9- Wave Period                 T
# End of specification of transport relation

```

Note that only the number 5, the marker #5 and the values on the next lines are required. All the other text is optional.

#### A.4 User defined transport routine for sand or bedload fractions

This section gives an example code for a user-defined transport routine for sand or bedload fractions. The interface of the routine for mud fractions is slightly different; it is described in [section A.5](#). This particular example implements the [Engelund and Hansen \(1967\)](#) formula as a total load transport formula; the code can be found in the source directory of the Delft3D installation on your computer.

The order and way in which arguments are passed to external functions differs among FORTRAN compilers. Most compilers allow you to change these settings, however, if these settings do not match the settings of the calling program the program will crash when trying to call the subroutine in the supplied library. It is, therefore, important to make sure that the settings that you use to compile the library match the settings used when compiling delftflow. It therefore recommended to generate the library using the same compiler as delftflow; at this moment this is the Intel Fortran 11 compiler<sup>1</sup> using default settings for a multithreaded program.

Most of the code is straightforward and standard Fortran, so it should be fairly easy to understand. Some statements may, however, require some explanation. The `!DEC$` statement is read by the compiler and makes sure the subroutine name is visible to the outside world. The real type "hp" is defined as a double precision quantity: even if the simulation runs in single precision, the communication with the library occurs in double precision hence all input and output arguments of the subroutine should be defined to be of the type "real(hp)".

The input quantities are provided using three linear arrays, namely a real array, an integer array and a character array. Each element of these arrays represents a different quantity; see the example for a description of the various input items. You may either use the various

<sup>1</sup>If you can't use this compiler then make sure that the following minimum conditions are met: multi-threaded library with calling convention "C, by reference" and "string length arguments after all arguments".

elements directly in your formulae or define local variables as done in the example; the latter approach keeps your own code more readable and separate from the Delft3D interface. The array approach for the input items allows us to add extra input parameters to the end of the arrays without breaking compatibility with older routines.

```

subroutine enghan(dll_integers, max_integers, &
                 dll_reals, max_reals, &
                 dll_strings, max_strings, &
                 sbc_total, sbc, sbcu, sbcv, sbwu, sbwv, &
                 equi_conc, cesus, ssus, sswu, sswv, t_relax, &
                 error_message)
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS: 'ENGHAN' :: ENGHAN
!--description-----
!
! Computes sediment transport according to
! Engelund and Hansen (1967)
!
!--pseudo code and references-----
! NONE
!--declarations-----
implicit none
!
! Local constants
! Interface is in high precision
!
integer, parameter :: hp = kind(1.0d0)
!
! Subroutine arguments: input
!
integer, intent(in) :: max_integers
integer, intent(in) :: max_reals
integer, intent(in) :: max_strings
integer, dimension(max_integers), intent(in) :: dll_integers
real(hp), dimension(max_reals), intent(in) :: dll_reals
character(len=256), dimension(max_strings), intent(in) :: dll_strings
!
! Subroutine arguments: output
!
real(hp), intent(out) :: sbc ! bedload due to currents, magnitude [m3/m/s]
real(hp), intent(out) :: sbcu ! bedload due to currents, m component [m3/m/s]
real(hp), intent(out) :: sbcv ! bedload due to currents, n component [m3/m/s]
real(hp), intent(out) :: sbwu ! bedload due to waves, m component [m3/m/s]
real(hp), intent(out) :: sbwv ! bedload due to waves, n component [m3/m/s]
real(hp), intent(out) :: cesus ! susp load concentration [m3/m3]
real(hp), intent(out) :: ssus ! susp load due to currents, magnitude [m3/m/s]
real(hp), intent(out) :: sswu ! susp load due to waves, m component [m3/m/s]
real(hp), intent(out) :: sswv ! susp load due to waves, n component [m3/m/s]
real(hp), intent(out) :: t_relax ! relaxation time in 2D mode [s]
character(len=256), intent(out) :: error_message ! not empty: echo and stop run
logical, intent(out) :: equi_conc ! true: contraction cesus returned by formula
! false: susp load ssus returned by formula
logical, intent(out) :: sbc_total ! true: bedload magnitude returned by formula
! false: bedload components returned

!
! Local variables for input parameters
!
integer :: l
integer :: m
integer :: n, nm
real(hp) :: ag
real(hp) :: chezy
real(hp) :: d10, d50, d90, dss, dstar
real(hp) :: h, hidexp, hrms
real(hp) :: mudfrac
real(hp) :: rhosol, rhowat, rlabda

```

```

real(hp)          :: sal
real(hp)          :: taub, tem, teta, timsec, tp
real(hp)          :: u, umod, uorb, utot, uuu
real(hp)          :: v, vicmol, vvv
real(hp)          :: ws
real(hp)          :: zumod
character(len=256) :: runid
!
! Local variables
!
real(hp)          :: acal
real(hp)          :: cf
real(hp)          :: delta
real(hp)          :: ustar
!
!! extract array variables -----
!
if (max_integers < 4) then
    error_message = 'Insufficient integer values provided by delftflow'
    return
endif
nm      = dll_integers( 1) ! nm index of the grid cell
m       = dll_integers( 2) ! m index of the grid cell
n       = dll_integers( 3) ! n index of the grid cell
l       = dll_integers( 4) ! number of the sediment fraction in the computation
!
if (max_reals < 30) then
    error_message = 'Insufficient real values provided by delftflow'
    return
endif
timsec  = dll_reals( 1)    ! current time since reference time [s]
u       = dll_reals( 2)    ! m component of effective depth-averaged velocity [m/s]
v       = dll_reals( 3)    ! n component of effective depth-averaged velocity [m/s]
utot    = dll_reals( 4)    ! magnitude of effective depth-averaged velocity [m/s]
uuu     = dll_reals( 5)    ! m component of characteristic velocity [m/s]
vvv     = dll_reals( 6)    ! n component of characteristic velocity [m/s]
umod    = dll_reals( 7)    ! magnitude of characteristic velocity [m/s]
zumod   = dll_reals( 8)    ! height above bed of characteristic velocity [m]
h       = dll_reals( 9)    ! water depth [m]
chezy   = dll_reals(10)    ! local Chezy value [m1/2/s]
hrms    = dll_reals(11)    ! wave height [m]
tp       = dll_reals(12)    ! wave period [s]
teta    = dll_reals(13)    ! angle between wave dir and local grid orientation [deg]
rlabda  = dll_reals(14)    ! wave length [m]
uorb    = dll_reals(15)    ! orbital velocity at the bed [m/s]
d50     = dll_reals(16)    ! sediment diameter of fraction [m]
dss     = dll_reals(17)    ! sediment diameter of fraction when in suspension [m]
dstar   = dll_reals(18)    ! critical dimensionless grain size parameter [-]
d10     = dll_reals(19)    ! 10-percentile diameter of local sediment mixture [m]
d90     = dll_reals(20)    ! 90-percentile diameter of local sediment mixture [m]
mudfrac = dll_reals(21)    ! mud fraction [-]
hidexp  = dll_reals(22)    ! hiding & exposure factor [-]
ws      = dll_reals(23)    ! settling velocity [m/s]
rhosol  = dll_reals(24)    ! solid sediment density [kg/m3]
rhowat  = dll_reals(25)    ! local water density [kg/m3]
sal     = dll_reals(26)    ! local salinity [ppt]
tem     = dll_reals(27)    ! local water temperature [degC]
ag      = dll_reals(28)    ! gravitational acceleration [m/s2]
vicmol  = dll_reals(29)    ! molecular viscosity of water [m2/s]
taub    = dll_reals(30)    ! bed shear stress [N/m2]
!
if (max_strings < 2) then
    error_message = 'Insufficient strings provided by delftflow'
    return
endif
runid    = dll_strings( 1) ! user-specified run-identification

```

```

filenm = dll_strings( 2) ! user-specified file name (keyword: InputFile)
!
!! executable statements -----
!
write(*,*) 'plugin_delftflow_traform.dll : enghan : called'
! The output argument error_message MUST have value ' ' to continue the calculation.
!
error_message = ' '
!
! If you want to indicate that this subroutine has encountered some invalid input or
! encountered some unexpected situation, you can set the error_message to a non-empty
! string. This error_message will then be shown in the log file of the calling program
! and the simulation will abort. This is shown by the next line, remove it to enable
! this subroutine.
!
! error_message = 'Use the Engelund Hansen formula inside \DFLOW'
!
! Set some parameters and compute derivative quantities.
!
delta = (rhosol - rhowat) / rhowat ! relative density of sediment particle
acal = 0.6_hp
cf = ag/chezy/chezy
ustar = sqrt(cf)*utot
!
! Set the transport rates and concentrations.
! Note: all transport quantities should be given in m3 solid material per s.
! i.e. rate (or concentration) in kg/s =
! rhosol * specified rate (or concentration)
!
sbc_total = .true. ! set flag to indicate that bedload magnitude is given
sbc = acal*0.05_hp*utot*ustar**4/ag**2/sqrt(cf)/delta**2/d50
! bedload magnitude is non-zero
sbcu = 0.0_hp ! bedload component, m direction (here dummy since sbc_total is true)
sbcv = 0.0_hp ! bedload component, n direction (here dummy since sbc_total is true)
!
! There should be no suspended load.
!
equi_conc = .false. ! set flag to indicate that susp load magnitude is given
cesus = 0.0_hp ! suspended load concentration (here dummy since equi_conc is false)
ssus = 0.0_hp ! zero suspended load transport
!
! This formula does not include wave driven transport.
!
sbwu = 0.0_hp ! bedload transport, m direction due to waves is zero
sbwv = 0.0_hp ! bedload transport, n direction due to waves is zero
sswu = 0.0_hp ! suspended load transport, m direction due to waves is zero
sswv = 0.0_hp ! suspended load transport, n direction due to waves is zero
!
! Since there is no suspended load, also the relaxation time for depth-averaged models can be
! set to zero.
!
t_relax = 0.0_hp ! relaxation time is zero
end subroutine enghan
!$

```

For the bedload (due to currents) the routine may either return the total transport rate (*sbc*) or the two transport components (*sbcu* and *sbcv*) in the two grid directions *m* and *n*. The logical flag *sbc\_total* indicates which values the routine has set (obviously true for the former choice and false for the latter choice). In the former case the sediment transport direction is automatically set equal to the near bed velocity direction in a 3D model and equal to the depth-averaged velocity direction corrected for secondary flow (see [Equation \(8.69\)](#)) in a 2D model.

For the suspended load (due to currents) there are again two options: the routine may either

return the (equilibrium) suspended sediment concentration (`cesus`) or the (equilibrium) suspended transport rate (`ssus`). The logical flag `equi_conc` indicates which value the routine has set (obviously true for the former choice and false for the latter choice). For sand fractions the (equilibrium) suspended sediment concentration will be computed in the latter case as  $S_{sus}/uH$  where  $u$  is the depth-averaged velocity and  $H$  is the water depth. For bedload fractions the reverse is done: if `cesus` is given then the suspended sediment transport rate is computed by multiplying it with  $uH$ .

If you want to distinguish between flow and wave driven transports, you may set the wave driven bedload and suspended load rate components separately using `sbwu`, `sbwv`, `sswu` and `sswv`. It should be noted that the suspended load due to currents (specified as either `cesus` or `ssus`) will be used to force the advection-diffusion equation for the suspended load. The suspended load due to waves (specified using `sswu` and `sswv`) is treated as a regular explicit sediment flux.

**Remark:**

- ◇ All transport quantities should be given in [m<sup>3</sup>] solid material, i.e. excluding any pore volumes.

In 3D simulations the advection and diffusion of sediment in the vertical direction results in a relaxation behaviour; the concentrations are imposed near the bed and it takes time for the model to reach the equilibrium concentration. In 2D simulations the processes in the vertical direction are lacking; for such applications a relaxation time is needed to reproduce this behaviour. You can specify it here as `t_relax`; if `t_relax` is equal to zero or if it is negative then the program will use the [Galappatti \(1983\)](#) formula.

## A.5 User defined transport routine for mud fractions

This section gives an example code for a user-defined transport routine for mud fractions. The interface of the routine for sand and bedload fractions is slightly different; it is described in [section A.4](#). This particular example implements the source and sink terms of [Partheniades \(1965\)](#) formulae; the code can be found in the source directory of the Delft3D installation on your computer.

The order and way in which arguments are passed to external functions differs among FORTRAN compilers. Most compilers allow you to change these settings, however, if these settings do not match the settings of the calling program the program will crash when trying to call the subroutine in the supplied library. It is, therefore, important to make sure that the settings that you use to compile the library match the settings used when compiling `delftflow`. It therefore recommended to generate the library using the same compiler as `delftflow`; at this moment this is the Intel Fortran 11 compiler<sup>2</sup> using default settings for a multithreaded program.

Most of the code is straightforward and standard Fortran, so it should be fairly easy to understand. Some statements may, however, require some explanation. The `!DEC$` statement is read by the compiler and makes sure the subroutine name is visible to the outside world. The real type “hp” is defined as a double precision quantity: even if the simulation runs in single precision, the communication with the library occurs in double precision hence all input and output arguments of the subroutine should be defined to be of the type “real(hp)”.

The input quantities are provided using three linear arrays, namely a real array, an integer

---

<sup>2</sup>If you can't use this compiler then make sure that the following minimum conditions are met: multi-threaded library with calling convention “C, by reference” and “string length arguments after all arguments”.



array and a character array. Each element of these arrays represents a different quantity; see the example for a description of the various input items. The input parameters for the mud transport formula are the same as those for the sand and bedload fractions, however, a number of input parameters are not defined in case of mud, namely the characteristic grain diameters  $D_{10}$ ,  $D_{50}$ ,  $D_{90}$ ,  $D_s$ ,  $D_*$ , the mud fraction and the hiding and exposure factor  $\xi$ . You may either use the various elements directly in your formulae or define local variables as done in the example; the latter approach keeps your own code more readable and separate from the Delft3D interface. The array approach for the input items allows us to add extra input parameters to the end of the arrays without breaking compatibility with older routines.

```

subroutine parkro(dll_integers, max_integers, &
                 dll_reals, max_reals, &
                 dll_strings, max_strings, &
                 sink, source, &
                 error_message)
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS: 'PARKRO' :: PARKRO
!!--description-----
!
! Computes source and sink terms according to
! Partheniades and Krone (1965)
!
!!--pseudo code and references-----
! NONE
!!--declarations-----
implicit none
!
! Local constants
! Interface is in high precision
!
integer, parameter :: hp = kind(1.0d0)
!
! Subroutine arguments: input
!
integer, intent(in) :: max_integers
integer, intent(in) :: max_reals
integer, intent(in) :: max_strings
integer, dimension(max_integers), intent(in) :: dll_integers
real(hp), dimension(max_reals), intent(in) :: dll_reals
character(len=256), dimension(max_strings), intent(in) :: dll_strings
!
! Subroutine arguments: output
!
real(hp), intent(out) :: source ! source term [kg/m2/s]
real(hp), intent(out) :: sink ! sink term [-] (to be multiplied with concentration)
character(len=256), intent(out) :: error_message ! not empty: echo and stop run
!
! Local variables for input parameters
!
integer :: l
integer :: m
integer :: n, nm
real(hp) :: ag
real(hp) :: chezy
real(hp) :: d10, d50, d90, dss, dstar
real(hp) :: h, hidexp, hrms
real(hp) :: mudfrac
real(hp) :: rhosol, rhowat, rlabda
real(hp) :: sal
real(hp) :: taub, tem, teta, timsec, tp
real(hp) :: u, umod, uorb, utot, uuu
real(hp) :: v, vicmol, vvv
real(hp) :: ws
real(hp) :: zumod
character(len=256) :: runid

```

```

!
! Local variables
!
real(hp)          :: eropar
real(hp)          :: taum, tcrero, tcrdep
!
!! extract array variables -----
!
if (max_integers < 4) then
    error_message = 'Insufficient integer values provided by delftflow'
    return
endif
nm      = dll_integers( 1) ! nm index of the grid cell
m       = dll_integers( 2) ! m index of the grid cell
n       = dll_integers( 3) ! n index of the grid cell
l       = dll_integers( 4) ! number of the sediment fraction in the computation
!
if (max_reals < 30) then
    error_message = 'Insufficient real values provided by delftflow'
    return
endif
timsec  = dll_reals( 1)    ! current time since reference time [s]
u       = dll_reals( 2)    ! m component of effective depth-averaged velocity [m/s]
v       = dll_reals( 3)    ! n component of effective depth-averaged velocity [m/s]
utot    = dll_reals( 4)    ! magnitude of effective depth-averaged velocity [m/s]
uuu     = dll_reals( 5)    ! m component of characteristic velocity [m/s]
vvv     = dll_reals( 6)    ! n component of characteristic velocity [m/s]
umod    = dll_reals( 7)    ! magnitude of characteristic velocity [m/s]
zumod   = dll_reals( 8)    ! height above bed of characteristic velocity [m]
h       = dll_reals( 9)    ! water depth [m]
chezy   = dll_reals(10)    ! local Chezy value [m1/2/s]
hrms    = dll_reals(11)    ! wave height [m]
tp      = dll_reals(12)    ! wave period [s]
teta    = dll_reals(13)    ! angle between wave dir and local grid orientation [deg]
rlabda  = dll_reals(14)    ! wave length [m]
uorb    = dll_reals(15)    ! orbital velocity at the bed [m/s]
!
!---- the following parameters are undefined for mud fractions -----
d50      = dll_reals(16)    ! sediment diameter of fraction [m]
dss      = dll_reals(17)    ! sediment diameter of fraction when in suspension [m]
dstar    = dll_reals(18)    ! critical dimensionless grain size parameter [-]
d10      = dll_reals(19)    ! 10-percentile diameter of local sediment mixture [m]
d90      = dll_reals(20)    ! 90-percentile diameter of local sediment mixture [m]
mudfrac  = dll_reals(21)    ! mud fraction [-]
hidexp   = dll_reals(22)    ! hiding & exposure factor [-]
!---- the parameters above are undefined for mud fractions -----
!
ws       = dll_reals(23)    ! settling velocity [m/s]
rhosol   = dll_reals(24)    ! solid sediment density [kg/m3]
rhowat   = dll_reals(25)    ! local water density [kg/m3]
sal       = dll_reals(26)    ! local salinity [ppt]
tem      = dll_reals(27)    ! local water temperature [degC]
ag       = dll_reals(28)    ! gravitational acceleration [m/s2]
vicmol   = dll_reals(29)    ! molecular viscosity of water [m2/s]
taub     = dll_reals(30)    ! bed shear stress [N/m2]
!
if (max_strings < 2) then
    error_message = 'Insufficient strings provided by delftflow'
    return
endif
runid    = dll_strings( 1)  ! user-specified run-identification
filenm   = dll_strings( 2)  ! user-specified file name (keyword: InputFile)
!
!! executable statements -----
!
write(*,*) 'plugin_delftflow_traform.dll : parkro : called'

```

```

! The output argument error_message MUST have value ' ' to continue the calculation.
!
error_message = ' '
!
! If you want to indicate that this subroutine has encountered some invalid input or
! encountered some unexpected situation, you can set the error_message to a non-empty
! string. This error_message will then be shown in the log file of the calling program
! and the simulation will abort. This is shown by the next line, remove it to enable
! this subroutine.
!
! error_message = 'Use the Partheniades Krone formula inside \DFLOW'
!
! Set some parameters and compute derivative quantities.
!
tcrero = 0.1_hp
tcrdep = 0.1_hp
eropar = 2.5e-6_hp
!
! Compute source and sink terms
!
taum    = max(0.0_hp, taub/tcrero - 1.0_hp)
source = eropar * taum
if (tcrdep > 0.0_hp) then
    sink = max(0.0_hp, 1.0_hp-taub/tcrdep)
else
    sink = 0.0_hp
endif
end subroutine parkro

```

Compared to the subroutine for sand and bedload fractions (described in [section A.4](#)) this routine has very few output arguments, namely only `source` and `sink`. The source term will be used explicitly and should be specified in kg (mud) per unit area ( $\text{m}^2$ ) per unit of time (s). The sink term is treated implicitly and reads `sink` times  $c^{t+1}w_s$  where  $c^{t+1}$  is the concentration at the new time level in  $[\text{kg}/\text{m}^3]$  and  $w_s$  is the local settling velocity in  $[\text{m}/\text{s}]$ ; hence the quantity `sink` to be returned by the routine is dimensionless.

#### Remarks:

- ◇ The unit for the source term is  $[\text{kg}/\text{m}^3/\text{s}]$ .
- ◇ The sink quantity is dimensionless since it will be multiplied with the concentration in  $[\text{kg}/\text{m}^3]$  and the settling velocity in  $[\text{m}/\text{s}]$  to give the actual sink term in the equation.

## A.6 User defined routine for the settling velocity

This section gives an example code for a user-defined routine that computes the settling velocity. This particular example implements a simple salinity dependent settling formula for mud, but the same routine interface can also be used for sand fractions.

The order and way in which arguments are passed to external functions differs among FORTRAN compilers. Most compilers allow you to change these settings, however, if these settings do not match the settings of the calling program the program will crash when trying to call the subroutine in the supplied library. It is, therefore, important to make sure that the settings that you use to compile the library match the settings used when compiling `delftflow`. It therefore recommended to generate the library using the same compiler as `delftflow`; at this moment this is the Intel Fortran 11 compiler<sup>3</sup> using default settings for a multithreaded program.

<sup>3</sup>If you can't use this compiler then make sure that the following minimum conditions are met: multi-threaded library with calling convention "C, by reference" and "string length arguments after all arguments".

Most of the code is straightforward and standard Fortran, so it should be fairly easy to understand. Some statements may, however, require some explanation. The `!DEC$` statement is read by the compiler and makes sure the subroutine name is visible to the outside world. The real type “hp” is defined as a double precision quantity: even if the simulation runs in single precision, the communication with the library occurs in double precision hence all input and output arguments of the subroutine should be defined to be of the type “real(hp)”.

The input quantities are provided using three linear arrays, namely a real array, an integer array and a character array. Each element of these arrays represents a different quantity; see the example for a description of the various input items. The input parameters for the mud transport formula are the same as those for the sand and bedload fractions, however, two input parameters are not defined in case of mud, namely  $D_{50}$  and  $D_s$ . You may either use the various elements directly in your formulae or define local variables as done in the example; the latter approach keeps your own code more readable and separate from the Delft3D interface. The array approach for the input items allows us to add extra input parameters to the end of the arrays without breaking compatibility with older routines.

```
subroutine settle(dll_integers, max_integers, &
                 dll_reals , max_reals , &
                 dll_strings , max_strings , &
                 ws , &
                 error_message )
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS: 'SETTLE' :: SETTLE
!!--description-----
!
! Computes simple salinity dependent settling velocity.
!
!!--pseudo code and references-----
! NONE
!!--declarations-----
implicit none
!
! Local constants
! Interface is in high precision
!
integer , parameter :: hp = kind(1.0d0)
!
! Subroutine arguments: input
!
integer , intent(in) :: max_integers
integer , intent(in) :: max_reals
integer , intent(in) :: max_strings
integer , dimension(max_integers), intent(in) :: dll_integers
real(hp) , dimension(max_reals) , intent(in) :: dll_reals
character(len=256), dimension(max_strings) , intent(in) :: dll_strings
!
! Subroutine arguments: output
!
real(hp) , intent(out) :: ws ! settling velocity [m/s]
character(len=256), intent(out) :: error_message ! not empty: echo and stop run
!
! Local variables for input parameters
!
integer :: k
integer :: l
integer :: m
integer :: n, nm
real(hp) :: ag
real(hp) :: cconc, chezy, conc, csoil
real(hp) :: d50, dss
real(hp) :: epstur
real(hp) :: h
```

```

real(hp)          :: ktur
real(hp)          :: rhol, rhowat
real(hp)          :: sal
real(hp)          :: tem, timsec
real(hp)          :: u, um
real(hp)          :: v, vicmol, vm
real(hp)          :: w
character(len=256) :: runid
!
! Local variables
!
real(hp)          :: f
real(hp)          :: pi
real(hp)          :: salmax
real(hp)          :: ws0, ws1
!
!! extract array variables -----
!
if (max_integers < 5) then
    error_message = 'Insufficient integer values provided by delftflow'
    return
endif
nm      = dll_integers( 1) ! nm index of the grid cell
m      = dll_integers( 2) ! m index of the grid cell
n      = dll_integers( 3) ! n index of the grid cell
k      = dll_integers( 4) ! layer number of the grid cell
l      = dll_integers( 5) ! number of the sediment fraction in the computation
!
if (max_reals < 21) then
    error_message = 'Insufficient real values provided by delftflow'
    return
endif
timsec  = dll_reals( 1)    ! current time since reference time [s]
u       = dll_reals( 2)    ! m component of the local velocity [m/s]
v       = dll_reals( 3)    ! n component of the local velocity [m/s]
w       = dll_reals( 4)    ! vertical component of the local velocity [m/s]
sal     = dll_reals( 5)    ! local salinity [ppt]
tem     = dll_reals( 6)    ! local water temperature [degC]
rhowat  = dll_reals( 7)    ! local water density [kg/m3]
conc    = dll_reals( 8)    ! sediment concentration [kg/m3] of considered fraction
cconc   = dll_reals( 9)    ! total sediment concentration [kg/m3] over all fractions
ktur    = dll_reals(10)    ! turbulent kinetic energy [m2/s2]
epstur  = dll_reals(11)    ! turbulent dissipation [m2/s3]
!
!---- the following parameters are undefined for mud fractions -----
d50     = dll_reals(12)    ! sediment diameter of fraction [m]
dss     = dll_reals(13)    ! sediment diameter of fraction when in suspension [m]
!---- the parameters above are undefined for mud fractions -----
!
rhol    = dll_reals(14)    ! solid sediment density [kg/m3]
rsoil   = dll_reals(15)    ! reference density for hindered settling calculations [kg/m3]
ag      = dll_reals(16)    ! gravitational acceleration [m/s2]
vicmol  = dll_reals(17)    ! molecular viscosity of water [m2/s]
h       = dll_reals(18)    ! water depth [m]
um      = dll_reals(19)    ! m component of effective depth-averaged velocity [m/s]
vm      = dll_reals(20)    ! n component of effective depth-averaged velocity [m/s]
chezy   = dll_reals(21)    ! local Chezy value [m1/2/s]
!
if (max_strings < 2) then
    error_message = 'Insufficient strings provided by delftflow'
    return
endif
runid   = dll_strings( 1)  ! user-specified run-identification
filnm   = dll_strings( 2)  ! user-specified file name (keyword: SettleInput)
!
!! executable statements -----

```

```
!
write(*,*) 'plugin_delftflow_traform.dll : settle : called'
! The output argument error_message MUST have value ' ' to continue the calculation.
!
error_message = ' '
!
! If you want to indicate that this subroutine has encountered some invalid input or
! encountered some unexpected situation, you can set the error_message to a non-empty
! string. This error_message will then be shown in the log file of the calling program
! and the simulation will abort. This is shown by the next line, remove it to enable
! this subroutine.
!
! error_message = 'Use the settling velocity routine inside \DFLOW'
!
! Set some parameters and compute derivative quantities.
!
ws1    = 5.0e-4_hp    ! settling velocity at S >= S_max
ws0    = 5.0e-4_hp    ! settling velocity at S = 0
salmax = 30.0_hp
!
pi = 4.0_hp * atan(1.0_hp)
!
! Compute settling velocity
!
if (sal > salmax) then
    f = 1.0_hp
else
    f = 0.5_hp * (1 - cos(pi*sal/salmax))
endif
ws = ws0 + (ws1 - ws0) * f
end subroutine settle
```

Compared to the subroutine for sand and bedload fractions (described in [section A.4](#)) this routine has very few output arguments, namely only `source` and `sink`. The source term will be used explicitly and should be specified in kg (mud) per unit area (m<sup>2</sup>) per unit of time (s). The sink term is treated implicitly and reads `sink` times  $c^{t+1}w_s$  where  $c^{t+1}$  is the concentration at the new time level in [kg/m<sup>3</sup>] and  $w_s$  is the local settling velocity in [m/s]; hence the quantity `sink` to be returned by the routine is dimensionless.

**Remarks:**

- ◇ The unit for the source term is [kg/m<sup>3</sup>/s].
- ◇ The sink quantity is dimensionless since it will be multiplied with the concentration in [kg/m<sup>3</sup>] and the settling velocity in [m/s] to give the actual sink term in the equation.

**A.7 Sediment transport and morphology boundary condition file**

File contents	Time-series for sediment transport and morphology boundary conditions
Filetype	ASCII
File format	Fix format for header information; free format for time-series data.
Filename	<name.bcm>
Generated	manually offline

**Record description:**

For each open boundary segment that according to the boundary characteristics given in the <\*.mor> file requires boundary data, the data is given in two related blocks:

- ◇ A header block containing a number of compulsory and optional keywords accompanied by their values.

- ◇ A data block containing the time dependent data.

Description header block:

Text	Required	Value
table-name	no	arbitrary string
location	yes	'name boundary section' (see <name.bnd> file)
time-function	no	{'non-equidistant'} or 'equidistant'
time-step	yes	time step only in case of time-function 'equidistant'
reference-time	yes	yyyymmdd, yyymmdd hhmmss or 'from model'
time-unit	no	'years', 'decades', 'days', 'hours', {'minutes'}, 'seconds', 'ddhhmmss' or 'date'
interpolation	no	{'linear'} or 'block'
extrapolation	no	'periodic', 'constant' or {'none'}
parameter	yes	'parameter name and location' units '[ccc]'
records-in-table	no	number of times/lines in the data block

**Remarks:**

- ◇ Default parameter values are indicated in braces.
- ◇ Reference-time not required if time-unit equals 'date'.
- ◇ Unit strings are currently not interpreted by Delft3D-FLOW.

The 'parameter name and location' strings depend on the boundary type chosen, i.e. quantity type to be specified. The following table lists the base parameter names. The full 'parameter name and location' string is a concatenation of the indicated base parameter name, optionally followed by a single space character and the user-defined sediment name, optionally followed by 'end A' and 'end B' location strings. Bedload transport should be specified for only the non-mud fractions (i.e. sand and bedload fractions only) whereas bed composition should be specified for all fractions. The parameters for multiple sediment fractions must occur in the same order as in which the sediment fractions have been defined. The location strings 'end A' and 'end B' can be used to indicate that the specified quantity linearly varies along the boundary; in case of a parameter for multiple sediment fractions, all parameter-sediment pairs must be specified for both 'end A' and 'end B' and all 'end A' conditions should precede the 'end B' conditions.

Boundary type	Base name	parameter	Unit	Multiplicity
<b>sediment transport and bed level</b>				
0: free	none		-	-
1: fixed	none		-	-
2: time series	depth		m	1
3: depth change prescribed	depth change		m/s	1
4: transport incl pores prescribed	transport incl pores		m <sup>3</sup> /s/m	#nonmud
5: transport excl pores prescribed	transport excl pores		m <sup>3</sup> /s/m	#nonmud
<b>bed composition</b>				
0: free	none		-	-
1: fixed	none		-	-
2: mass fraction prescribed	mass fraction		-	#sediment
3: volume fraction prescribed	volume fraction		-	#sediment

Description data block:

Record	Record description
each record	Time in time-units after the reference-time and followed by as many values as parameters have been defined in the description block (all reals). In case of time-function 'equidistant', the first (time) column should be dropped. In case of time-unit 'date' the date and time should be specified as one string using the format: yyyyymmddhhmmss.

**Remarks:**

- ◇ Maximum record length is 512.
- ◇ The morphological boundary conditions will only be used at inflow boundaries.
- ◇ Bed composition boundary conditions are only relevant if you do not impose incoming bedload transport.
- ◇ The parameter name of the column should read 'time'.

**Example:**

Model with morphological boundary conditions imposed at two boundaries. At both boundaries the depth and mass fractions for two sediment fractions 'Sediment fine' and 'Sediment coarse' respectively are prescribed. The file structure allows you to either combine boundary conditions in one table, or to use individual tables. The example shows both approaches.

```
location          'East Boundary'
time-function      'non-equidistant'
reference-time     19941001
time-unit          'minutes'
interpolation      'linear'
parameter          'time' unit '[min]'
parameter          'depth' unit '[m]'
parameter          'mass fraction Sediment fine' unit '[-]'
```



```

parameter          'mass fraction Sediment coarse' unit '[-]'
    0.0000    5.0      0.3      0.7
    2880.0000  6.0      0.4      0.6
location            'West boundary'
time-function        'non-equidistant'
time-unit            'date'
interpolation        'linear'
parameter            'time' unit '[]'
parameter            'depth end A' unit '[m]'
parameter            'depth end B' unit '[m]'
19941001000000    5.0      5.5
19941003000000    6.0      6.5
location            'West boundary'
time-function        'equidistant'
reference-time       19941001
time-unit            'days'
time-step            2
interpolation        'linear'
parameter            'mass fraction Sediment fine end A' unit '[-]'
parameter            'mass fraction Sediment coarse end A' unit '[-]'
parameter            'mass fraction Sediment fine end B' unit '[-]'
parameter            'mass fraction Sediment coarse end B' unit '[-]'
    0.3      0.7      0.35    0.75
    0.4      0.6      0.45    0.65

```

#### A.8 Morphological factor file

File contents	Time-series for morphological factor
Filetype	ASCII
File format	Fix format for header information; free format for time-series data.
Filename	<name.mft>
Generated	manually offline

#### **Record description:**

The data is given in two related blocks:

- ◇ A header block containing a number of compulsory and optional keywords accompanied by their values.
- ◇ A data block containing the time dependent data.

Description header block:

Text	Required	Value
table-name	no	arbitrary string
hline location	no	should be blank if specified
time-function	no	{'non-equidistant'} or 'equidistant'
time-step	yes	time step only in case of time-function 'equidistant'
reference-time	yes	yyyymmdd, yyyymmdd hhmmss or 'from model'
time-unit	no	'years', 'decades', 'days', 'hours', {'minutes'}, 'seconds', 'ddhhmmss' or 'date'
interpolation	yes	'block' (default value 'linear' should not be used)
extrapolation	no	'periodic', 'constant' or {'none'}
parameter	yes	'parameter name and location' units '[ccc]'
records-in-table	no	number of times/lines in the data block

**Remarks:**

- ◇ Maximum record length is 512.
- ◇ The parameter name of the column should read 'time'.
- ◇ The 'parameter name and location' string should read 'MorFac'.
- ◇ Default parameter values are indicated in braces.
- ◇ Interpolation method should be 'block' for MorFac!
- ◇ Reference-time not required if time-unit equals 'date'.
- ◇ Unit strings are currently not interpreted by Delft3D-FLOW.

Description data block:

Record	Record description
each record	Time in time-units after the reference-time and followed by as many values as parameters have been defined in the description block (all reals). In case of time-function 'equidistant', the first (time) column should be dropped. In case of time-unit 'date' the date and time should be specified as one string using the format: yyyymmddhhmmss.

**Example:**

The following file prescribes a morphological factor of 5 until Jan 2, 1994 0:00 and a factor of 10 thereafter.

```

time-function      'non-equidistant'
reference-time     19941001
time-unit          'minutes'
interpolation      'block'
extrapolation      'constant'
parameter          'time' unit '[min]'
parameter          'MorFac' unit '[-]'
      0.0000      5.0
     1440.0000    10.0

```

## A.9 Initial bed composition file

The initial bed composition file allows you to specify the initial composition of multiple layers in the bed. If the bed is initially vertically homogeneous, you can use the `IniSedThick` (or older `SdBUni`) keywords in the `<*.sed>` file. If the bed is initially not completely homogeneous in the vertical direction, you should use this initial bed composition file. This `<*.inb>` file is keywords based.

**Table A.10:** Initial bed composition file keywords

Keyword	Record description
<b>BedCompositionFileInformation</b>	
<code>FileCreatedBy</code>	contains version number of FLOW-GUI
<code>FileCreationDate</code>	creation date and time of the <code>&lt;*.inb&gt;</code> file
<code>FileVersion</code>	version number, currently 01.00
<b>Layer</b>	
<code>Type</code>	Layer type (1 string) options: mass fraction: requires <code>Thick</code> and <code>Fractionx</code> keywords volume fraction: requires <code>Thick</code> and <code>Fractionx</code> keywords sediment mass: requires <code>SedBedx</code> keywords sediment thickness: requires <code>SedBedx</code> keywords
<code>Thick</code>	thickness of sediment layer [m] in case of either 'mass fraction' or 'volume fraction' type layer uniform value (1 real) or filename <code>&lt;*.thk&gt;</code> with non-uniform values at cell centres (1 string)
<code>Fraction1,</code> <code>Fraction2,</code> ...	mass or volume fraction in case of 'mass fraction' and 'volume fraction' type layer respectively uniform value (1 real) or filename <code>&lt;*.frc&gt;</code> with non-uniform values at cell centres (1 string)
<code>SedBed1,</code> <code>SedBed2, ...</code>	mass or thickness in case of 'sediment mass' and 'sediment thickness' type layer respectively uniform value (1 real) or filename <code>&lt;*.sdb&gt;</code> with non-uniform values at cell centres (1 string)
The Layer block can be repeated as often as needed.	

### Example of an initial bed composition file:

The example file contains two layers. The first (top) layer has a spatially varying thickness as given by the QUICKIN file `<layer1.thk>` while the composition is uniform 30 % of sediment fraction 1 and 70 % of sediment fraction 2. The characteristics of the second layer are given as sediment mass [ $\text{kg/m}^2$ ]: a constant  $1600 \text{ kg m}^{-2}$  of sediment fraction 2 and a spatially varying amount of sediment fraction 1 (as specified in the QUICKIN file `<layer2fraction1mass.sdb>`).

```
[BedCompositionFileInformation]
FileCreationDate = Thu Dec 08 2005, 14:47:50
```

```

FileVersion      = 01.00
[Layer]
  Type           = mass fraction
  Thick          = layer1.thk
  Fraction1      = 0.3
  Fraction2      = 0.7
[Layer]
  Type           = sediment mass
  SedBed1        = layer2fraction1mass.sdb
  SedBed2        = 1600

```

#### A.10 Dredge and dump characteristics

**File contents**                      Characteristics of all dredging, dumping and sediment nourishment activities in the simulation (Data Group *Operations - Dredge and dump*).

**Filetype**                            ASCII

**File format**                        Fix formatted for text variables, free formatted for real and integer values.

**Filename**                            <name.dad>

**Generated**                          QUICKIN, or manually offline

##### **Record description:**

The file consists of a header block (containing information about versions) followed by an optional general block with global settings for all dredge/dump blocks and all domains, one (or more) optional domain blocks with settings for the specified domain, a dredge block for each dredge area, a nourishment block for each sediment nourishment measure and an optional dump block for each dump area. [Table A.11](#) gives an overview of all supported keywords and their purpose. The name of the dredge and dump polygon file should be specified in the general block, but for reasons of backward compatibility it is also accepted that the `PolygonFile` is located in the header block.

**Table A.11:** Dredge and dump input file with keywords

Keyword	Format	Record description
<b>DredgeFileInformation</b>		
FileCreatedBy	string	program name and version
FileCreationDate	string	creation date and time of the <*.dad> file
FileVersion	string	version number of the <*.dad> file ('01.02')
<b>General</b>		
PolygonFile	string	name of polygon file with polylines defining dump and dredge areas

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
InPolygon	1 I	default flag to indicate how to check whether a grid cell is inside or outside a dredge or dump polygon (1–3, default: 2). This option can be used to study the sensitivity of the simulation for changes in polygon sizes. A grid cell is inside the polygon if <ol style="list-style-type: none"> <li>1 all corners of the grid cell lie within the polygon (minimum area)</li> <li>2 the centre of the grid cell lies within the polygon (default)</li> <li>3 one of the corners of the grid cell lies within the polygon (maximum area)</li> </ol>
RefPlane	1 R or string	elevation of reference plane above reference level of the simulation for dredging and dumping for this domain: constant value or file name (default: 0 m) Overruled by value for current domain.
DepthDef	1 I	default flag to indicate meaning of depth definitions (1–4; default: 1) ) See description in dredge block.
DredgeDepth	1 R	default depth to be maintained by dredging (default: -999.) Set to -999. if dredging is not limited by depth.
MaxVolRate	1 R	default maximum dredging or sediment nourishment rate in m <sup>3</sup> /morphological year (volume including pores) (default: -999.) Set to -999. if dredging rate is unlimited.
DredgeDistr	1 I	default distribution of dredging activities when limited by rate (1–8, default: 3) See description in dredge block.
Clearance	1 R	default additional depth to dredge when dredging occurs (default: 0 m).
TriggerAll	1 L	default flag to indicate that if one point in the dredge area exceeds the dredging threshold, all points should be dredged to clearance level irrespective whether they exceed the trigger level (default: false)
DredgeWhenDry	1 L	default flag to indicate whether dredging should continue at dry points (default: false).

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
DredgeWhileMorfac	0 L	default flag to indicate whether dredging activities should occur during morphological startup period or periods with morfac=0 (default: true). This flag affects only dredging activities not limited by dredging rate; activities that are limited by a maximum dredging rate are always inactive during startup and other periods with morfac=0 as the effective morphological time is zero.
ObeyCmp	1 L	default flag to indicate whether dredging should be limited to the amount of sediment available (default: true). If false: excess dredged volume is recorded but cannot be dumped as composition is unknown and considered to be irrelevant for the simulation.
TimeSeries	string, optional	name of file containing time-dependent dredging activities
TS_MorTimeScale	1 L	flag to indicate whether times in TimeSeries file are specified on hydrodynamical or morphological time scale (true = morphological time scale; default: false = hydrodynamical time scale)
DistrOverDump	1 I	default method of distributing sediment over dump areas. (1–3; default: 1) See description in dredge block.
DumpDistr	1 I	default method of distributing sediment within a dump area. (1–4; default: 1) See description in dump block.
MinimumDumpDepth	1 R	default minimum remaining depth after dumping: when specified, dumping continues until the specified level is reached. Any surplus of sediment is removed from the model (default: -999.) Set to -999. if dumping should not be restricted.
DumpWhenDry	1 L	default flag to indicate whether dumping should continue at dry points (default: false)
UseDunes	1 L	flag to indicate whether simulated dune heights should be included in volume computations when dredging and dumping; if included, dune height will be set to 0 after dredging and dumping (default: false)
AlphaDuneHeight	[0 0.5]	if UseDunes is true, then the effective bed level is increased by this fraction of the dune height when checking whether dredging threshold is exceeded (default: 0.5)
<b>Domain</b>		

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
Name	string	name of the domain
RefPlane	1 R or string	elevation of reference plane above reference level of the simulation for dredging and dumping for this domain: constant value or file name (default: constant as specified in General block) The format of the file is a QUICKIN compatible file with data at cell centres.
<b>Dredge</b>		
Name	string	name of the dredge area: should correspond to a blockname in the polygon file
InPolygon	1 I	flag to indicate how to check whether a grid cell is inside or outside the dredge polygon (1–3, default: as indicated in General block). See description in General block.
DepthDef	1 I	flag to indicate meaning of depth definitions (1–4; default: as specified in General block) 1 relative to reference plane 2 relative to water level 3 relative to maximum of reference plane and water level 4 relative to minimum of reference plane and water level
DredgeDepth	1 R	depth to be maintained by dredging relative (default: as specified in General block) Set to -999. if dredging is not limited by depth.
MaxVolRate	1 R	maximum dredging rate in m <sup>3</sup> /morphological year (volume including pores) (default: as specified in General block) Set to -999. if dredging rate is unlimited. This maximum volume per year will only be reached if dredging takes place year-round and never runs out of available dredging material, i.e. it doesn't increase the dredging rate per time step if the dredging strategy isn't active for a while.

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
DredgeDistr	1 I	<p>in case the maximum dredging rate is reached in a certain timestep, the model has to decide what sediment to remove (1–8; default: as specified in General block). Eight rules have been implemented</p> <ol style="list-style-type: none"> <li>1 remove same sediment thickness from every grid cell</li> <li>2 remove highest sediment deposits first</li> <li>3 remove sediment proportionally to the amount of sediment available for dredging (default)</li> <li>4 remove sediment from highest point first (gives more or less same results as 2 for small time steps, but may give erratic behavior when large time steps are used)</li> <li>5 remove sediment from lowest point first</li> <li>6 remove sediment from shallowest areas first</li> <li>7 remove sediment from shallowest point first (gives more or less same results as 6 for small time steps, but may give erratic behavior when large time steps are used)</li> <li>8 remove sediment from deepest point first</li> </ol>
Clearance	1 R	additional depth to dredge when dredging occurs (default: as specified in General block)
TriggerAll	1 L	flag to indicate that if one point in the dredge area exceeds the dredging threshold, all points should be dredged to clearance level irrespective whether they exceed the trigger level (default: as specified in General block)
DredgeWhenDry	1 L	flag to indicate whether dredging should continue at dry points (default: as specified in General block)
DredgeWhileMorfac	1 L	flag to indicate whether dredging activities should occur during morphological startup period or periods with morfac=0 (default: as specified in General block). This flag affects only dredging activities not limited by dredging rate.
ObeyCmp	1 L	flag to indicate whether dredging should be limited to the amount of sediment available (default: as specified in General block). If false: excess dredged volume is recorded but cannot be dumped as composition is unknown and considered to be irrelevant for the simulation.

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
DumpLimited	1 L	flag to indicate that dredging is limited by dump capacity (default: false)
DistrOverDump	1 I	method of distributing sediment over dump areas (old keyword <code>DumpDistr</code> still supported). Three methods have been implemented (1–3, default: 1) 1 based on user specified percentages 2 fill dump areas in specified order 3 distribute sediment based on dump capacity
Dump	string	name of the dump area: should correspond to a blockname in the polygon file
Sediment	string, optional	name of sediment fraction
Percentage	1 R	percentage of dredged material of the indicated sediment fraction to be dumped in the indicated dump area; if no sediment fraction is indicated: uniform value for all fractions.
<b>Nourishment</b>		
Name	string, optional	name of the nourishment source. Contrary to the Name in the dredge and dump blocks, this name is not associated with a specific polygon.
Volume	1 R	total sediment volume (including pores) to be supplied
MaxVolRate	1 R	maximum sediment nourishment rate in m <sup>3</sup> /morphological year (volume including pores) (default: as specified in General block) This rate will be converted into a rate per time step assuming that nourishment occurs at a constant rate year-round, i.e. it does not try to compensate for periods of limited dumping capacity or periods of inactivity as optionally specified in <code>TimeSeries</code> file.
Sediment	string	name of sediment fraction
SedPercentage	1 R	composition of supplied sediment: volumetric percentage of the indicated sediment fraction

R = Real; I = Integer; L = Logical; C = Character

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Table A.11 — continued from previous page

Keyword	Format	Record description
DistrOverDump	1 I	method of distributing sediment over dump areas (old keyword <code>DumpDistr</code> still supported). Three methods have been implemented (1–3, default: 1) 1 based on user specified percentages 2 fill dump areas in specified order 3 distribute sediment based on dump capacity
Dump	string	name of the dump area: should correspond to a blockname in the polygon file
Sediment	string, optional	name of sediment fraction
Percentage	1 R	percentage of dredged material of the indicated sediment fraction to be dumped in the indicated dump area; if no sediment fraction is indicated: uniform value for all fractions.
<b>Dump</b>		
Name	string	name of the dump area: should correspond to a blockname in the polygon file
InPolygon	1 I	flag to indicate how to check whether a grid cell is inside or outside the dump polygon (1–3, default: as indicated in General block). See description in General block.
DepthDef	1 I	flag to indicate meaning of depth definitions (1–4; default: as specified in General block) 1 relative to reference plane 2 relative to water level 3 relative to maximum of reference plane and water level 4 relative to minimum of reference plane and water level
MinimumDumpDepth	1 R	minimum remaining depth after dumping: when specified, dumping continues until the specified level is reached. Any surplus of sediment is removed from the model (default: as specified in General block) Set to -999. if dumping should not be restricted.

R = Real; I = Integer; L = Logical; C = Character

continued on next page

Table A.11 — continued from previous page

Keyword	Format	Record description
DumpDistr	1 I	determines how the sediment is dumped within the dump area. Four options have been implemented (1–4; default as specified in General block) 1 dump with uniform thickness 2 fill in lowest parts first (horizontal reference plane) 3 fill in deepest parts first 4 dump proportional to capacity (only for dumping areas with limited capacity)
DumpWhenDry	1 L	flag to indicate whether dumping should continue at dry points (default: as specified in General block)

R = Real; I = Integer; L = Logical; C = Character

#### Warning:

- ◇ QUICKIN does not yet recognize all keywords and will remove all keywords it does not recognize when you attempt to edit a manually edited dredge and dump file with QUICKIN. Backup old <\*.dad> files before you try to do so!

#### Restrictions:

- ◇ The maximum record length in the file is 256 characters.
- ◇ Dredge and dump activities may be combined with domain decomposition simulations. However, please note that in such cases one should select the same <\*.dad> for all domains and use the **domain** block if there are differences between the domains.
- ◇ Dumping conditions (to a certain minimum depth or to flooded points only) may not exactly be satisfied if multiple dredging and dumping overlap. In case of dredging limited by dumping capacity similar interactions may also cause deviations from requested behaviour.

#### Remarks:

- ◇ The order of the data blocks is arbitrary.
- ◇ To remove sediment from the model, specify one (or more) dump areas outside the grid.
- ◇ Dredging measures are processed in the order in which the **dredge** blocks are specified in the input file.
- ◇ Dumping measures are processed in the order in which they are specified in the **dredge** and **nourishment** blocks of the input file.

#### Example:

The number of dredge areas is 3. 'dredge 1' and 'dredge 2' will be dredged to a depth of 10 m. All dredged material is dumped in area 'dump 1'. Area 'dredge 3' is dredged to a depth of 20 m and the material removed from that area is dumped in 'dump 2'.

```
[DredgeFileInformation]
  FileCreatedBy    = Deltares, QUICKIN Version 4.20.00.30984, Nov 12 2013, 09:50:44
  FileCreationDate = 2013-11-28, 16:01:21
  FileVersion      = 01.03
[General]
```

```
PolygonFile      = dad_areas.pol
[Dredge]
  Name           = dredge 1
  DredgeDepth    = 10.00
  Dump           = dump 1
  Percentage      = 100.0
[Dredge]
  Name           = dredge 2
  DredgeDepth    = 10.00
  Dump           = dump 1
  Percentage      = 100.0
[Dredge]
  Name           = dredge 3
  DredgeDepth    = 20.00
  Dump           = dump 2
  Percentage      = 100.0
```

### A.11 Dredge and nourishment time-series

File contents	Time-series for dredge and nourishment activities; filename specified in dredge and dump characteristics file.
Filetype	ASCII
File format	Fix format for header information; free format for time-series data.
Filename	<name.ddt>
Generated	manually offline

#### **Record description:**

The file may contain one or more time-series for dredging and sediment nourishment activities. A time-series will be used for all dredging and sediment nourishment activities if the `location` equals 'General'. It will be used only for a single dredging or sediment nourishment activity if the `location` equals the name of the dredging or sediment nourishment activity. The order of the paired header/data blocks is arbitrary.

Description header block:

Keyword	Record description
location	'General' or name of dredging or sediment nourishment activity (1 quoted string)
time-function	time function type (quoted string: 'non-equidistant')
reference-time	reference time (integer formatted as yyyyymmdd or quoted string 'from model')
time-unit	time unit (quoted string: 'decades', 'years', 'days', 'hours', 'minutes', 'seconds', 'ddhhmmss', 'absolute')
interpolation	interpolation type (quoted string: 'block')
parameter	parameter name (quoted string: 'time' or 'active') followed by keyword <code>unit</code> and dummy unit specification (quoted string: time-unit or '-')

Description data block:

Record	Record description
each record	<p>time specified in time-unit since reference-time or absolute time specified as an integer formatted as yyyyymmddhh-mmss</p> <p>value indicating whether dredging (or sediment nourishment) is active from the specified time onwards (0=inactive, 1=active).</p>

**Example:**

Model with multiple dredging and nourishment activities. All specified activities will be active during the first two days except for the dredging activity called 'dredge 3' which is active during days two till four.

```

location          'General'          '
time-function      'non-equidistant'  '
reference-time     'from model'       '
time-unit         'days'             '
interpolation      'block'            '
parameter         'time'              '      unit ' '
parameter         'active'            '      unit '-'
      0.0000      1.0
      2.0000      0.0
location          'dredge 3'          '
time-function      'non-equidistant'  '
reference-time     'from model'       '
time-unit         'days'             '
interpolation      'block'            '
parameter         'time'              '      unit ' '
parameter         'active'            '      unit '-'
      0.0000      0.0
      2.0000      1.0
      4.0000      0.0

```

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## References

- Abreu, M., P. Silva, F. Sancho and A. Temperville, 2010. "Analytical approximate wave form for asymmetric waves." *Coastal Engineering* 7: 656–667.
- Bagnold, R. A., 1966. *An approach to the sediment transport problem from general physics*. US government Print Office.
- Bailard, J. A., 1981. "An Energetics Total Load Sediment Transport Model for Plane Sloping Beaches." *Journal of Geophysical Research* 86 (C11): 10938–10954.
- Battjes, J., 1975. "Modeling of Turbulence in the Surf Zone." In S. S. Y. Wang, ed., *Symposium on Modelling Techniques: 2d Annual Symposium of the Waterways, Harbors, and Coastal Engineering Division of ASCE, San Francisco*, page 1050–1061.
- Battjes, J. and M. Stive, 1985. "Calibration and verification of a dissipation model for random breaking waves." *Journal of Geophysical Research* 90 (C5): 9159–9167.
- Bezuijnen, A., H. den Adel and P. Lubking, 1987. *Heranalyse doorlatendheidsmetingen door middel van de Forchheimer relatie*. rapport deltares, Grondmechanica Delft (GD), Delft.
- Boechat Albernaz, M., G. Ruessink, H. R. A. B. Jagers and M. G. Kleinmans, 2019. "Effects of Wave Orbital Velocity Parameterization on Nearshore Sediment Transport and Decadal Morphodynamics." *Journal of Marine Science and Engineering* 7 (6). DOI: [10.3390/jmse7060188](https://doi.org/10.3390/jmse7060188), URL <https://www.mdpi.com/2077-1312/7/6/188>.
- Chassagne, C. and Z. Safar, 2020. "Modelling flocculation: Towards an integration in large-scale sediment transport models." *Marine Geology* 430: 106361. DOI: <https://doi.org/10.1016/j.margeo.2020.106361>, ISSN 0025-3227.
- Dohmen-Janssen, C. M., 1999. *Grain size influence on sediment transport in oscillatory sheet flow, phase lags and mobile-bed effects*. Ph.D. thesis, Delft University of Technology, Delft, The Netherlands.
- Eckart, C., 1958. "Properties of water, Part II. The equation of state of water and sea water at low temperatures and pressures." *American Journal of Science* 256: 225–240.
- Engelund, F. and E. Hansen, 1967. *A monograph on Sediment Transport in Alluvial Streams*. Teknisk Forlag, Copenhagen.
- Gaeuman, D., E. Andrews, A. Krause and W. Smith, 2009. "Predicting fractional bed load transport rates: Application of the Wilcock-Crowe equations to a regulated gravel bed river." *Water Resources Research* 45.
- Galappatti, R., 1983. *A depth integrated model for suspended transport*. Tech. rep., Delft University of Technology, Delft, The Netherlands.
- Grasmeijer, B., 2002. *Process-based cross-shore modelling of barred beaches*. Ph.D. thesis, Utrecht University.
- Grasmeijer, B. and L. Van Rijn, 1998. "Breaker bar formation and migration." *Coastal Engineering* pages 2750–2758. Virginia, USA.
- Guérin, T., X. Bertin, T. Coulombier and A. de Bakker, 2018. "Impacts of wave-induced circulation in the surf zone on wave setup." *Ocean Modelling* 123: 86–97. DOI: <https://doi.org/10.1016/j.ocemod.2018.01.006>, ISSN 1463-5003, URL <https://www.sciencedirect.com/science/article/pii/S1463500318300246>.

- Ikeda, S., 1982. "Incipient Motion of Sand Particles on Side Slopes." *Journal of the Hydraulics Division, ASCE* 108 (1): 95–114.
- Ikeda, S., 1988. *Lateral bedload transport on side slopes*. No. 2 in Civil Engineering Practice. Technomic Publishing Company.
- Isobe, M. and K. Horikawa, 1982. "Study on water particle velocities of shoaling and breaking waves." *Coastal Engineering in Japan* 25: 109–123.
- Koch, F. G. and C. Flokstra, 1980. "Bed level computations for curved alluvial channels." In *Proceedings of the XIXth congress of the International Association for Hydraulic Research, 2-7 Feb. 1981, New Delhi, India*, vol. 2, pages 357–364.
- Kolmogorov, A. N., 1942. "Equations of turbulent motion in incompressible fluid." *Izv. Akad. Nauk. SSR, Seria fizicheskaya* No.1 2 (1-2): 56–58. English translation: 1968 Imperial College, Mech. Eng. Dept. Rept. ON/6.
- Komar, P. D. and M. C. Miller, 1975. "On the comparison between the threshold of sediment motion under waves and unidirectional currents with a discussion of the practical evaluation of the threshold; reply." *Journal of Sedimentary Research* 45 (1): 362–367. DOI: [10.1306/212F6D66-2B24-11D7-8648000102C1865D](https://doi.org/10.1306/212F6D66-2B24-11D7-8648000102C1865D), ISSN 1527-1404, URL <https://doi.org/10.1306/212F6D66-2B24-11D7-8648000102C1865D>.
- Lesser, G., J. van Kester and J. A. Roelvink, 2000. *On-line sediment transport within Delft3D-FLOW*. Tech. Rep. Z2899, WL | Delft Hydraulics, Delft, The Netherlands.
- Manning, A. J. and K. R. Dyer, 2007. "Mass settling flux of fine sediments in Northern European estuaries: Measurements and predictions." *Marine Geology* 245: 107–122. DOI: [10.1016/j.margeo.2007.07.005](https://doi.org/10.1016/j.margeo.2007.07.005).
- Maynard, S. T., 1978. *Practical riprap design*. Tech. rep., US Army Engineer Waterways Experiment Station.
- Neill, C. R., 1968. "Note on initial movement of coarse uniform bed-material." *Journal of hydraulic research* 6 (2): 173–176.
- Nielsen, P., 1992. *Coastal Bottom Boundary Layers and Sediment Transport*, vol. 4 of *Advanced Series on Ocean Engineering*. World Scientific.
- Nipius, K. G., 1998. *Transverse transport modelling using Bailard applied to Grevelingen-mouth delta*. Delft University of Technology, Delft, The Netherlands. M.Sc. thesis, in Dutch (Dwarstransportmodellering m.b.v. Bailard toegepast op de Voordelta Grevelingenmond).
- O'Donoghue, T., J. Doucette, J. J. van der Werf and J. S. Ribberink, 2006. "The dimensions of sand ripples in full-scale oscillatory flows." *Coastal Engineering* 53 (12): 997–1012.
- Parker, G. and E. D. Andrews, 1985. "Sorting of bed load sediment by flow in meander bends." *Water Resources Research* 21: 1361–1373.
- Partheniades, E., 1965. "Erosion and Deposition of Cohesive Soils." *Journal of the Hydraulics Division, ASCE* 91 (HY 1): 105–139. January.
- Prandtl, L., 1945. "Über ein neues Formelsystem für die ausgebildete Turbulenz." *Nachrichten von der Akademie der Wissenschaften in Göttingen. Mathematisch-Physikalische Klasse* pages 6–19.



- Reyns, J., R. McCall, R. Ranasinghe, A. van Dongeren and D. Roelvink, 2023. "Modelling wave group-scale hydrodynamics on orthogonal unstructured meshes." *Environmental Modelling & Software* 162: 105655. DOI: 10.1016/j.envsoft.2023.105655, URL <https://doi.org/10.1016/j.envsoft.2023.105655>.
- Rhee, C. van, 2010. "Sediment Entrainment at High Flow Velocity." *Journal of Hydraulic Engineering* 136 (9): 572-582. DOI: 10.1061/(ASCE)HY.1943-7900.0000214, URL <https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29HY.1943-7900.0000214>.
- Richardson, J. F. and W. N. Zaki, 1954. "Sedimentation and fluidization: Part I." *I. Trans. Institution of Chemical Engineers* 32: 35-53.
- Rienecker, M. M. and J. D. Fenton, 1981. "A Fourier approximation method for steady water waves." *Journal of Fluid Mechanics* 104: 119-137. DOI: 10.1017/S0022112081002851.
- Rijn, L. C. van, 1984a. "Sediment transport, Part I: bed load transport." *Journal of Hydraulic Engineering* 110 (10): 1431-1456.
- Rijn, L. C. van, 1984b. "Sediment transport, Part II: suspended load transport." *Journal of Hydraulic Engineering* 110 (11): 1613-1640.
- Rijn, L. C. van, 1984c. "Sediment transport, Part III: bed form and alluvial roughness." *Journal of Hydraulic Engineering* 110 (12): 1733-1754.
- Rijn, L. C. van, 1993. *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications, The Netherlands.
- Rijn, L. C. van, 2001. *General view on sand transport by currents and waves: data analysis and engineering modelling for uniform and graded sand (TRANSPOR 2000 and CROS-MOR 2000 models)*. Z2899.20 / Z2099.30 / Z2824.30. WL | Delft Hydraulics, Delft, The Netherlands.
- Rijn, L. C. van, 2003. "Sediment transport by currents and waves; general approximation formulae Coastal Sediments." In *Corpus Christi, USA*.
- Rijn, L. C. van, 2007a. "Unified View of Sediment Transport by Currents and Waves. I: Initiation of Motion, Bed Roughness, and Bed-Load Transport." *Journal of Hydraulic Engineering* 133 (6): 649-667.
- Rijn, L. C. van, 2007b. "Unified View of Sediment Transport by Currents and Waves. II: Suspended Transport." *Journal of Hydraulic Engineering* 133 (6): 668-689.
- Rijn, L. C. van, J. A. Roelvink and W. T. Horst, 2000. *Approximation formulae for sand transport by currents and waves and implementation in DELFT-MOR*. Tech. Rep. Z3054.40, WL | Delft Hydraulics, Delft, The Netherlands.
- Rijn, L. van, D. Walstra, B. Grasmeijer, J. Sutherland, S. Pan and J. Sierra, 2003. "The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models." *Coastal Engineering* 47: 295-327.
- Rodi, W., 1984. "Turbulence models and their application in Hydraulics, State-of-the-art paper article sur l'etat de connaissance." *IAHR Paper presented by the IAHR-Section on Fundamentals of Division II: Experimental and Mathematical Fluid Dynamics*, The Netherlands.
- Roelvink, D., R. McCall, S. Costas and M. van der Lugt, 2019. "Controlling swash zone slope is key to beach profile modelling." In *Coastal Sediments 2019*. World Scientific.

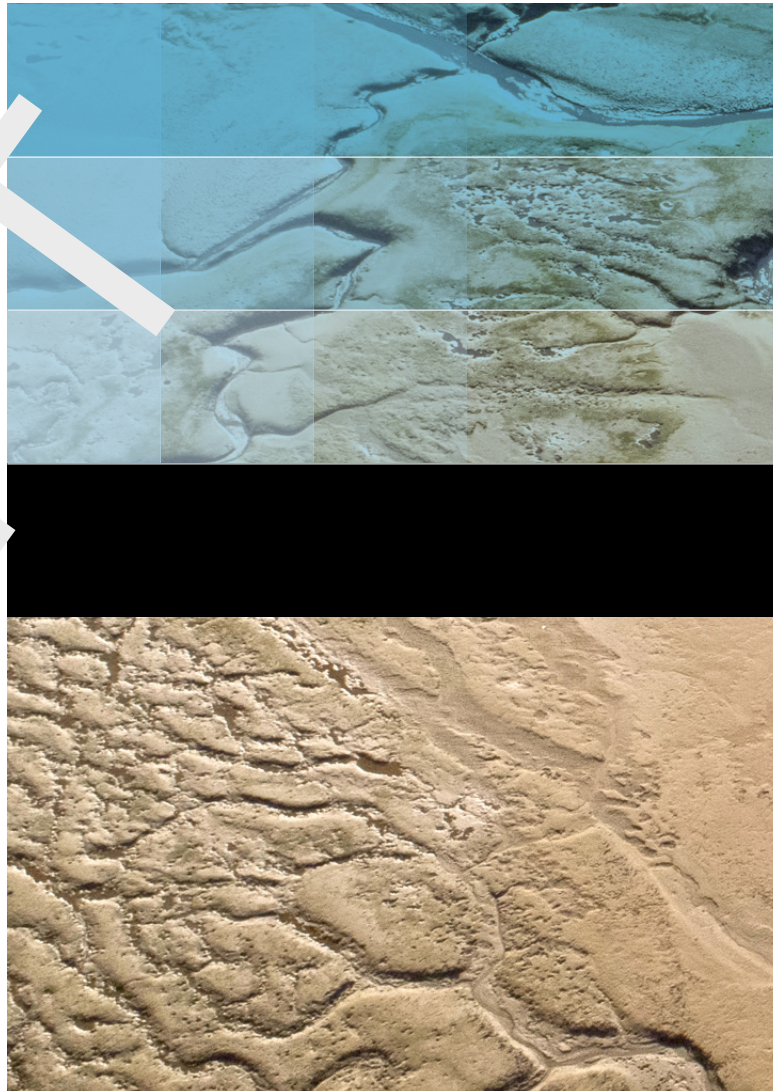
- Roelvink, D., A. Reniers, A. van Dongeren, J. van Thiel de Vries, R. McCall and J. Lescinski, 2009. "Modelling storm impacts on beaches, dunes and barrier islands." *Coastal Engineering* 56 (11-12): 1133–1152. DOI: [10.1016/j.coastaleng.2009.08.006](https://doi.org/10.1016/j.coastaleng.2009.08.006), URL <https://doi.org/10.1016/j.coastaleng.2009.08.006>.
- Roelvink, J. A. and M. J. F. Stive, 1989. "Bar-generating cross-shore flow mechanisms on a beach." *Journal of Geophysical Research* 94 (C4): 4785–4800.
- Ruessink, B., G. Ramaekers and L. van Rijn, 2012. "On the parameterization of the free-stream non-linear wave orbital motion in nearshore morphodynamic models." *Coastal Engineering* 65: 56–63. DOI: <https://doi.org/10.1016/j.coastaleng.2012.03.006>, ISSN 0378-3839, URL <https://www.sciencedirect.com/science/article/pii/S0378383912000488>.
- Shields, A., 1936. *Anwendung der Ähnlichkeitsmechanik und Turbulenzforschung auf die Geschiebebewegung*. Ph.D. thesis, Versuchsanstalt für Wasserbau und Schiffbau, 26, Berlin, Germany. (in German).
- Soulsby, R., 1997. *Dynamics of marine sands, a manual for practical applications*. Thomas Telford, London.
- Soulsby, R. L., A. G. Davies, J. Fredsøe, D. A. Huntley, I. G. Jonnson, D. Myrhaug, R. R. Simons, A. Temperville and T. J. Zitman, 1993. "Bed shear stresses due to combined waves and currents." In *Abstracts-in-depth of the Marine Science and Technology G8-M overall workshop, Grenoble.*, pages 2.1-1/2.1–4. EC.
- Soulsby, R. L., A. J. Manning, J. Spearman and R. J. S. Whitehouse, 2013. "Settling velocity and mass settling flux of flocculated estuarine sediments." *Marine Geology* 339: 1-12. DOI: <https://doi.org/10.1016/j.margeo.2013.04.006>, ISSN 0025-3227.
- Stive, M. J. F., 1986. "A model for cross-shore sediment transport." In *Proceedings 20th International Coastal Engineering Conference*, pages 1550–1564. American Society of Civil Engineers, New York.
- Swart, 1974. *Offshore sediment transport and equilibrium beach profiles*. Ph.D. thesis, Delft University of Technology, Delft, The Netherlands. Delft Hydraulics Publ. 131.
- Talmon, A. M., N. Struiksmā and M. C. L. M. van Mierlo, 1995. "Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes." *Journal of Hydraulic Research* 33 (4): 495–517.
- Thiel de Vries, J. S. M. van, 2009. *Dune Erosion during Storm Surges*. Ph.D. thesis, Delft University of Technology.
- UNESCO, 1981. *Background papers and supporting data on the international equation of state 1980*. Tech. Rep. 38, UNESCO.
- Van der A, D. A., J. S. Ribberink, J. J. Van der Werf, T. O'Donoghue, R. H. Buijsrogge and W. M. Kranenburg, 2013. "Practical sand transport formula for non-breaking waves and currents." *Coastal Engineering* 76: 26–42.
- Verney, R., R. Lafite, J. Claude Brun-Cottan and P. Le Hir, 2011. "Behaviour of a flocculation population during a tidal cycle: Laboratory experiments and numerical modelling." *Continental Shelf Research* 31 (10, Supplement): S64-S83. DOI: <https://doi.org/10.1016/j.csr.2010.02.005>, ISSN 0278-4343. Proceedings of the 9th International Conference on Nearshore and Estuarine Cohesive Sediment Transport Processes.
- Vet, P. L. M. de, 2014. *Modelling sediment transport and morphology during overwash and breaching events*. Master's thesis, Delft University of Technology.

- Walstra, D. J. R. and J. A. Roelvink, 2000. "3D Calculation of Wave Driven Cross-shore Currents." In *Proceedings 27th International Conference on Coastal Engineering, Sydney, Australia, July 16-21, 2000*, pages 1050–1063.
- Walstra, D. J. R., J. A. Roelvink and J. Groeneweg, 2000. "Calculation of Wave-Driven Currents in a 3D Mean Flow Model." In *Proceedings 27th International Conference on Coastal Engineering, Sydney, Australia, July 16-21, 2000*.
- Wilcock, P. and J. Crowe, 2003. "Surface-based transport model for mixed-size sediment." *Journal of Hydraulic Engineering* 129 (2): 120–128.

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