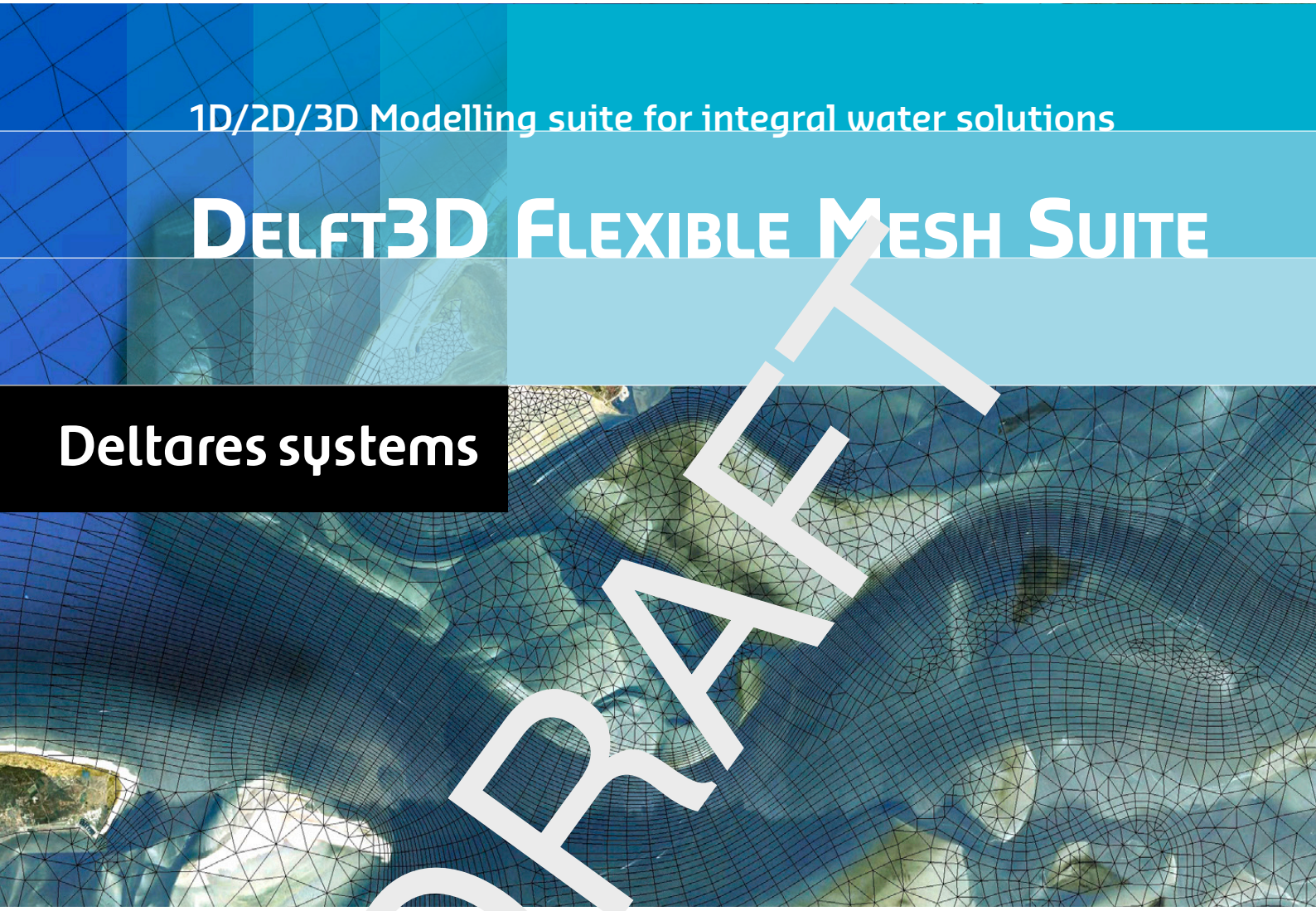
1D/2D/3D Modelling suite for integral water solutions

Delft3D Flexible Mesh Suite



Deltares systems

D-Flow Flexible Mesh

Deltares

Enabling Delta Life

User Manual

D-Flow Flexible Mesh

D-Flow FM in Delta Shell

User Manual

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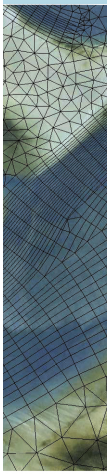

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1 A guide to this manual

1.1 Introduction

This User Manual describes the hydrodynamic module D-Flow Flexible Mesh (D-Flow FM) which is part of the Delft3D Flexible Mesh Model Suite.

This module is part of several Modelling suites, released by Deltares as Deltares Systems or Dutch Delta Systems. These modelling suites are based on 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, D-Rainfall Run-off.

Therefore, this user manual is shipped with several modelling suites. In the start-up screen links are provided to all relevant User Manuals (and Technical Reference Manuals) for that modelling suite. It will be clear that the Delta Shell User Manual is shipped with all these modelling suites. Other user manuals can be referenced. In that case, you need to open the specific user manual from the start-up screen 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.

If this is your first time to start working with D-Flow FM we suggest you to read Chapter 3, Getting started and practice the tutorial of Chapter 19. These chapters explain the user interface and guide you through the modelling process resulting in your first simulation.

Chapter 2: Introduction to D-Flow Flexible Mesh, provides specifications of D-Flow FM, such as the areas of application, the standard and specific features provided, coupling to other modules and utilities.

Chapter 3: Getting started, gives an overview of the basic features of the D-Flow FM GUI and will guide you through the main steps to set up a D-Flow FM model.

Chapter 4: All about the modelling process, provides practical information on the GUI, setting up a model with all its parameters and tuning the model.

Chapter 5: Running a model, discusses how to validate and execute a model run. Either in the GUI, or in batch mode and/or in parallel using MPI. It also provides some information on run times and file sizes.

Chapter 6: Visualize results, explains in short the visualization of results within the GUI. It introduces the programs Quickplot and Muppet to visualize or animate the simulation results, and Matlab for general post-processing.

Chapter 7: Hydrodynamics, gives some background information on the conceptual model of the D-Flow FM module.

Chapter 8: Transport of matter, discusses the modeled tranport processes, their governing equations, boundary and initial conditions and user-relevant numerical and physical settings.

Chapter 9: Turbulence provides a detailed insight into the modelling of turbulence.

Chapter 10: Heat transport, provides a detailed insight into (the modelling of) heat transport.

Chapter 11: Wind, gives background information of how wind fields should be imposed, the relevant definitions and the supported file formats.

Chapter 12: Hydraulic structures, gives background information of the available hydraulic structures in D-Flow FM, the relevant definitions and the supported file formats.

Chapter 15: Coupling with D-Waves (SWAN), provides guidance on the integrated modelling of hydrodynamics (D-Flow FM) and waves (D-Waves).

Chapter 16: Coupling with D-RTC (RTC-Tools), provides guidance on the integrated modelling of hydrodynamics (D-Flow FM) and real time control of hydraulic structures (D-RTC).

Chapter 17: Coupling with D-Water Quality (Delwaq), provides guidance on the integrated modelling of hydrodynamics (D-Flow FM) and water quality (D-Water Quality).

Chapter 18: Sediment transport and morphology, describes the three-dimensional transport of suspended sediment, bedload transport and morphological updating of the bottom.

Chapter 19: Tutorial, gives you some first hands-on experience in using the D-Flow FM GUI to define the input of a simple problem, in validating this input, in executing the simulation and in inspecting the results.

Chapter 20: Calibration and data assimilation, describes how the OpenDA toolbox could be deployed to apply calibration and data assimilation.

1.3 Manual version and revisions

This manual applies to:

- the D-HYDRO Suite, version 2016.2
- the Delft3D Flexible Mesh Suite, version 2017
- SOBEK 3, version 3.6.1 (and higher)

1.4 Typographical conventions

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

Example	Description
Module **Project**	Title of a window or a sub-window are in given in **bold**. Sub-windows are displayed in the **Module** window and cannot be moved. Windows can be moved independently from the **Module** window, such as the **Visualisation Area** window.

Example	Description
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 the Linux and UNIX environment a forward slash (/) is used instead of the backward slash (\) for PCs.
"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^{-1}] [–]	Units are given between square brackets when used next to the formulae. Leaving them out might result in misinterpretation.

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
```

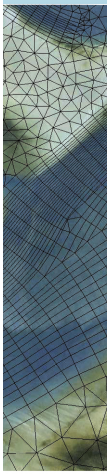
1.5 Changes with respect to previous versions

Several descriptions of β-functionality are added or marked as β-functionality.

2 Introduction to D-Flow Flexible Mesh

Note: The 3D modelling is a β-functionality.

D-Flow Flexible Mesh (D-Flow FM) is a hydrodynamic simulation program developed by Deltares. It is part of Deltares' unique, fully integrated computer software suite for a multi-disciplinary approach and 1D, 2D and 3D computations for coastal, river and estuarine areas. It can carry out simulations of flows, waves, water quality and ecology.



It has been designed for experts and non-experts alike. The Delft3D Flexible Mesh Suite is composed of several modules, grouped around a mutual interface, while being capable to interact with one another. D-Flow FM, which this manual is about, is one of these modules. D-Flow FM is a multi-dimensional (1D, 2D and 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on structured and unstructured, boundary fitted grids. The term Flexible Mesh in the name refers to the flexible combination of unstructured grids consisting of triangles, quadrangles, pentagons and hexagons. In 3D simulations the vertical grid is using the σ co-ordinate approach. As an alternative a fixed z layers approach is also possible. The 2D functionality in D-Flow FM has been released, while the functionality for 3D and 1D is in development.

2.1 Areas of application

- ◇ Tide and wind-driven flows (i.e., storm surges).
- ◇ Stratified and density driven flows.
- ◇ River flow simulations.
- ◇ Rural channel networks.
- ◇ Rainfall runoff in urban environments.
- ◇ Simulation of tsunamis, hydraulic jumps, bores and flood waves.
- ◇ Fresh-water river discharges in bays.
- ◇ Salt intrusion.
- ◇ Cooling water intakes and waste water outlets.
- ◇ Transport of dissolved material and pollutants.

2.2 Standard features

- ◇ Tidal forcing.
- ◇ The effect of the Earth's rotation (Coriolis force).
- ◇ Density driven flows (pressure gradients terms in the momentum equations).
- ◇ Advection-diffusion solver included to compute density gradients.
- ◇ Space and time varying wind and atmospheric pressure.
- ◇ Advanced turbulence models to account for the vertical turbulent viscosity and diffusivity based on the eddy viscosity concept. Four options are provided: 1) constant, 2) algebraic, 3) k-ε and 4) k-τ model.
- ◇ Time varying sources and sinks (e.g., river discharges).
- ◇ Simulation of the thermal discharge, effluent discharge and the intake of cooling water at any location and any depth.
- ◇ Robust simulation of drying and flooding of inter-tidal flats and river winter beds.

2.3 Special features

- ◇ Built-in automatic switch converting 2D bottom-stress coefficient to 3D coefficient.
- ◇ Built-in anti-creep correction to suppress artificial vertical diffusion and artificial flow due to σ-grids.
- ◇ Heat exchange through the free water surface.
- ◇ Wave induced stresses and mass fluxes.
- ◇ Influence of waves on the bed shear stress.
- ◇ Optional facility to calculate the intensity of the spiral motion phenomenon in the flow (e.g., in river bends) which is especially important in sedimentation and erosion studies (for depth averaged — 2DH — computations only).
- ◇ Non-linear iterations in the solver can be enabled for accurate flooding results.
- ◇ Optional facility for tidal analysis of output parameters.
- ◇ Optional facility for special structures such as pumping stations, fixed weirs, controllable barriers (1D, 2D and 3D)
- ◇ Default advection scheme suitable for various flow regimes, from bore propagation to eddy shedding.
- ◇ Domain partitioning for parallellized runs on MPI-based High Performance Computing clusters.

2.4 Important differences compared to Delft3D-FLOW

The most noticeable difference between Delft3D-FLOW and D-Flow FM is the use of unstructured grids. Large regions with quadrangles can be coupled with much greater freedom than before, using triangles, pentagons and hexagons. Grid refinement (and coarsening) without DD-coupling is now possible in one and the same model grid. In future, 1D networks will be coupled to 2D grids, either adjacent to each other or the 1D network overlying the 2D grid. Finally, many of Delft3D-FLOW's grid restrictions are now gone: since there are no true grid 'rows' and 'columns' anymore, rows of grid cells may be coupled to columns, in any direction and at any position.

In addition to the unstructured grid files, all geometric model input is now specified in geographical coordinates, either in Cartesian or spherical coordinates (x, y or longtitude, latitude). This is different from Delft3D-FLOW which required model input in grid indices. This so-called model-independent coordinates input allows for easy change of a model grid, after which the remaining model input can remain the same.

The new Delta Shell graphical user interface provides a much more powerful and integrated environment for setting up D-Flow FM models and inspecting model input such as time-dependent forcings (boundary conditions and barrier control). Another improvement within Delta Shell is the use of scripting for running and live interaction with a model.

Coupled running of D-Flow FM with other modules has been extended with real time control of hydraulic structures, as listed in the following section.

Like Delft3D-FLOW, D-Flow FM implements a finite volume solver on a staggered grid. However, since there is no concept of grid 'rows' and 'columns', there is also no ADI-solver possible. The continuity equation is solved implicitly for all points in a single combined system. Time integration is done explicitly for part of the advection term, and the resulting dynamic time-step limitation is automatically set based on the Courant criterium. The possible performance penalty that may result from this approach can often be remedied by refining and coarsening the computational grid at the right locations.

In D-Flow FM, the advection scheme is suitable for both subcritical and critical flows. The scheme is 'shock proof', is capable of reproducing correct bore propagation velocities.

2.5 Coupling to other modules

The hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and vertical eddy diffusivity) calculated in the D-Flow FM module are used as input to the other modules of the Delft3D Flexible Mesh Suite, which are:

Module	Description
D-Waves (SWAN)	short wave propagation, see also chapter 15
D-Water Quality (Delwaq)	far-field water quality, see also chapter 17
D-Real Time Control	flow-triggered control of hydrodynamic structures

Module couplings that are not yet available are summarized below:

Module	Description
D-Waq PART	mid-field water quality and particle tracking
Delft3D-SED	cohesive and non-cohesive sediment transport

For using D-Flow FM the following utilities are important:

Module	Description
Delta Shell	for complete model set-up and model runs, see chapter 3 and chapter 4
RGFGRID	for generating curvilinear and unstructured grids
Delft3D-QUICKPLOT	for visualisation and animation of simulation results
OpenEarthTools	set of MATLAB scripts for postprocessing of output files, see http://www.openearth.eu
DFMOUTPUT	for merging partitioned map files into one, see Section 5.2.5.

For details on using these utility programs you are referred to the respective User Manuals.

2.6 Installation

Separate installation are provided for DeltaShell and the computational core.

2.6.1 Installation of DeltaShell

Delta Shell is only available for Windows operating systems. You can either install the msi-version or copy the zip-version. For the msi-version first follow the steps in the installation programme. Consequently, start the application from *Start* →*All Programs* →*Deltares* or by double-clicking the short-cut on your desktop. For the zip-version you don't have to install anything. First unpack the zip, consequently go to bin and double-click <DeltaShell.Gui.x64.exe> to start the application.

2.6.2 Installation of the computational core

For the installation of the computational core a separate Installation Manual is provided.

2.7 Examples

An extensive set of example models is available as part of this D-Flow FM release. Throughout this User Manual, references to these testcases are made via the directory names as follows:

- ◇ <f05_boundary_conditions/c019_waterlevel_bc_cmp_varying/>
- ◇ <f17_sources_sinks/c020_sourcesink_3D/>

3 Getting started

3.1 Introduction

The D-Flow FM plugin is part of the Delta Shell framework. For an introduction to the general look-and-feel and functionalities of the Delta Shell framework you are referred to the Delta Shell User Manual. This chapter gives an overview of the basic features of the D-Flow FM plugin and will guide you through the main steps to set up a D-Flow FM model. For a more detailed description of the GUI features you are referred to chapter 4. For technical documentation you are referred to D-Flow FM TRM (2015).

3.2 Overview of D-Flow FM GUI

When you start the application for the first time the lay-out will look like Figure 3.1. The basic lay-out consists of the following items:

- **Ribbon** - top
- **Project** window - up left
- **Map** window - down left
- central (map) window - up centre
- **Messages** window - down centre
- **Toolbox**, **Chart**, **Region** and **Operations** window - up right
- **Properties** window - down right

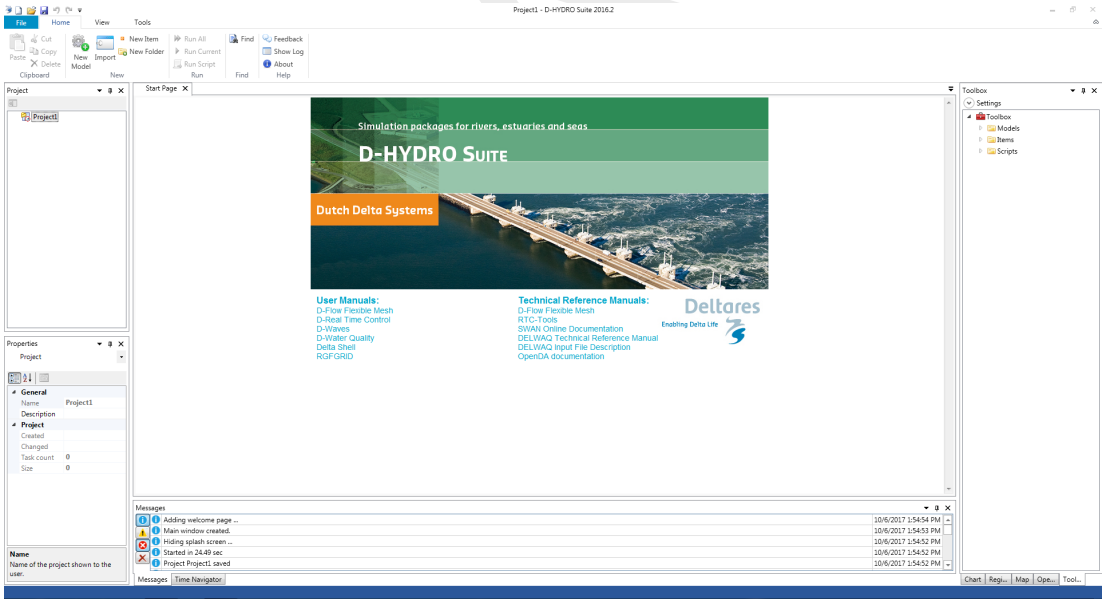


Figure 3.1: *Start-up lay-out Delta Shell*

All the windows can be customized/hidden according to your own preferences.

These settings will be automatically saved for the next time you the application.

The most important windows for the D-Flow FM plugin are the Project, central (map), Map, Messages and Time navigator windows.

The contents of these windows are briefly discussed in the subsections below.

3.2.1 Project window

After adding or importing a D-Flow FM model (see section 3.5.1 and section 3.5.9), the *Project* window will be extended with D-Flow FM specific features (see Figure 3.2). The *Project* window provides you with the basic steps to set up a D-Flow FM model.

The *Project* window consists of the following features:

General	general model information such as depth layer specification, model coordinate system and angle of latitude
Area	geographical (GIS based) features, such as observation points, structures, dry points and land boundaries
Domain	computational grid (**Note:** still to be implemented, for now under general)
Bed Level	model bed level
Time Frame	model time frame and time step
Processes	active physical processes in the model such as salinity, temperature, wind and tide generating forces
Initial conditions	initial conditions for water levels and other physical processes
Boundary conditions	model boundaries and boundary condition specification
Physical parameters	physical settings for processes such as roughness, viscosity, wind and temperature
Sources and sinks	location and time series specification for point sources and sinks
Numerical parameters	numerical simulation settings
Output parameters	output specification
Output	output after running the simulation

Upon clicking the items in the *Project* window the corresponding tab (in case of non-geographic model settings), attribute table (in case of geographic model settings) or editor view (in case of advanced editing options) will open. Using the right mouse button gives options such as importing/exporting model data.

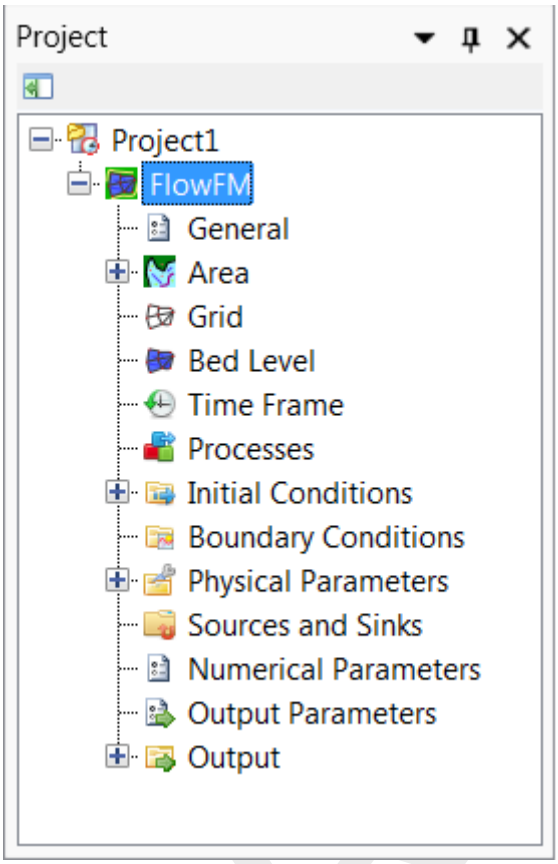


Figure 3.2: Project *window of D-Flow FM plugin*

3.2.2 Central (map) window

The central window shows the contents of the main editor you are working with. In most cases this will be the central map with tabulated input fields (see Figure 3.3). The map is used to edit geographic model data, the tabulated input fields to edit overall model settings. Moreover, the contents of the central window can also be a specific editor such as the time point editor or the boundary condition editor. Each of these editors will open as a separate view.

Figure 3.3: *Central map with contents of the D-Flow FM plug-in*

3.2.3 Map window

The map tree allows the user to control the visibility of the contents of the central map using checkboxes. Furthermore, the user can add (wms) layers, such as satellite imagery or open street maps (see Figure 3.4).

Note: Please note that the map usually has a different coordinate system than the model. In rendering the model attributes they are transformed to the map coordinate system (for visual inspection on the map), but the model will be saved in the model coordinate system.

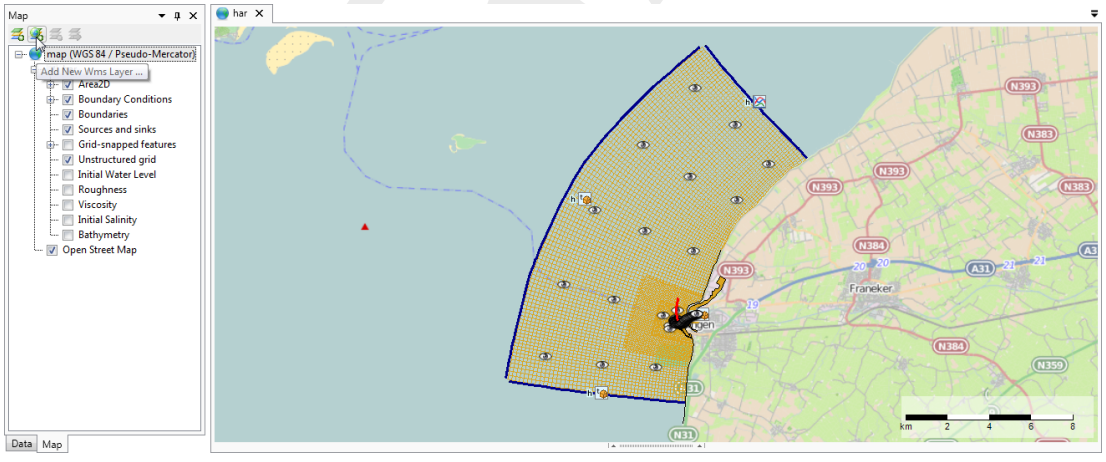


Figure 3.4: *Map tree controlling map contents*

3.2.4 Messages window

The message window (Figure 3.5) provides a log of information on the recent activities in Delta Shell. It also provides warning and error messages.

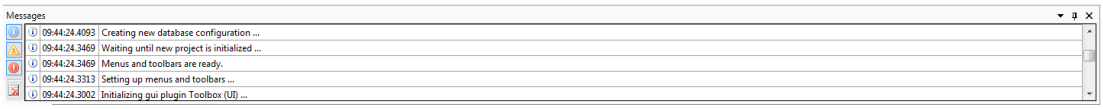


Figure 3.5: *Log of messages, warnings and errors in message window*

3.2.5 Time navigator window

The time navigator (Figure 3.6) can be used to step through time dependent model output and other time dependent geographic features on the map.

Figure 3.6: *Time navigator in Delta Shell*

3.3 Dockable views

The Delta Shell framework offers lots of freedom to customize dockable views, which are discussed in this section.

3.3.1 Docking tabs separately

Within the Delta Shell framework the user can dock the separate windows according to personal preferences. These preferences are then saved for future use of the framework. An example of such preferences is presented in Figure 3.7, where windows have been docked on two screens.

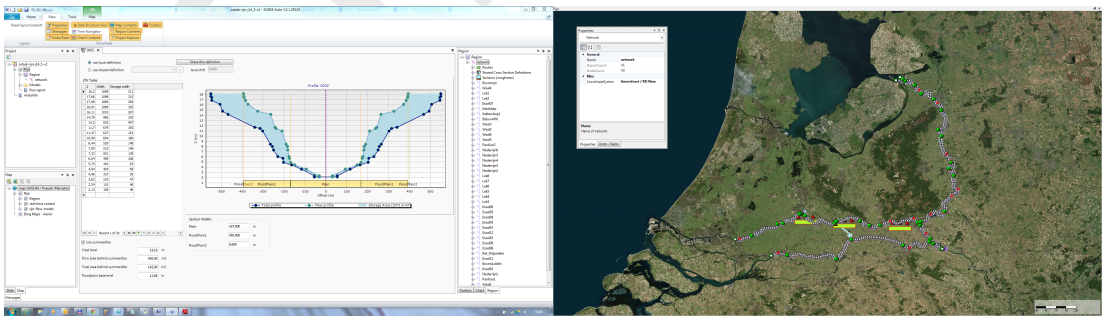


Figure 3.7: *Docking windows on two screens within the Delta Shell framework.*

3.3.2 Multiple tabs

In case two windows are docked in one view, the underlying window (tab) can be brought to the front by simply selecting the tab, as is shown here.

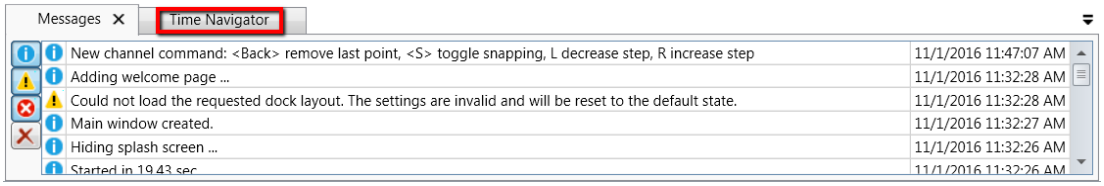


Figure 3.8: *Bringing the* ***Time Navigator*** *window to the front*

By dragging dockable windows with the left mouse button and dropping the window left, right, above or below another one the graphical user interface can be customized according to personal preferences. Here an example of the **Time Navigator** window being docked above the **Properties** window.

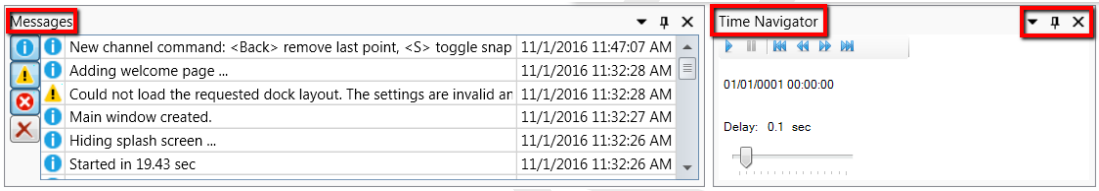


Figure 3.9: *Docking the* ***Time Navigator*** *window.*

Additional features are the possibility to remove or (auto) hide the window (top right in Figure 3.9). In case of removal, the window can be retrieved by a mouse-click on *Time Navigator* in the *View* ribbon. Hiding the **Time Navigator** window results in:

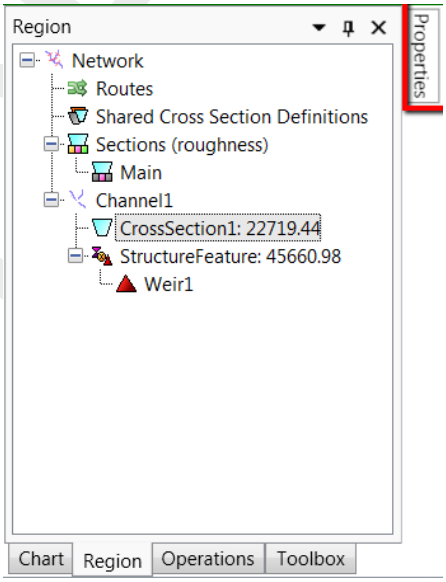


Figure 3.10: *Auto hide the* ***Properties*** *window*

3.4 Ribbons and toolbars

The user can access the toolbars arranged in *ribbons*. Model plug-ins can have their own model specific *ribbon*. The *ribbon* may be auto collapsed by activating the *Collapse the Ribbon* button when right-mouse-clicking on the *ribbon*.

3.4.1 Ribbons (shortcut keys)

Delta Shell makes use of ribbons, just like Microsoft Office. You can use these ribbons for most of the operations. With the ribbons comes shortcut key functionality, providing shortcuts to perform operations. If you press `Alt`, you will see the letters and numbers to access the ribbons and the ribbon contents (i.e. operations). For example, `Alt + H` will lead you to the *Home*-ribbon (Figure 3.11).

Note: Implementation of the shortcut key functionality is still work in progress.

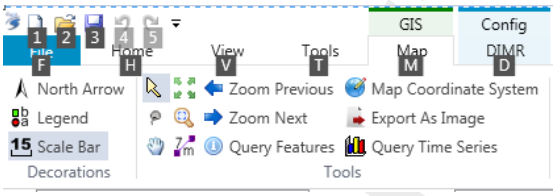


Figure 3.11: *Perform operations using the shortcut keys*

3.4.2 File

The left-most *ribbon* is the *File* ribbon. It has menu-items comparable to most Microsoft applications. Furthermore, it offers users import and export functionality, as well as the *Help* and *Options* dialogs, as shown in Figure 3.12 and Figure 3.13.

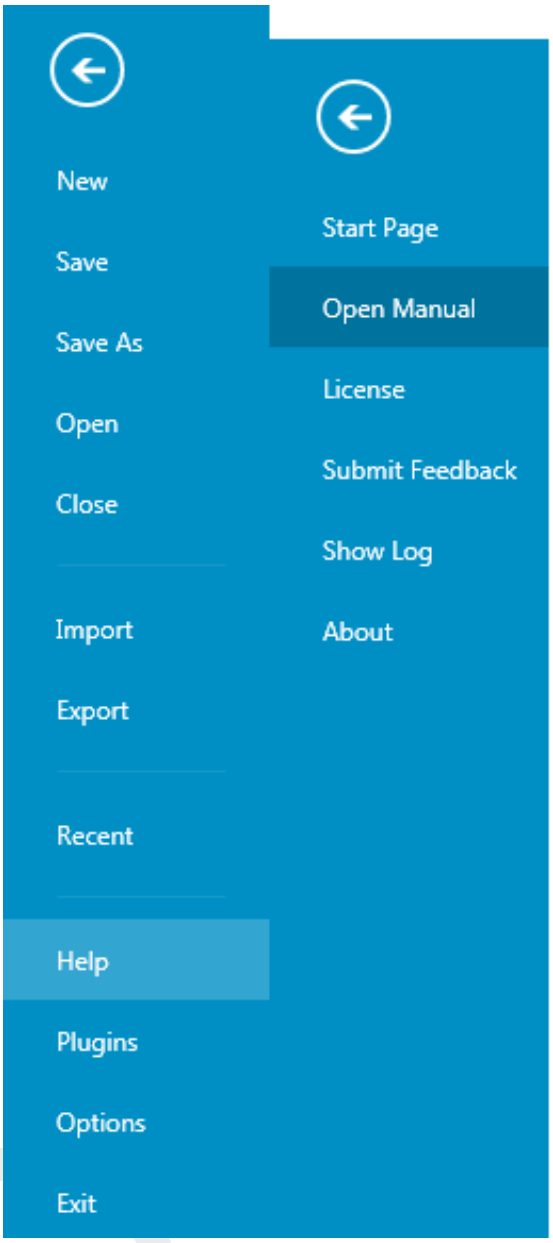


Figure 3.12: *The* File *ribbon.*

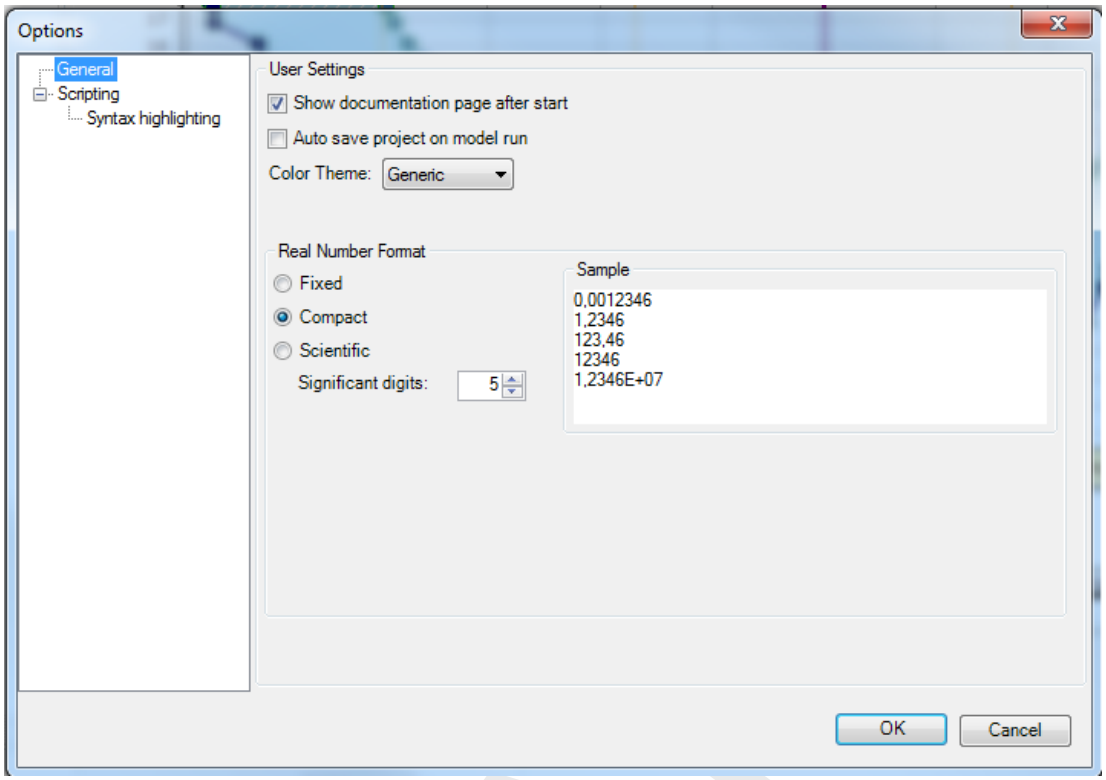


Figure 3.13: *The Delta Shell options dialog.*

3.4.3 Home

The second *ribbon* is the *Home* ribbon (Figure 3.14). It harbours some general features for clipboard actions, addition of items, running models, finding items within projects or views, and help functionality.

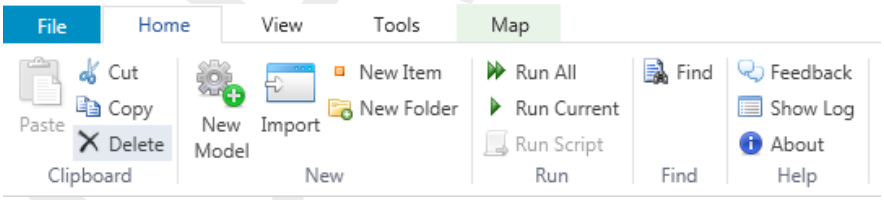


Figure 3.14: *The* Home *ribbon.*

3.4.4 View

The third *ribbon* is the *View* ribbon (Figure 3.15). Here, the user can show or hide windows.

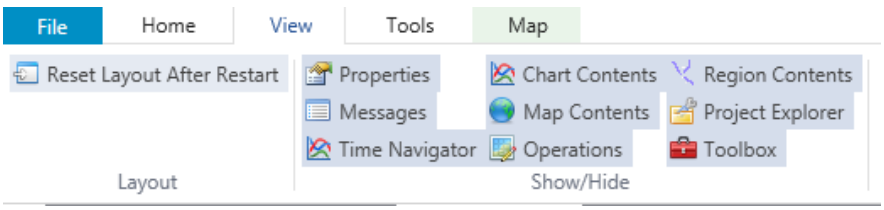


Figure 3.15: *The* View *ribbon.*

3.4.5 Tools

The fourth *ribbon* is the *Tools* ribbon (Figure 3.16). By default, it contains only the *Open Case Analysis View* tool. Some model plug-ins offer the installation of extra tools that may be installed. These are documented within the user documentation of those model plug-ins.

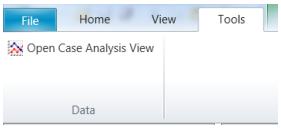


Figure 3.16: *The* Tools *ribbon contains just the* Data *item.*

3.4.6 Map

The last *ribbon* is the *Map* ribbon (Figure 3.17).

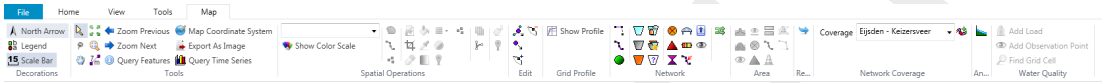


Figure 3.17: *The* Map *ribbon.*

This will be used heavily, while it harbours all *Geospatial* functions, like:

- *Decorations* for the map
  - North arrow
  - Scale bar
  - Legend
  - ...
- *Tools* to customize the map view
  - Select a single item
  - Select multiple items by drawing a curve
  - Pan
  - Zoom to Extents
  - Zoom by drawing a rectangle
  - Zoom to Measure distance
  - ...
- *Edit* polygons, for example within a network, basin, or waterbody
  - Move geometry point(s)
  - Add geometry point(s)
  - Remove geometry point(s)
- Creation of a model *Network*, for example for D-Flow 1D
  - Add new Branch
  - Split Branch
  - Add Cross section
  - Add Weir
  - Add Pump
  - ...

Still, all functions of the category can be activated as they will appear in the drop-down panel.

3.4.7 Scripting

When you open the scripting editor in Delta Shell, a Scripting *ribbon* category will appear. This ribbon has the following additional options (see also Figure 3.18), which are described in Table 3.1:

Figure 3.18: *The scripting* ribbon *within Delta Shell.*

Table 3.1: *Functions and their descriptions within the scripting* ribbon *of Delta Shell.*

Function	Description
Run script	Executes the selected text. If no text is selected then it will execute the entire script
Clear cached variables	Clears all variables and loaded libraries from memory
Debugging	Enables/Disables the debug option. When enabled you can add breakpoint to the code (using `F9` or clicking in the margin) and the code will stop at this point before executing the statement (use F10 (step over) or F11 (step into) for a more step by step approach)
Python variables	Show or hide python variables (like _var_) in code completion
Insert spaces/tabs	Determines if spaces or tab characters are added when pressing tab
Tab size	Sets the number of spaces that are considered equal to a tab character
Save before run	Saves the changes to the file before running
Create region	Creates a new region surrounding the selected text
Comment selection	Comments out the selected text
Convert to space indenting	Converts all tab characters in the script to spaces. The number of spaces is determined by Tab size
Convert to tab indenting	Converts all x number of space characters (determined by Tab size) in the script to tabs
Python (documentation)	Opens a link to the python website, showing you the python syntax and standard libraries
Delta Shell (documentation)	Opens a link to the Delta Shell documentation website (generated documentation of the Delta Shell api)

3.4.8 Shortcuts

The shortcut keys of the scripting editor within Delta Shell are documented in Table 3.2.

Table 3.2: *Shortcut keys within the scripting editor of Delta Shell.*

Shortcut	Function
`Ctrl + Enter`	Run selection (or entire script with no selection)
`Ctrl + Shift + Enter`	Run current region (region where the cursor is in)
`Ctrl + X`	Cut selection

Table 3.2: *Shortcut keys within the scripting editor of Delta Shell.*

Shortcut	Function
`Ctrl + C`	Copy selection
`Ctrl + V`	Paste selection
`Ctrl + S`	Save script
`Ctrl + -`	Collapse all regions
`Ctrl + +`	Expand all regions
`Ctrl + "`	Comment or Uncomment current selection
`Ctrl + W`	Add selection as watch variable
`Ctrl + H`	Highlight current selection in script (press esc to cancel)
`F9`	Add/remove breakpoint (In debug mode only)
`F5`	Continue running (In debug mode only — when on breakpoint)
`Shift + F5`	Stop running (In debug mode only — when on breakpoint)
`F10`	Step over current line and break on next line (In debug mode only - when on breakpoint)
`F11`	Step into current line if possible, otherwise go to next line (In debug mode only — when on breakpoint). This is used to debug functions declared in the same script (that have already runned)

3.4.9 Quick access toolbar

Note: The user can make frequently used functions available by a single mouse-click in the *Quick Access Toolbar*, the top-most part of the application-window. Do this by right-mouse-clicking a ribbon item and selecting *Add to Quick Access Toolbar*.

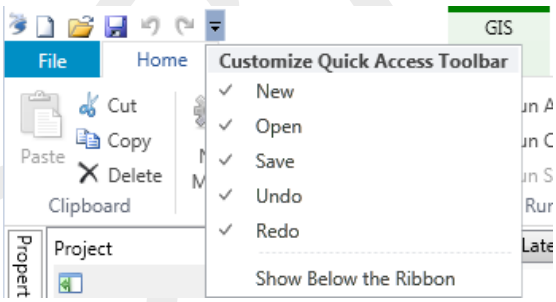


Figure 3.19: *The quick access toolbar.*

3.5 Basic steps to set up a D-Flow FM model

This section shows the basic steps to set up a D-Flow FM model. For a more detailed description of the steps and GUI features you are referred to chapter 4.

3.5.1 Add a D-Flow FM model

After starting the application for the first time, the start page will open with a default project (i.e. “project1”, see Figure 3.1). To add a D-Flow FM model to the project you have the following options:

- click “New Model” in the “Home”-ribbon (Figure 3.20)
- use the Right Mouse Button on “project1” in the *Project* window, go to “Add” and “New Model” (Figure 3.21)

From the list of available models (which can vary depending on your installation), select “D-Flow FM model” (Figure 3.22).

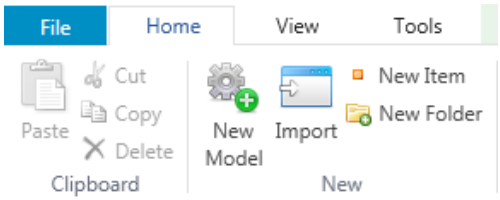


Figure 3.20: *Adding a new model from the ribbon*

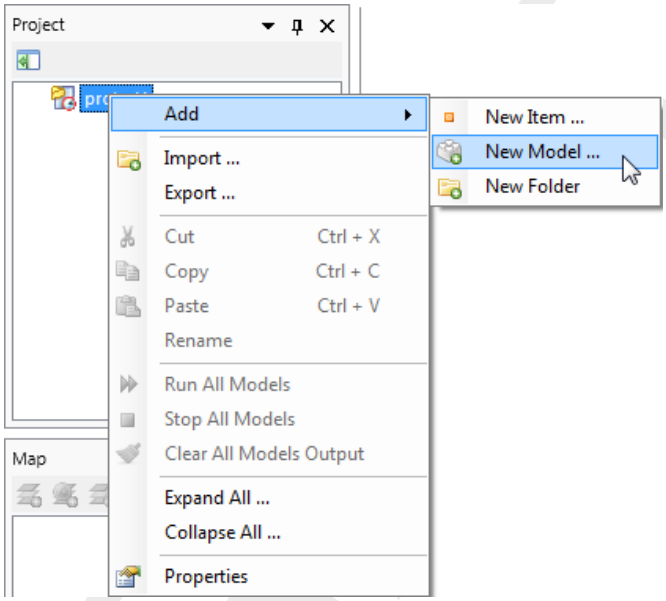


Figure 3.21: *Adding a new model using the Right Mouse Button on “project1” in the* Project *window*

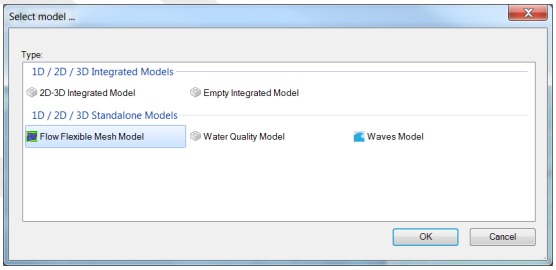


Figure 3.22: *Select “D-Flow FM model”*

3.5.2 Set up a D-Flow FM model

To set up the D-Flow FM model follow the steps in the *Project* window. For a more detailed description, see chapter 4.

3.5.3 Multiple input files

The input of a D-Flow FM model is stored in a MDU file and in a number of attribute files, which are explained in section 4.5. In general, all items of a certain quantity are stored in one

attribute file. This is the standard approach. However, D-Flow FM also allows to have more input files for all quantities, such as thin dams, dry points, cross sections and fixed weirs, gates.

In the MDU file multiple input files per quantity can be specified. These input files have to be separated by a " " (whitespace) in the MDU file. For a description of the MDU file we refer to Appendix A. In Figure 3.23 this is illustrated by using two files for the observation points, namely main_locations.xyn and secondary_locations.xyn. In a similar way the other quantities like fixed weirs and thin dams can be stored in multiple files.

036-b (FM model) | Observation Points

Group name	Name	X	Y
Main_locations.xyn	(mp13,r3), Bokkegat	42264	4,0979E+05
Main_locations.xyn	(mp14,r3), Schenge	42130	4,1003E+05
Main_locations.xyn	(mp15,r3), Welsinge	41978	4,1026E+05
Main_locations.xyn	(mp16,r3), Indus	42031	4,1047E+05
Main_locations.xyn	(nulpunt meetraai 4	40504	4,0832E+05
Main_locations.xyn	(mp17,r4), Scouden	40940	4,0843E+05
Secondary_locations.xyn	osm111(mp1,r1)	42260	4,0285E+05
Secondary_locations.xyn	osm105(mp2,r1)	42223	4,0335E+05
Secondary_locations.xyn	osm108(mp3,r1)	42194	4,0403E+05
Secondary_locations.xyn	osm110(mp4,r1)	42080	4,0455E+05
Secondary_locations.xyn	osm112(mp5,r2)	42180	4,0687E+05
Secondary_locations.xyn	osm120(mp6,r2)	42193	4,0715E+05

Figure 3.23: *Illustration of multiple input files for observation points*

3.5.4 Converting a Delft3D-FLOW model into D-Flow FM

Existing Delft3D-FLOW models can be converted into a set of input files suitable for D-Flow FM (to a large extent). The conversion can be done by some Matlab utitilies, which are described in section B.6.1.2.

3.5.5 Validate D-Flow FM model

You can check whether your model setup is valid by using the right mouse button in the *Project* window and select “Validate” (Figure 3.24). This will produce a validation report (Figure 3.25). Red exclamation marks indicate the parts of the model that are still invalid. By clicking the hyperlink you will be automatically redirected to the invalid step in the model setup, so that you can correct it.

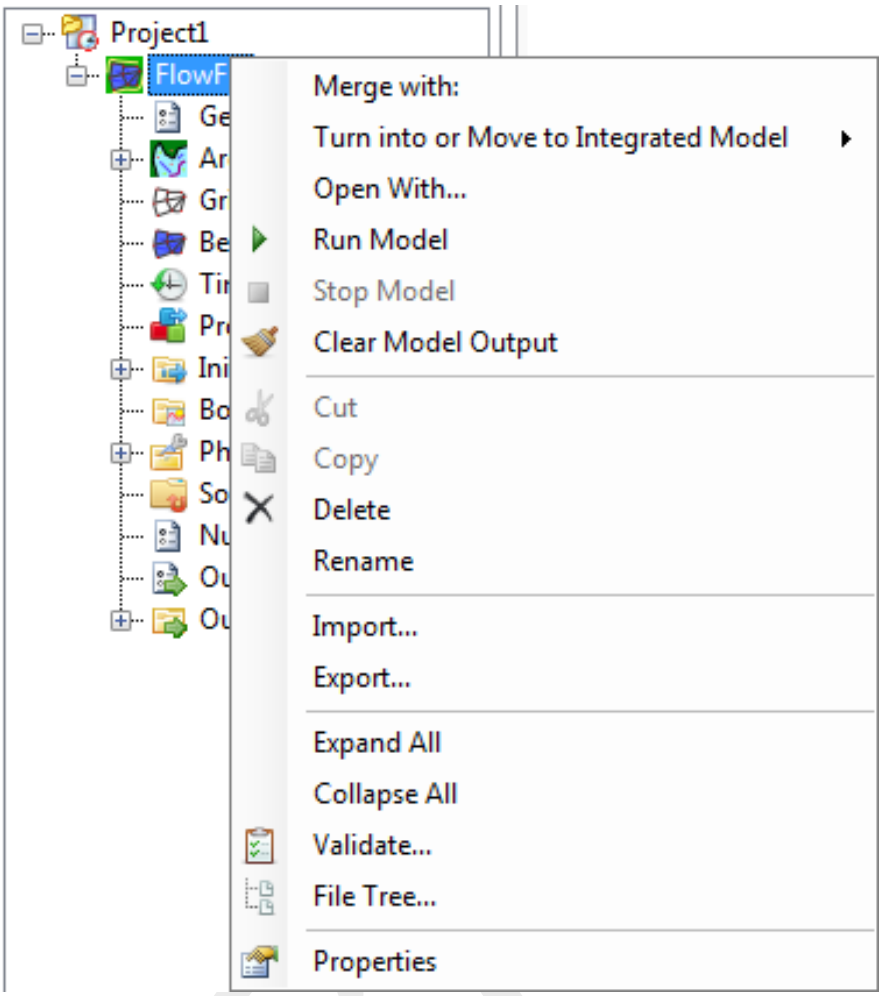


Figure 3.24: *Validate model*

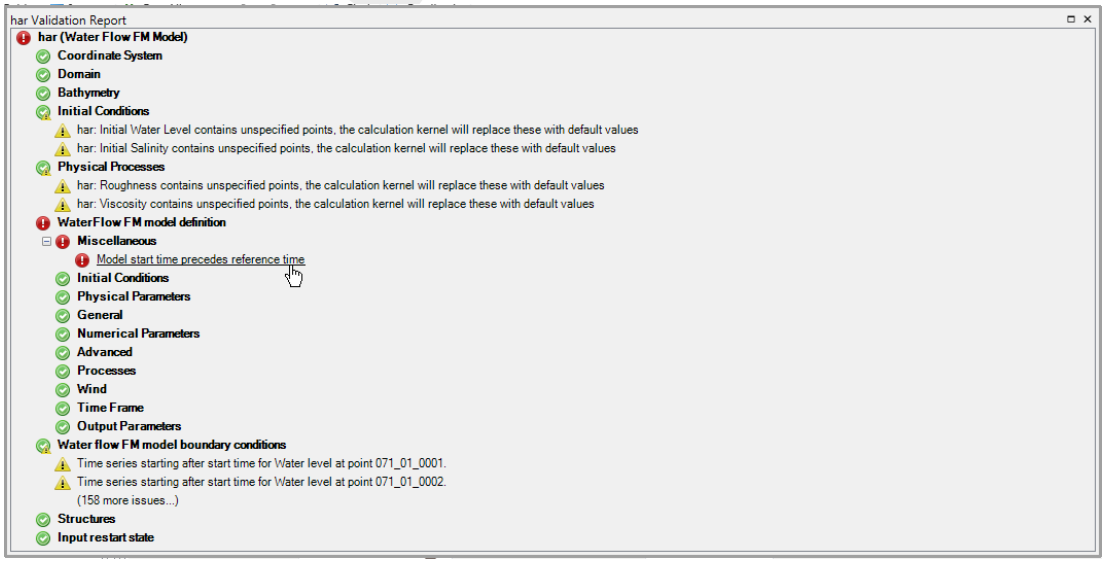


Figure 3.25: *Validation report*

3.5.6 File tree

To check the file paths and names of the attribute files which are linked to your model, you can select “File tree” using the right mouse button on your model in the *Project* window.

3.5.7 Run D-Flow FM model

If you are satisfied with the model setup, you can run it from Delta Shell using the right mouse button on model and select “Run model” (Figure 3.26).

Note: it is also possible to run D-Flow FM outside Delta Shell using the command line.

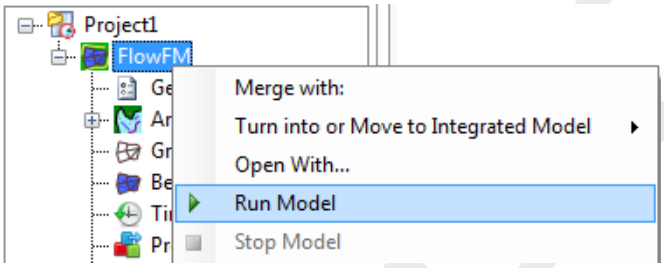


Figure 3.26: *Run model*

3.5.8 Inspect model output

The simulation will start and the output will be stored in the output folder in the *Project* window (Figure 3.27). Delta Shell provides some basic tools to inspect the model output. For more extensive and advanced options you are referred to Quickplot and Muppet.

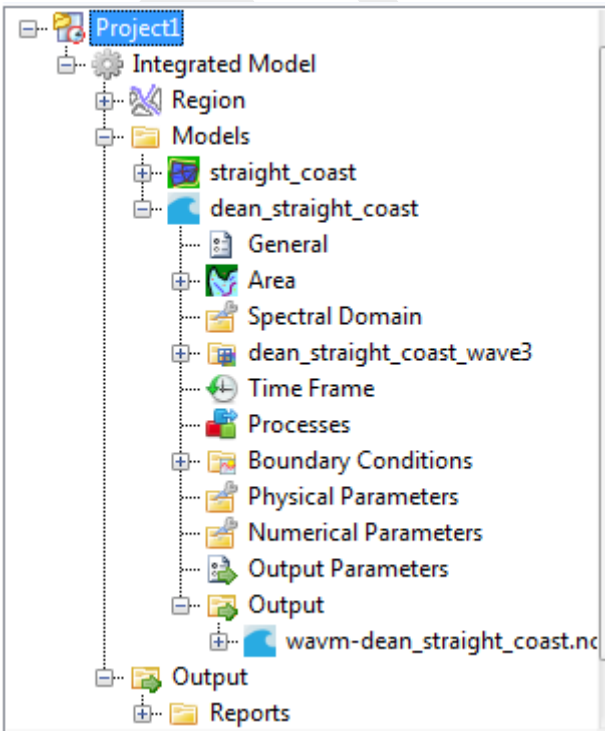


Figure 3.27: *Output of wave model in* Project *window*

3.5.9 Import/export or delete a D-Flow FM model

To import an existing D-Flow FM model either use the right mouse button on the project level in the *Project* window (Figure 3.28) or go to the *File*-ribbon and press *Import* (Figure 3.29). Likewise you can export a model or delete a model.

For the steps in the *Project* window that are linked to attribute files (observation points, grid, bed level, etc.) you can use the right mouse button to import or export these attribute files.

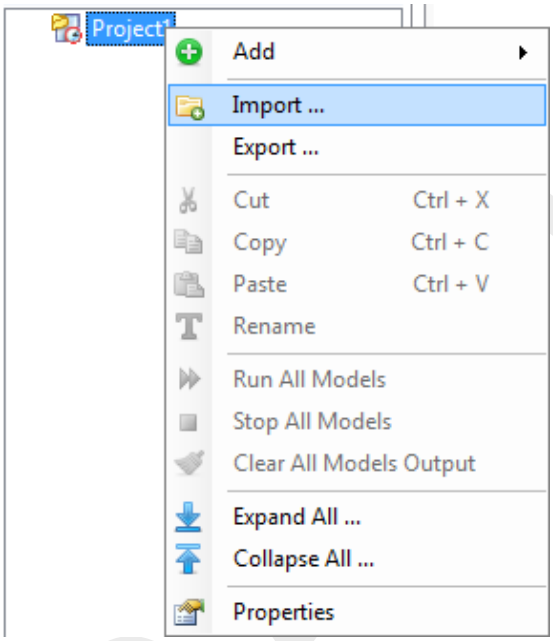


Figure 3.28: *Import wave model from* Project *window*

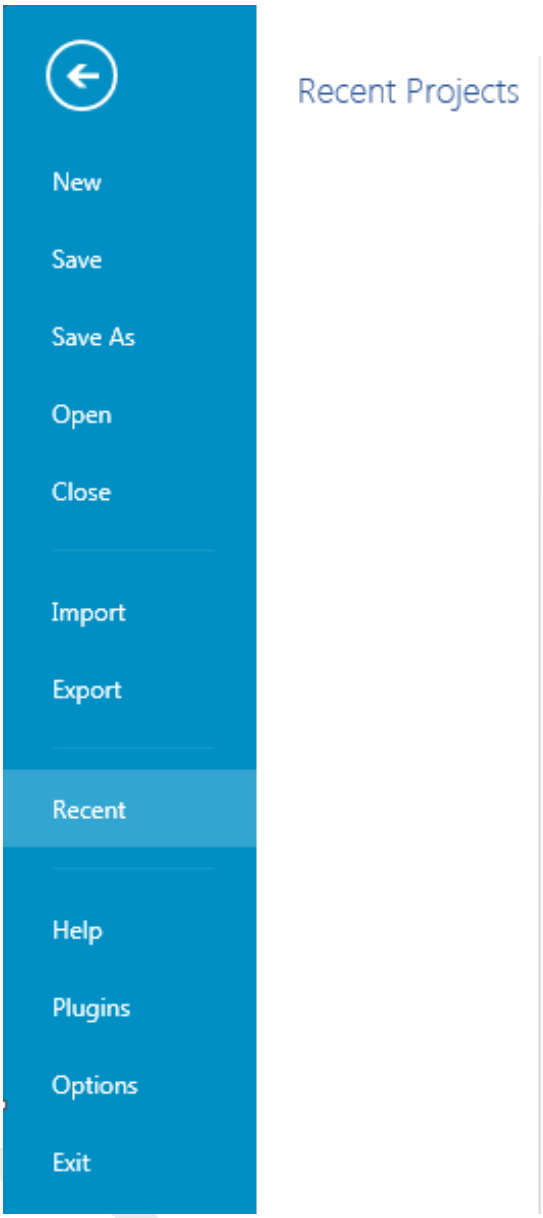


Figure 3.29: *Import wave model from file ribbon*

3.5.10 Save project

To save the project (and, hence, the model) use the disk-icon on the Quick Access Toolbar or the *File*-ribbon (Figure 3.29). If you would like to save the project under a different name use *Save As*.

3.5.11 Exit Delta Shell

If you are finished you can exit Delta Shell using the red cross or pressing the *Exit* button in the *File*-ribbon (Figure 3.29).

3.6 Important differences compared to Delft3D-FLOW GUI

The differences between the former Delft3D-FLOW GUI and the D-Flow FM plugin in Delta Shell in lay-out and functionality are numerous. Here, we address only the most important differences in the workflow.

3.6.1 Project vs model

The entity “project” is new in the Delta Shell GUI. In the hierarchy the entity“project” is on a higher level than the entity “model”. A project can contain multiple models, which can either run standalone or coupled. The user can run all models in the project at once (on project level) or each model separately (on model level). When the user saves the project, the project settings will be saved in a $<*$.dsproj$>$ configuration file and the project data in a $<$*.dsproj_data folder$>$. The $<$*.dsproj_data$>$ folder contains folders with all input and output files for the models within the project. There is no model intelligence in the $<*$.dsproj$>$ configuration file, meaning that the models can also be run outside the GUI from the $<$*.dsproj_data$>$ folder.

3.6.2 Load/save vs import/export

The user can load an existing Delta Shell project, make changes in the GUI and, consequently, save all the project data. Loading and saving means working on the original project data, i.e. the changes made by the user overwrite the original project data. Alternatively, use *Save As* to keep the original project data and save the changes project data at another location (or with another name).

Import/export functionality can be used to copy data from another location into the project (import) or, vice versa, to copy data from the project to another location (export). Import/export is literally copying, e.g.:

- ◇ import: changes on the imported data will only affect the data in the project and not the source data (upon saving the project)
- ◇ export: the model data is copied to another location “as is”, changes made afterwards will only affect the data in the project not the exported data (upon saving the project)

3.6.3 Working from the map

One of the most important differences with the former GUI is the central map. The central map is comparable with the former “visualization area”, but with much more functionality and flexibility. The map helps you to see what you are doing and inspect the model at all times. You can use the *Region* and *Map* ribbons to add/edit model features in the map.

3.6.4 Coordinate conversion

With the map as a central feature, functionality to convert model and map coordinates is an indispensable feature. In the *General* tab you can set the model coordinate system. In the map tree you can set the map coordinate system using the right mouse button (Figure 3.30). The coordinate systems are subdivided in geographic and projected systems. Use the quick search bar to find the coordinate system you need either by name or EPSG code (Figure 3.31).

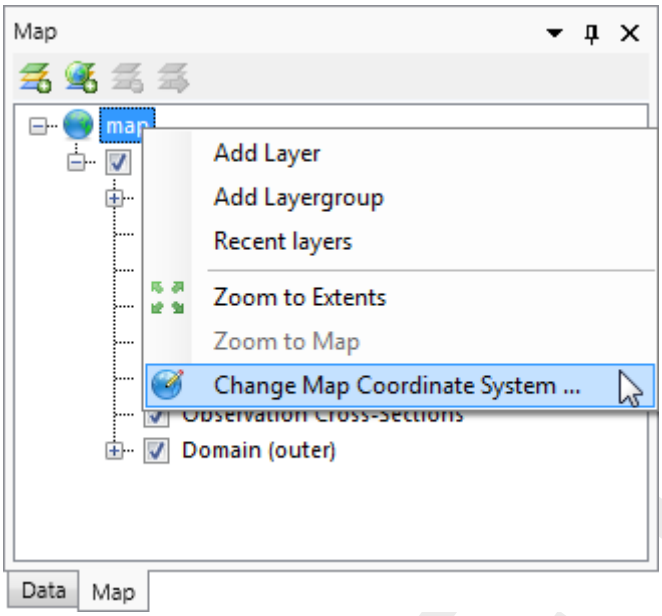


Figure 3.30: *Set map coordinate system using right mouse button*

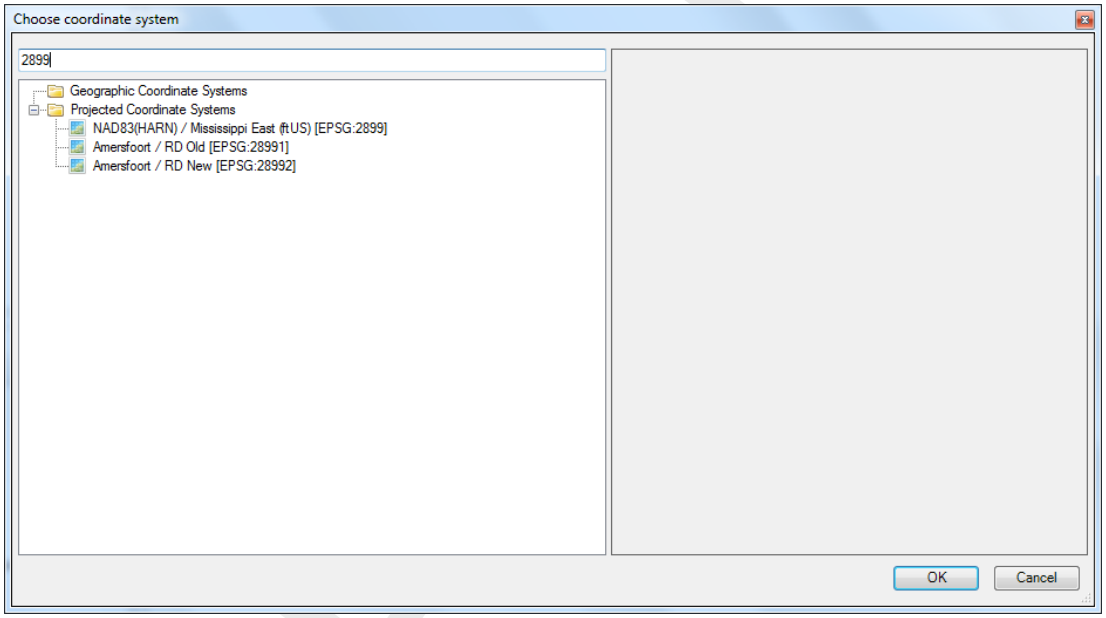


Figure 3.31: *Select a coordinate system using the quick search bar*

3.6.5 Model area

The model area contains geographical features, such as observation points & curves and obstacles. In contrast to the former GUI, these features can even exist without a grid or outside the grid and they are not based on grid coordinates, implying that their location remains the same when the grid is changed (for example by (de-)refining).

Finally, for the computations, the SWAN computational core interpolates the features to the grid. In the future we would like to show to which grid points the features are snapped before running the computation. However, this requires some updates in the SWAN computational core.

3.6.6 Integrated models (model couplings)

The Delta Shell framework implements the concept of an *Integrated model* in order to couple different models, such as: hydrodynamics coupled with the controlling of structures, waves, morphology and/or water quality.

Two types of coupling are distinguished: *offline* and *online* coupling. In case of an *Integrated model* with *offline* coupling, the entire hydrodynamic simulation is done first, i.e., *separately* from the second simulation. The file-based hydrodynamic output serves as input for the second simulation. As such, the hydrodynamic flow drives the controlling of structures or the simulation of waves or water quality. In this case there is no feedback on the hydrodynamic simulation. For many applications, this is good practice.

An *online* coupling, on the other hand, exchanges data *every time* after computing a specified time interval. This tight coupling allows for direct feedback of the various processes on one another. This is crucial for controlling structures.

Note: *Offline* is also referred to as *sequential* coupling and *online* as *parallel* coupling.

3.6.7 Ribbons (shortcut keys)

Delta Shell makes use of ribbons, just like Microsoft Office. You can use these ribbons for most of the operations. With the ribbons comes shortcut key functionality, providing shortcuts to perform operations. If you press `Alt`, you will see the letters and numbers to access the ribbons and the ribbon contents (i.e. operations). For example, `Alt + H` will lead you to the *Home*-ribbon (Figure 3.32).

Note: Implementation of the shortcut key functionality is still work in progress.

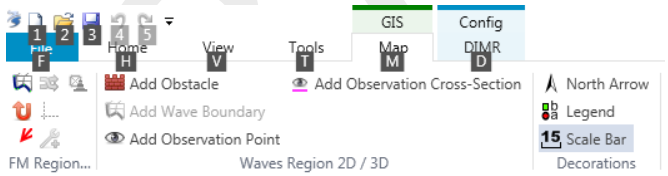


Figure 3.32: *Perform operations using the shortcut keys*

3.6.8 Context menus

Context menus are the menus that pop up using the right mouse button. These context menus provide you with some handy functionality and shortcuts specific for the selected item. The functionality is available in all Delta Shell windows and context dependent. You can best try it yourself to explore the possibilities.

3.6.9 Scripting

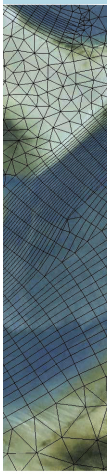
Delta Shell has a direct link with scripting in Iron Python (NB: this is not the same as C-Python). This means that you can get and set data, views and model files by means of scripting instead of having to do it all manually. Scripting can be a very powerful tool to automate certain steps of your model setup or to add new functionality to the GUI. You can add a new script by adding a new item, either in the *Home*-ribbon or through the right mouse button.

4 All about the modelling process

4.1 Introduction

In order to set up a hydrodynamic model you must prepare an input file. All parameters to be used originate from the physical phenomena being modelled. Also from the numerical techniques being used to solve the equations that describe these phenomena, and finally, from decisions being made to control the simulation and to store its results. Within the range of realistic values, it is likely that the solution is sensitive to the selected parameter values, so a concise description of all parameters is required. This input data is collected into the Master Definition Unstructured file, called a mdu-file.

In section 4.2 we discuss some general aspects of the mdu-file and its attribute files. The sections thereafter describe how the actual modelling process can be done in the GUI.



4.2 mdu-file and attribute files

The Master Definition Unstructured file (mdu-file) is the input file for the hydrodynamic simulation program. It contains all the necessary data required for defining a model and running the simulation program. In the mdu-file you can define attribute files in which relevant data (for some parameters) is stored. This will be particularly the case when parameters contain a large number of data (e.g., time-dependent or space varying data). The mdu-file and all possible user-definable attribute files are listed and described in Appendix A.

Although you are not supposed to work directly on the mdu-file it is useful to have some ideas on it as it reflects the idea of the designer on how to handle large amounts of input data and it might help you to gain a better idea on how to work with this file.

The basic characteristics of an mdu-file are:

- ◇ It is an ASCII file.
- ◇ Each line contains a maximum of 256 characters.
- ◇ Each (set of) input parameter(s) is preceded by a (set of) *keyword*(s).

The results of all modules are written to platform independent binary (NetCDF-)files, so also these result files you can transfer across hardware platforms without any conversion.

The mdu-file contains several sections, denoted by square brackets, below are the most relevant ones:

`[model]` this section contains the program name and its version.

`[geometry]` in this section, the main entry comprises the specification of the grid (i.e. the netcdf network file). In addition, thin dams and thin dykes can be specified.

`[numerics]` this section contains the settings of specific parts of the flow solver, such as limiters and the iterative solver type.

`[physics]` in this field, physical model parameters can be inserted, for instance related to friction modelling and turbulence modelling.

`[wind]` the wind section prescribed the dependency of the wind drag coefficient to the wind velocity through 2 or 3 breakpoints. This field also contains pressure information.

`[time]` in this section, the start time and the stop time of the simulation are specified in hours, minutes or seconds. The other times specified are specified in seconds.

`[restart]` in this section, the restart file can be specified, either as a <∗_map.nc>-file or as an <∗_rst.nc> file.

`[external forcing]` this section only contains the name of the external forcings file.
`[output]` in this section, the writing frequency of output data can be prescribed.

Appendix A contains the full list of MDU sections and keywords.

4.3 Filenames and conventions

Filenames and file extensions hardly have any strict requirements in D-Flow FM, but we do advise to use the suggested file naming patterns below:

file pattern	description
mdu_name.mdu	mdu-file
∗_net.nc	Unstructured grid (network) file
∗.xyz	Sample file (for spatial fields)
∗.ldb	Landboundary file (polyline file format)
∗_thd.pli	Thin dam file (polyline file format)
∗_fxw.pliz	Fixed weir file (polyline file format with z values)
∗_part.pol	Partitioning polygon file (polyline file format)
∗.ext	External forcings file
pli_name.pli	Boundary condition location file (polyline file format)
*pli_name*_000X.tim	Timeseries boundary data file at point #X
*pli_name*_000X.cmp	Astronomic/harmonical component boundary data file at point #X
∗.bc	BC-format boundary data file with polyline and point labels in file
∗.xyn	Observation station file
∗_crs.pli	Observation cross-sections file
*mdu_name*_map.nc	Output map file
*mdu_name*_his.nc	Output his file
mdu_name.dia	Output diagnostics (log) file

4.4 Setting up a D-Flow FM model

This chapter describes how to set up a D-Flow FM model in an empty Delta Shell project. When you open the GUI, an empty project is automatically created. Starting from scratch, you have to create an empty D-Flow FM model in a Delta Shell project:

- ◇ In the ribbon menu items, go to *Home* and click on *New Model*. The *Select model ...* window appears (Figure 4.1). Click on D-Flow FM model and click *OK*. Alternatively, you can also double click on D-Flow FM model to open it directly.
- ◇ Or use the right mouse button on the name of your project (project1 by default). In the context menu that appears, select *Add* and click *New Model*. Again, the *Select model ...* window appears allowing you to add an empty D-Flow FM model.

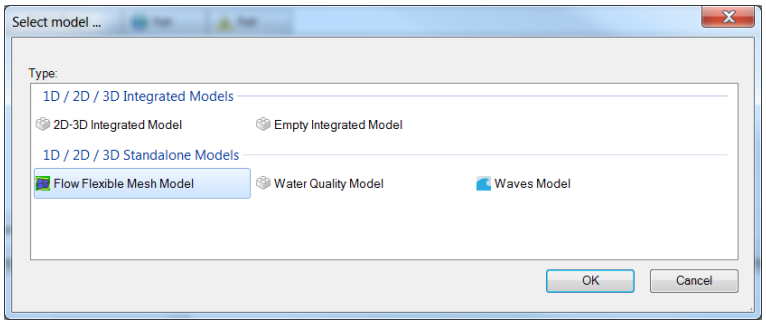


Figure 4.1: *The* Select model ... *window*

In the *Project* window, an empty model has appeared (Water Flow FM Model (1) by default). Click the plus sign (+) before the name of the model to expand all model attributes in the *Project* window: General, Area, Grid, Bed Level, Time Frame, Processes, Initial Conditions, Boundary Conditions, Physical Parameters, Sources and Sinks, Numerical Parameters, Output Parameters and Output. In the following paragraphs, all model attributes are treated separately.

4.4.1 General

When you double click on *General* in the *Project* window, tabulated input fields appear underneath the central map (Figure 4.2). The general tab contains general model information such as the model grid (will be moved to domain in later release), the number of vertical layers and vertical model, the model coordinate system and the angle of latitude.

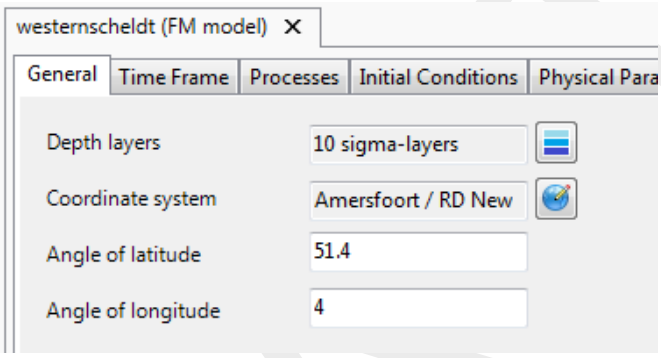


Figure 4.2: *Overview of general tab*

4.4.1.1 Vertical layer specification

When you click on the blue striped icon next to the vertical layers text box (depth layers), the **Edit depth layers** window appears (Figure 4.3). This window allows you to choose the type of layering and the corresponding number of layers. The drop down menu contains two distinct layering types:

1 Single
2 Z
3 Sigma (β-functionality)

Note: Currently, only the Single and Sigma type layering are presented.

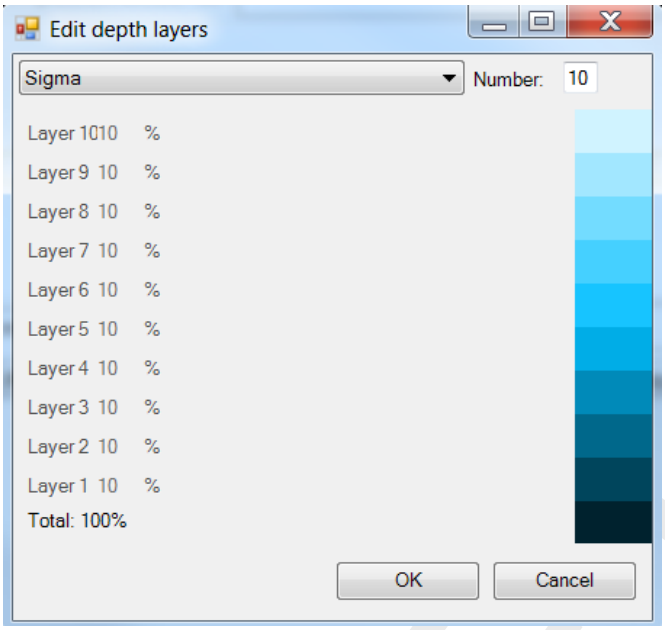


Figure 4.3: *Vertical layer specification window (σ-model is β-functionality)*

The recommended type of vertical layering differs depending on the model application and the processes that you are interested in. Layers in the σ-model increase or decrease in thickness as the water depth in the model increases or decreases. The relative thickness distribution of the different layers however remains fixed. Layers in the Z-model have a fixed thickness, which does not change as the water depth in the model varies. If the water depth drops below the cumulative thickness of all z-layers, layer(s) will fall dry. When *Single* is chosen, the model contains only 1 vertical layer. (An extensive description of σ- and z-type layering is found in section 7.3).

If your model contains more than 1 layer, the thickness distribution of the vertical layers can be specified. In Delta Shell, user can specify the number of layers and then automatically obtain uniformly distributed layer thicknesses (The total percentage is 100 %). As shown in Figure Figure 4.3, setting 10 layers results in 10 % thickness distribution for each layer. Specifying non-uniformly distributed layer thickness is β-functionality and can be done through the MDU file.

4.4.1.2 Model coordinate system

A very important property of your model is the coordinate system in which it is specified. Within the interface, there is a clear distinction between the coordinate system of your model and all of its attributes and the coordinate system of the central map and all of its items. Both coordinate systems can be set independent from each other. Keep in mind, that the coordinate system of your model is saved and used when you run your model. Only coordinate systems supported by the computational core are supported.

The model coordinate system can be set using the globe icon next to the Coordinate system text box. After clicking this button, the coordinate system wizard is opened (Figure 4.4). This wizard allows you to choose one of many possible coordinate systems and apply it to your model. You can use the search bar to browse the various coordinate systems (searching possible by name and EPSG code). If your model is specified in a certain coordinate system already, it is possible to convert the model coordinate system using the same button. After clicking *OK*, all model attributes are converted to the system of choice. Note that you have to

close and re-open all map views for the changes to take effect in these views.

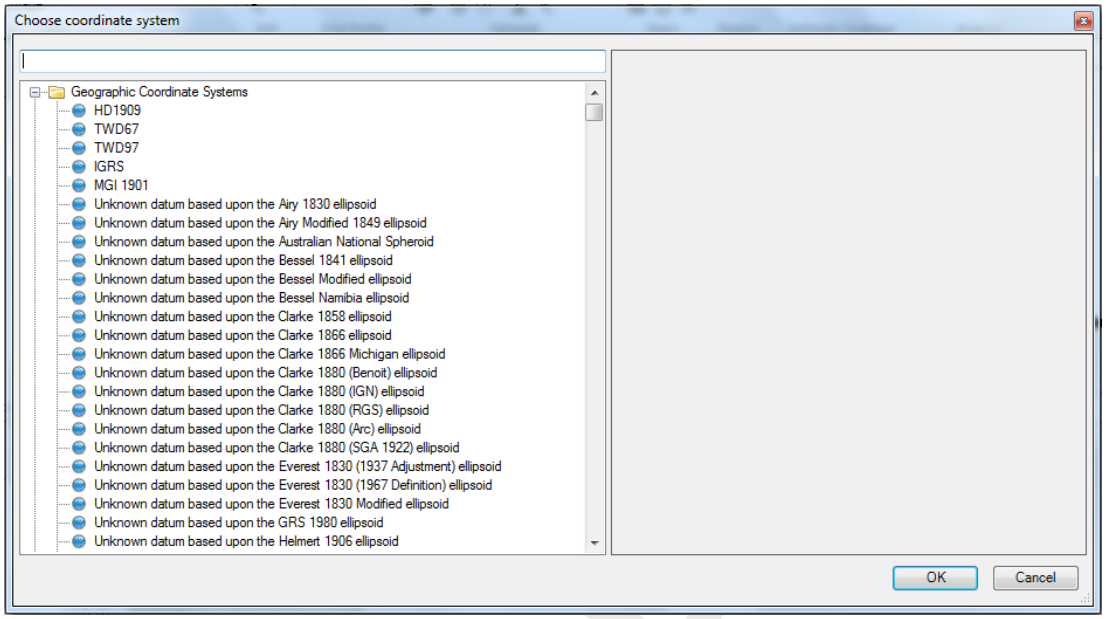


Figure 4.4: *Coordinate system wizard*

The map coordinate system applies to all items in the map *Project* window. To change the map coordinate system, navigate the menu ribbons to *Map* and click on *Map coordinate system*. Alternatively, right mouse click on *map* in the map *Project* window and select *Change Map Coordinate System*. The coordinate system wizard appears, allowing you to set the map coordinate system of your choice. When the original model coordinate system differs from the selected map coordinate system, all map items are automatically converted to the specified map coordinate system.

4.4.1.3 Angle of latitude

For a Cartesian grid you have to specify the latitude of the model area; this is used to calculate a fixed Coriolis force for the entire area. For a spherical grid the Coriolis force is calculated from the latitude coordinates in the grid file and thus varies in the latitude direction. Typically, you use spherical co-ordinates for large areas, such as a regional model. When a value of 0 is entered, the Coriolis force is not taken into account.

4.4.2 Area

The model area contains all geographical features, such as the observation points, structures and land boundaries. These features can exist without a grid or outside the grid as they are not based on grid coordinates but xy-coordinates. This means that the location of the model area features remains the same when the grid is changed (for example by (de-)refining). When you expand the model attribute *Area* in the *Project* window, a list of possible geographical features is displayed (Figure 4.5).

Figure 4.5: *Overview of geographical features*

Figure 4.6 displays an overview of the map ribbon. The left red box indicates the *FM Region*

2D / 3D of the map ribbon. To add a geographical feature, click the corresponding item in this box and use your mouse to indicate the location of the desired feature on the central map. Importing and exporting of all model features is done via the context menu by using your right mouse button on the different features. The red box on the right highlights the various editing buttons available to edit the locations of the geographical features. The specifics for each feature are discussed separately in the following sections.

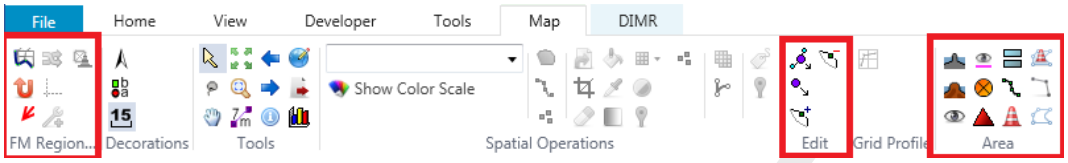


Figure 4.6: *Overview of map ribbon. Left red box highlights* FM Region 2D / 3D *menu containing icons used to add features. Right red box highlights* Edit *menu which contains icons used to edit geographical features (move/add)*

4.4.2.1 Grid snapped features

All geographical features of your model that are described by x-, and y-coordinates have to be interpolated to your computational grid when you run your model. The computational core of D-Flow FM automatically assigns these features to the corresponding parts of your grid. The graphical user interface allows you to inspect the interpolated locations of these features.

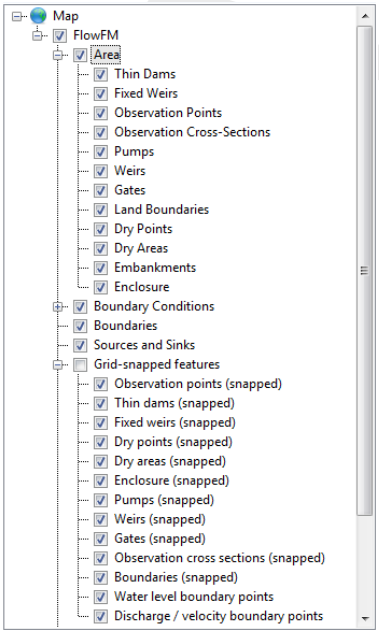


Figure 4.7: *Example of expanded grid snapped features attribute in map tree*

Figure 4.7 shows a part of the map tree, showing the Area2D and Grid-snapped features attributes. The x- and y-locations of all spatial model features are shown within the Area2D attribute. You can hide or show any of these attributes by means of clicking the check boxes in front of the attributes. When you enable the Grid-snapped features, all items within the Area2D attribute, as well as all boundaries are interpolated to their corresponding locations on the computational grid. The interpolation is performed instantaneously by the computational core of D-Flow FM, which enables you to directly inspect the numerical interpretation of all features on the computational grid. Figure 4.8 shows an example of four observation points

and one thin dam in the central map, showing both the x- and y-locations of these features as well as their representation on the computational grid.

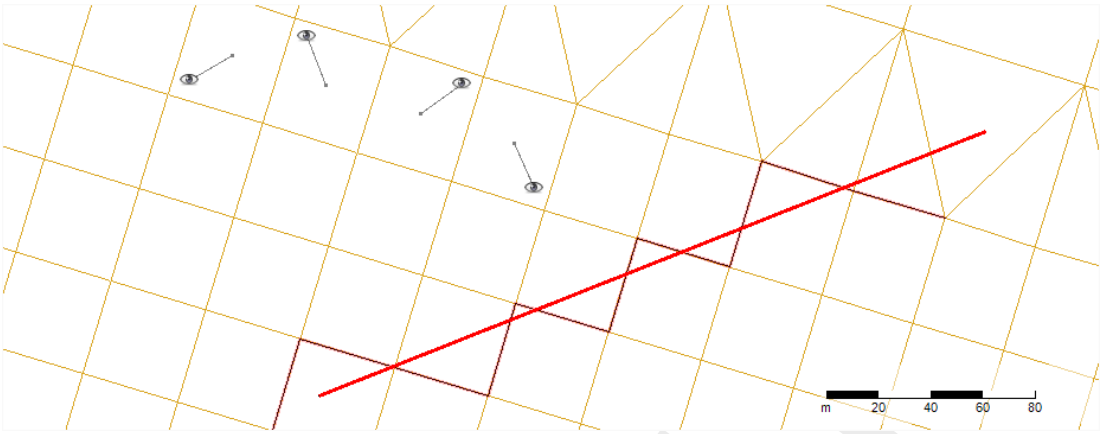


Figure 4.8: *Example of grid snapped features displayed on the central map*

4.4.2.2 Observation points

Observation points are used to monitor the time-dependent behaviour of one or all computed quantities as a function of time at a specific location, i.e. water elevations, velocities, fluxes, salinity, temperature and concentration of the constituents . Observation points represent an Eulerian viewpoint at the results. (**Note: Sediment transport is a β-functionality**)

To add an observation point, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). By clicking in the central map, observation points are placed in your model. Selected observation points (first click the *Select* icon from the "Tools" menu in the map ribbon) can be deleted using backspace or directly from the attribute table (explained below). The grid snapped representation (Figure 4.9) is indicated by a line linking the observation points to the closest cell center, indicating that output will be stored of this cell. Importing and exporting of observation points is possible via the context menu of "Observation points" in the *Project* window (right mouse button).

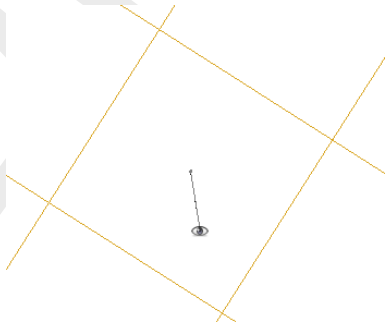


Figure 4.9: *Geographical and grid snapped representation of an observation point*

When you double click the *Observation points* attribute in the *Project* window, the observation points tab is displayed underneath the central map (Figure 4.10). This tab shows an attribute table with the names, x- and y-locations (in the model coordinate system) of the various observation points within the model. When one of the entries is selected, the corresponding observation point is highlighted in the central map.

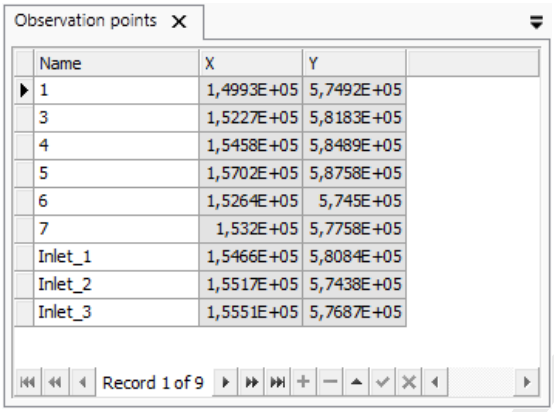


Figure 4.10: *Attribute table with observation points*

4.4.2.3 Observation cross-sections

Cross-sections (Figure 4.11) are used to store the sum of computed fluxes (hydrodynamic), flux rates (hydrodynamic), fluxes of matter (if existing) and transport rates of matter (if existing) sequentially in time at a prescribed interval.

To add a cross section, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). By clicking in the central map, cross section points are added. Note that a cross section consists of a minimum of two points, but an arbitrary amount of intermediate points can be added. The last point is indicated by double clicking the left mouse button. The distance in meters (independent of the local coordinate system) in between the last point and the mouse pointer is indicated in pink; in case more than two points are used, the cumulative length of the entire cross section is shown in black. Once highlighted in the central map, a cross section is deleted with backspace or directly from the attribute table described below. The positive direction through the cross section is indicated by a pink arrow. The direction of this arrow is dependent on the order in which the cross section points are drawn (to change the direction, flip the start and end points). Importing and exporting of cross sections is possible via the context menu of “Observation cross-sections” in the *Project* window (right mouse button).

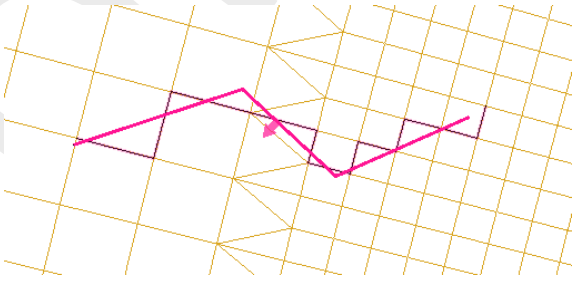


Figure 4.11: *Geographical and grid snapped representation of a cross section*

Double clicking the *Observation cross-sections* attribute in the *Project* window enables the Observation cross-sections tab in the central map view (Figure 4.12). Alternatively, you can double click on any cross section in the map. The attribute table displayed in the tab contains the names of the various cross sections of your model. When one of the entries is selected, the corresponding cross section is highlighted in the central map. A cross section entry can be deleted from the table via the context menu (right mouse button).

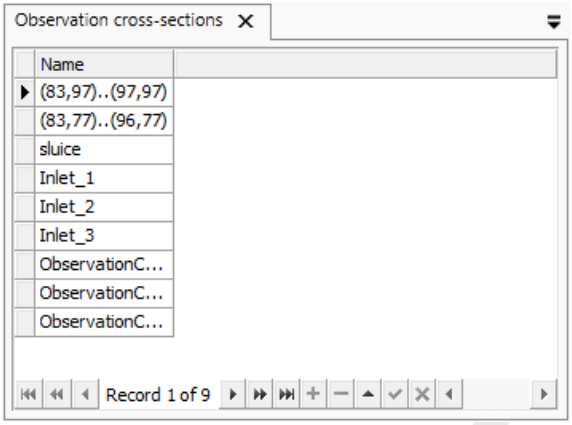


Figure 4.12: *Attribute table with observation cross sections*

4.4.2.4 Thin dams

Thin dams (Figure 4.13) are infinitely thin objects defined at the velocity points which prohibit flow exchange between the two adjacent computational cells without reducing the total wet surface and the volume of the model. The purpose of a thin dam is to represent small obstacles (e.g. breakwaters, dams) in the model which have sub-grid dimensions, but large enough to influence the local flow pattern. A thin dam is assumed to have an infinite level in the model; no water will ever overflow a thin dam.

To add a thin dam, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). Adding, deleting, importing and exporting of a line feature such as a thin dam is discussed in more detail in section 4.4.2.3 on cross sections.

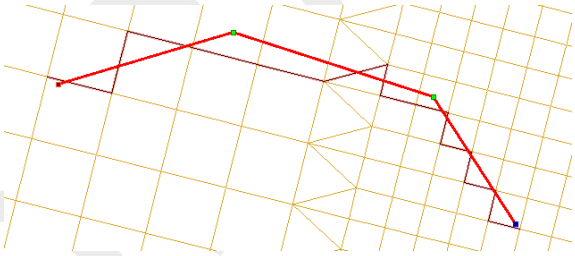


Figure 4.13: *Geographical and grid snapped representation of a thin dam*

When you double click the *Thin dams* attribute in the *Project* window, the corresponding Thin dams tab appears underneath the central map (Figure 4.14). Alternatively, you can also double click on any thin dam in the central map. Within this tab, an attribute table is shown which displays the names of all thin dams within your model. When one of the entries is selected, the corresponding item is highlighted in the central map. A thin dam entry can be deleted from the table via the context menu (right mouse button).

Figure 4.14: *Attribute table with thin dams*

4.4.2.5 Fixed weirs

A fixed weir (Figure 4.15) has the same function as a thin dam (section 4.4.2.4). However, unlike a thin dam, a fixed weir can be assigned both xy- and z-values. Furthermore, a fixed weir can be assigned a crest length (a thin dam is infinitely thin). The z-values correspond to the crest level of the fixed weir at the corresponding x- and y-locations; the level can vary in space, but is constant in time (Figure 4.16). Consequently, a fixed weir can overflow if the water level exceeds the crest level of the fixed weir. The level is specified with regard to the same vertical reference level as all other model items with level specifications (e.g. bed level values and initial water levels).

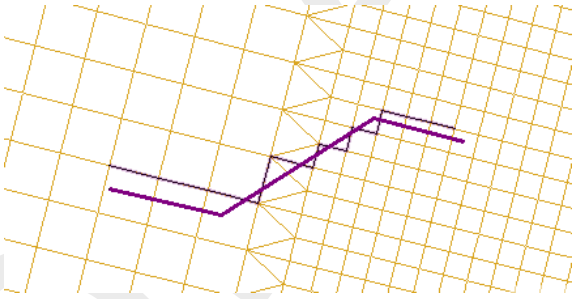


Figure 4.15: *Geographical and grid snapped representation of a fixed weir*

Figure 4.16: *Schematic representation of a fixed weir*

To add a fixed weir, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). Adding, deleting, importing and exporting of a line feature such as a fixed weir is discussed in more detail in section 4.4.2.3 on cross sections.

When you double click the *Fixed weirs* attribute in the *Project* window, the corresponding

Fixed weirs tab appears underneath the central map (Figure 4.17). Alternatively, you can also double click on any fixed weir in the central map. Within this tab, an attribute table is shown which displays the names of all fixed weirs within your model. When one of the entries is selected, the corresponding item is highlighted in the central map. A fixed weir entry can be deleted from the table via the context menu (right mouse button).

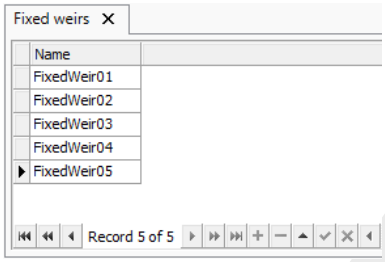


Figure 4.17: *Attribute table with fixed weirs*

When you double click on a fixed weir in the central map, the fixed weir editor opens in a separate view (Figure 4.18). On the right, a graphic representation (top view) of the fixed weir is displayed. The support point that is selected in the table is highlighted by means of a blue circle. On the left, a table is displayed showing the following properties of each support point of the fixed weir under consideration:

- X: x-location of the support point
- Y: y-location of the support point
- Crest level: level of fixed weir (spatially varying but fixed in time)
- Crest length: length of the crest (instead of an infinitely thin crest)
- Left ground level: ground level to the left of the crest; together with crest level determines slope of crest on the left side
- Right ground level: ground level to the right of the crest; together with crest level determines slope of crest on the right side

Figure 4.18: *Fixed weir editor*

4.4.2.6 Land boundaries

A land boundary (Figure 4.19) encloses the main geographic features surrounding your model and indicates the intersection of the water and land masses. When you set up your computational grid in RGFGRID, a land boundary determines the onshore extent of your model. When you open RGFGRID to edit your grid, the land boundary is automatically transferred and displayed. For more details on grid generation, you are referred to the User Manual of RGFGRID (RGFGRID UM, 2016).

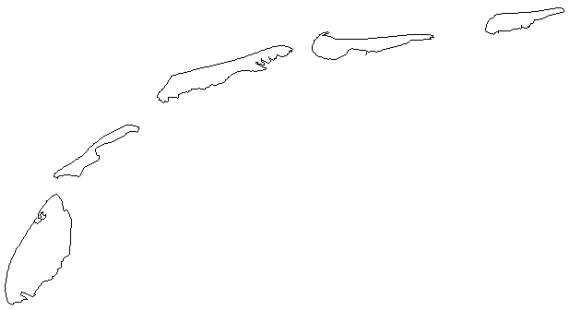


Figure 4.19: *Geographical representation of a land boundary*

To add a land boundary, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). Adding, deleting, importing and exporting of a line feature such as a land boundary is discussed in more detail in section 4.4.2.3 on cross sections.

When you double click the *Land boundaries* attribute in the *Project* window, the corresponding land boundaries tab appears underneath the central map (Figure 4.20). Alternatively, you can also double click on any land boundary in the central map. Within this tab, an attribute table is shown which displays the names of all land boundaries within your model. When one of the entries is selected, the corresponding item is highlighted in the central map. A land boundary entry can be deleted from the table via the context menu (right mouse button).

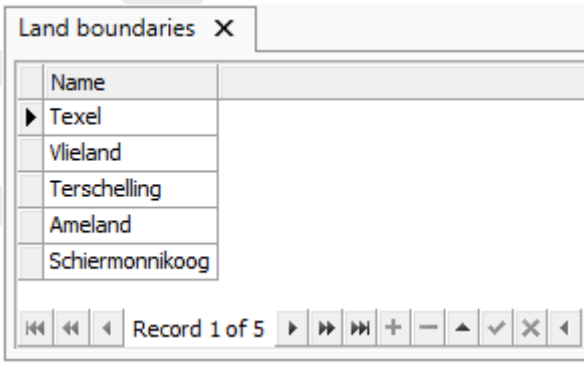


Figure 4.20: *Attribute table with land boundaries*

4.4.2.7 Dry points and dry areas

Dry points are grid cells centred around a water level point that are permanently dry during a computation, irrespective of the local water depth and without changing the water depth as seen from the wet points. Dry areas are the same, but provide an easy way of defining many grid points as a single dry area at once.

Note that the flexibility of unstructured grids makes the use of dry points less necessary than with structured grid models, such as Delft3D-FLOW. In the interior of unstructured grids, some or more grid cells can easily be deleted during grid manipulation, e.g., in RGFGRID. Still, a dry points file can be used to explicitly mark locations or regions inside the grid as dry cells.

Dry points in the GUI

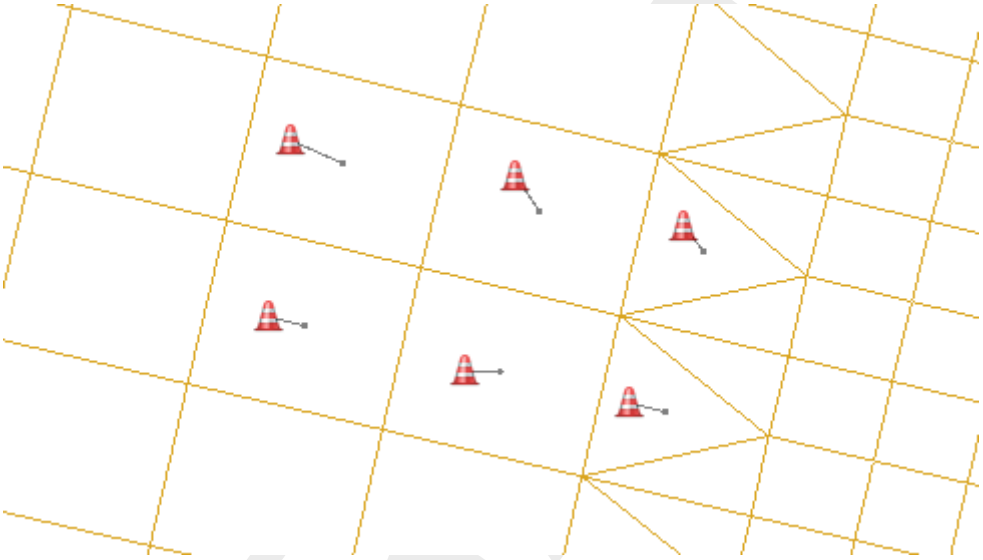


Figure 4.21: *Geographical and grid snapped representation of several dry points*

To add a dry point, click the corresponding icon from the *FM Region 2D / 3D* menu in the map ribbon (Figure 4.6). Adding, deleting, importing and exporting of a point feature such as a dry point is discussed in more detail in section 4.4.2.2 on observation points. The grid snapped representation of a dry point (Figure 4.21) is indicated by a line linking the dry point to the closest cell center.

When you double click the “Dry points” attribute in the *Project* window, the corresponding Dry points tab appears underneath the central map (Figure 4.22). Alternatively, you can also double click on any dry point in the central map. Within this tab, an attribute table is shown which displays the names of all dry points within your model. When one of the entries is selected, the corresponding item is highlighted in the central map. A dry point entry can be deleted from the table via the context menu (right mouse button).

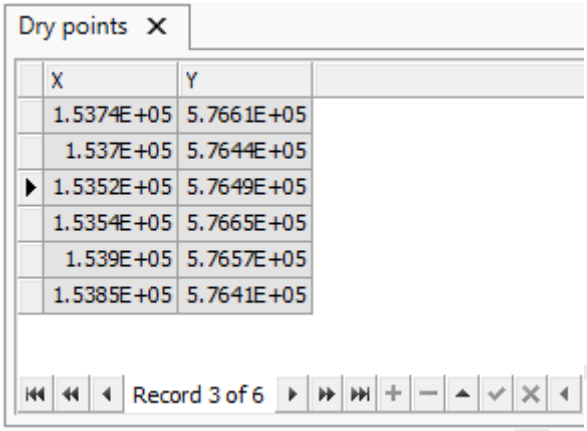


Figure 4.22: *Attribute table with dry points*

Dry areas in the GUI

Dry areas (Figure 4.23), like dry points, indicate areas that permanently dry during a computation. Instead of adding many separate dry points, you can draw a polygon that encloses all required computational cells. Only cells which centers are strictly inside the polygon are taken into account. The grid snapped representation of the dry area clearly indicates which cells are considered within the dry area.

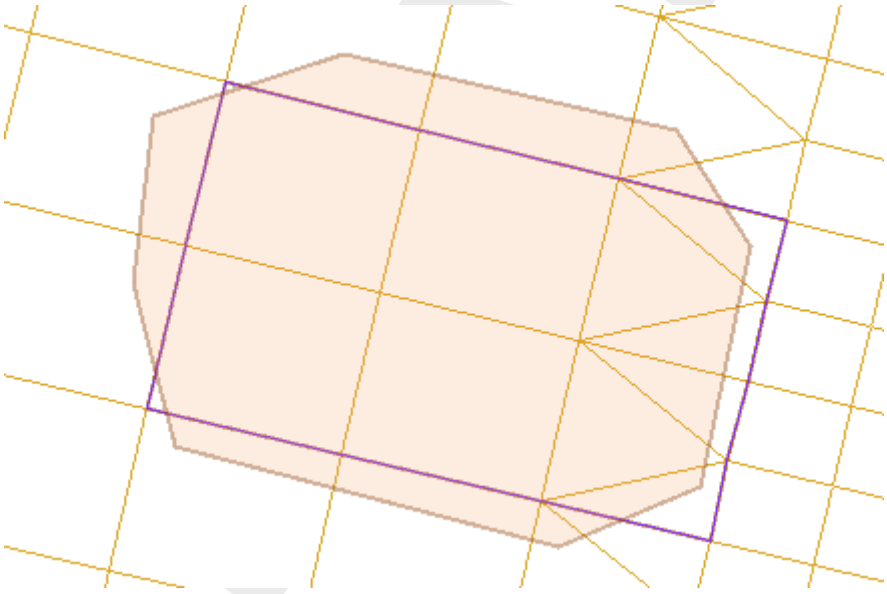


Figure 4.23: *Geographical and grid snapped representation of a dry area*

When you double click the *Dry areas* attribute in the *Project* window, the corresponding Dry areas tab appears underneath the central map (Figure 4.24). Alternatively, you can also double click on any dry area in the central map. Within this tab, an attribute table is shown which displays the names of all dry areas within your model. When one of the entries is selected, the corresponding item is highlighted in the central map. A dry area entry can be deleted from the table via the context menu (right mouse button).

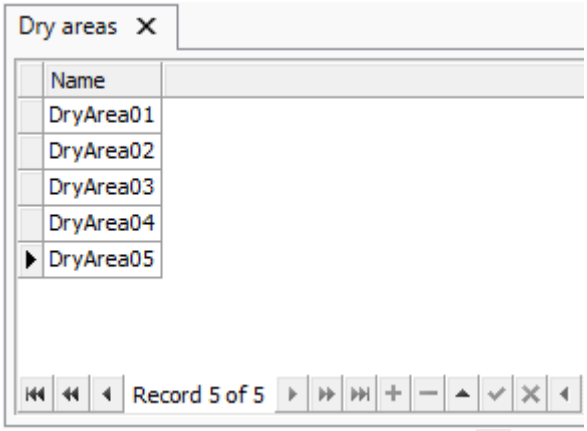


Figure 4.24: *Attribute table with dry areas*

Dry points file input

Dry points are defined by a sample file <∗.xyz>, dry areas are defined by a polygon file <∗.pol>. Add the filename to the MDU as below:

```
[geometry]
# ...
DryPointsFile = <filename.xyz> # Dry points file *.xyz, third column dummy z values,
                               # or polygon file *.pol.
```

The format of the sample file is defined in section B.3. The format of the polygon file is defined in section B.2. All grid cells that contain a sample point are removed from the model grid, and as a result do not appear in any of the output files. Alternatively, for a polygon file, all grid cells whose mass center lies within the polygon will be removed from the model grid.

Finally, an optional flag can be set in the polygon file to invert the masking behavior of the polygon. That is: all points *outside* of the polygon will be marked as dry and therefore removed. To realize this, the polygon block should have three columns, and the first point should have a z-value of -1 in the third column.

4.4.2.8 Pumps

Pumps are a type of structures in D-Flow FM. Unlike the other structures, pumps can force the flow only on one direction. This direction is determined by arrow in D-Flow FM. The direction of pump can be reverted by mouse right-click and selecting "Reverse line(s)".

Like all other structures in D-Flow FM, the pump can be defined by a polygon. The input data of the pumps can be given by selecting and editing the pump polygon (see Figure 4.25). Right click on the pump polygon and selecting "Delete Selection" leads to deletion of the selected pump. Double clicking the pump polygons (or right click the pump in the list and select "Open view"), it opens a tab for editing the pump properties. The tab includes pump capacity. If the pump capacity is time dependent, it can be given by time series data (Figure 4.25).

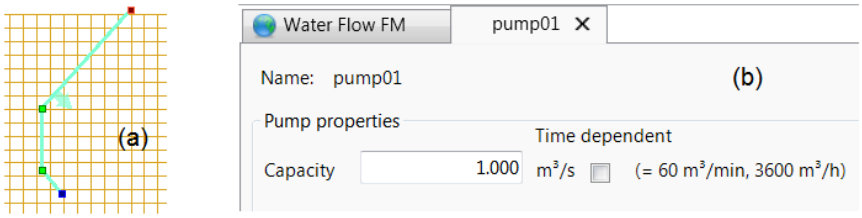


Figure 4.25: *Polygon for pump (a) and adjustment of physical properties (b).*

Right clicking the pumps attribute in the *Project* window opens a pop-down window on which you can select to import or export pumps. The pumps can be imported as polyline by a <∗.pli> file or by a structure file, and they can be exported as a <∗.pli> file, structure file, or <*shapefile*>.

Double clicking the pumps attribute in the *Project* window opens the pumps tab underneath the central map. The attribute table in this tab shows all pumps with their corresponding properties. When one of the pumps is selected, the corresponding item is highlighted in the central map. Double clicking any of the pumps in the central map opens the Structure Editor as a new map view in which all parameters related to the pump can be set (Figure 4.26).

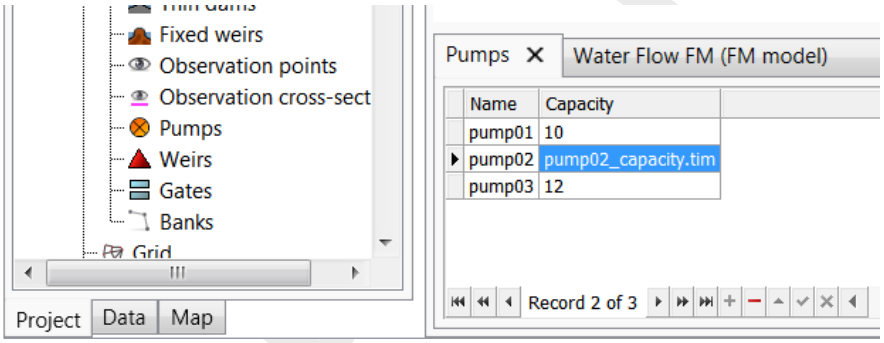


Figure 4.26: *Selection of the pumps*

4.4.2.9 Weirs

Unlike the fixed weir, weir (or adjustable weir) can be adjusted based on the user requirements. To set an adjustable weir in the computational domain, you can select the icon *weir* from the toolbar, and draw a line by mouse. This line includes direction, which defines the sign of total flux passing above the weir (positive flux in the direction of weir, otherwise negative). This direction can be inverted by mouse right-click and selecting *Reverse line(s)*. By double-click on the weir, you can add the geometrical and time-dependent parameters such as *Crest level*, *Crest width*, *Crest level time series* and *Lateral concentration coefficient* (See Figure 4.27).

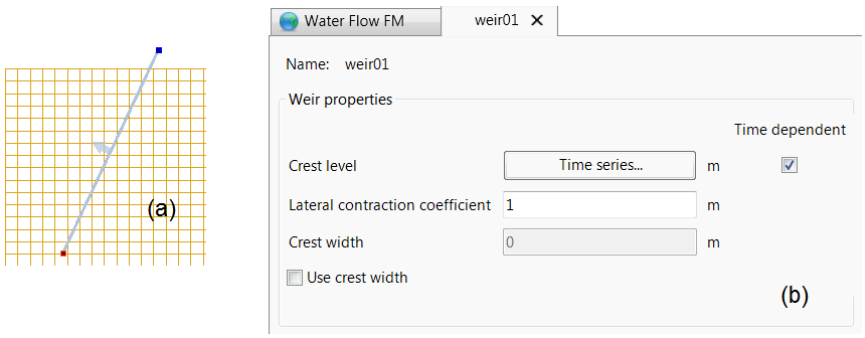


Figure 4.27: *Polygon for adjustable weir (a) and adjustment of geometrical and temporal conditions (b).*

Moreover, the time series of the crest level can be set in the case the crest level is time dependent. The time dependency diagram can be defined by the help of time series diagram as shown in Figure 4.28. The time series can also be imported (and exported) from external <csv>-file.

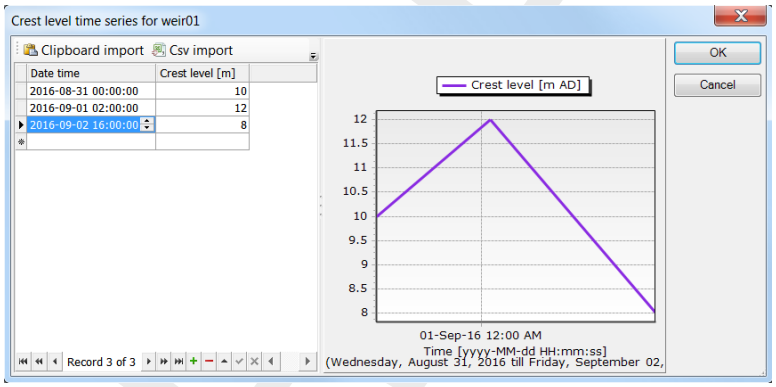


Figure 4.28: *Time series for crest level.*

The weirs can be deleted, imported and exported. By right clicking on the weir polygon, and selecting "Delete Selection" from the pop-down window, you can delete the selected weir. Right clicking the "Weirs" attribute in the *Project* window opens the "Weirs" tab opens the options for import and export. You can import weirs as polygon (<∗.pli> file) or as a structure by structure file. The weirs can also be exported to a polygon file, to a structure data file, or by be the help of shapefile.

Double clicking the "Weirs" attribute in the *Project* window opens the "Weirs" tab underneath the central map. The attribute table in this tab shows all weirs with their corresponding properties. When one of the weirs is selected, the corresponding item is highlighted in the central map. Double clicking any of the weirs in the central map opens the Structure Editor as a new map view in which all parameters related to the weir can be set (Figure 4.29).

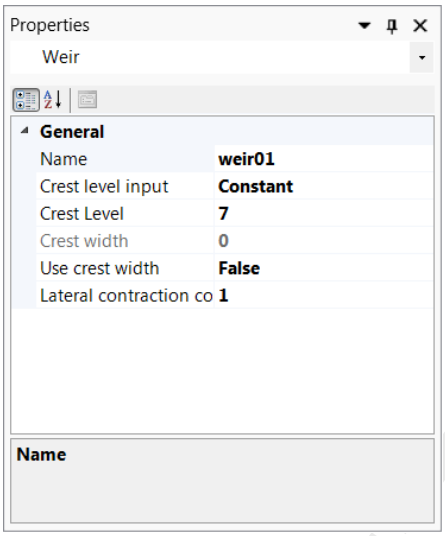


Figure 4.29: *Time series for crest level.*

4.4.2.10 Gates

In D-Flow FM the gates can be imposed by polygon, and can be edited in a similar way as the other structures (see Figure 4.30). Like the other structures, mentioned above, the gates can be imported and exported by means of structure file or <∗.pli> file.

Figure 4.30 shows the edit tab of the gate properties. The gate can be opened horizontally, as well as vertically.

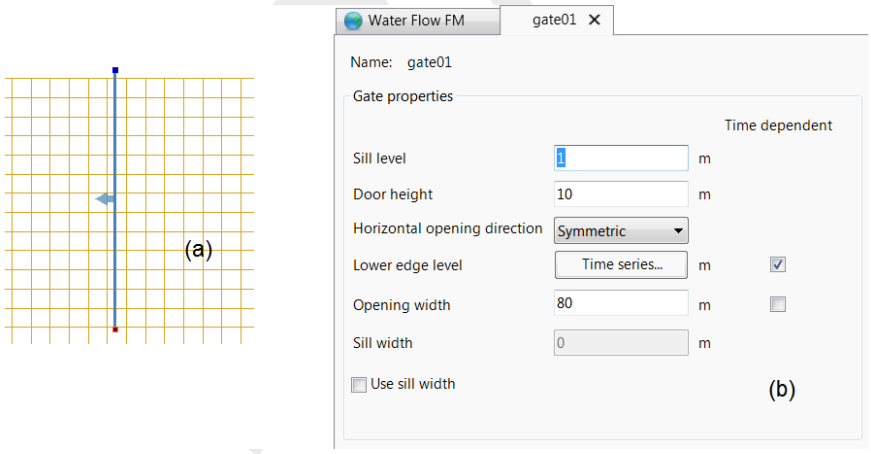


Figure 4.30: *Polygon for gate (a) and adjustment of geometrical and temporal conditions (b).*

4.4.3 Computational grid

To set up your grid, click on the *Edit grid* button which opens the program RGFGRID. All features of grid setup in RGFGRID are treated separately in RGFGRID UM (2016). If a land boundary is present in your project, this is exported to RGFGRID automatically. Once you have setup your grid in RGFGRID, click *File* →*Save Project* and close the program. The grid will now be visible within the central map. Editing of the grid remains possible at any point in time during the setup of your model by means of clicking the *edit grid* button. Any changes you make are always saved after clicking *File* →*Save Project* and loaded back into the central map.

4.4.4 Bed Level

When you double click on *Bed level* in the *Project* window or select *Bed level* from the drop-down box in the spatial editor section of the *Map* ribbon, the spatial editor is activated (Figure 4.31). This editor can be used to generate a bathymetry for your computational grid. How to work with the spatial editor is described in Appendix F. Be aware that the bathymetry in D-Flow FM is defined as the bed level (e.g. positive upward), implying that all bed levels below the reference plane are negative. By default the bed levels are defined on the net nodes.

Note: Please note that, currently, other bed level definition types (e.g. BedlevTypes) are not visually supported by the GUI. If you would like to switch the bed level defintions to another type, you have to set the BedlevType in the *Physical Parameters* tab. However, the bed level locations will not be updated accordingly in the central map.

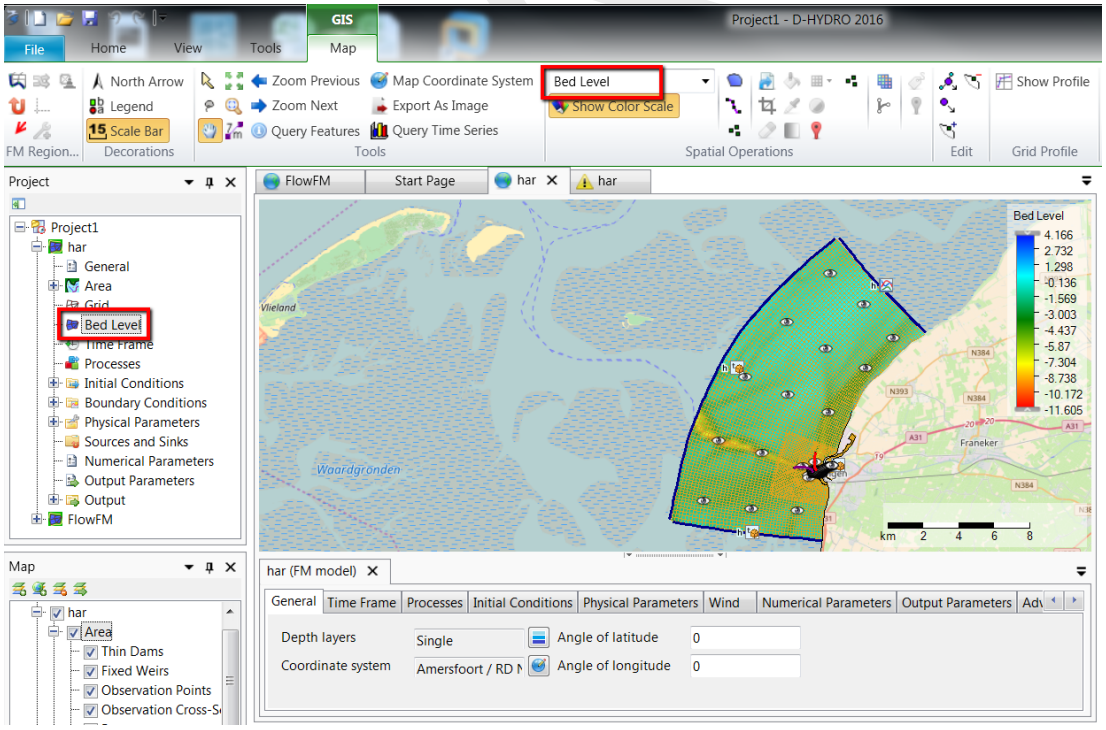


Figure 4.31: *Bed level activated in the spatial editor*

4.4.5 Time frame

In the settings tab, in the sub-tab time frame (Figure 4.32), you can specify everything related to the time frame in which your model will run.

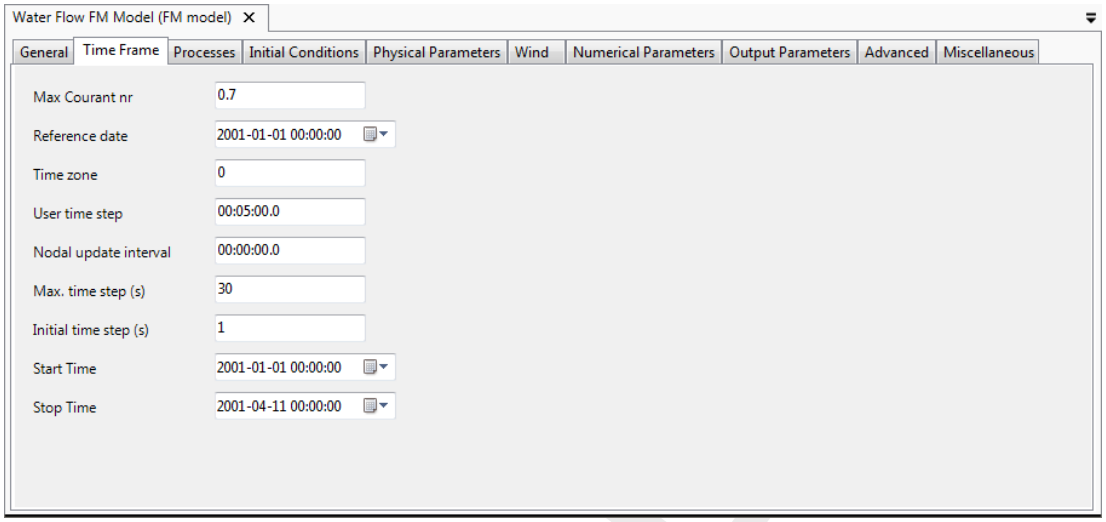


Figure 4.32: *Overview time frame tab*

In general, the time frame is defined by a reference date and a start and stop time. The time step size of your model is automatically limited (every time step) based on a Courant condition. In more detail, you must define the following input data:

Max Courant nr The maximum allowed Courant number, which is used to compute the time step size from the CFL criterium. D-Flow FM uses an explicit advection scheme, therefore a value of 0.7 or lower is advised.
Remark:

- ◇ You should check the influence of the time step on your results at least once.

Reference date The reference date and time of the simulation. It defines the (arbitrary) $t = 0$ point for all time-series as used in the simulation. In the GUI, time-specifications are always absolute, but in the underlying model input files, these are stored as time values relative to the reference date. Typically, input time-series files are specified in minutes after this $t = 0$ point. See for an illustration Figure 4.33.

Time zone The time difference between local time and UTC.
The time zone is defined as the time difference (in hours) between the local time (normally used as the time frame for D-Flow FM) and Coordinated universal time (UTC). The local Time Zone is used for for two processes:

- ◇ To determine the phases in local time of the tidal components when tide generating forces are included in the simulation, see section 7.10.
- ◇ To compare the local time of the simulation with the times at which meteo input is specified, e.g., wind velocities and atmospheric pressure. These can be specified in a different time zone.

If the *Time Zone* = 0 then the simulation time frame will refer to UTC.

User time step The interval that is highest in the hierarchy. It specifies the interval with which the meteorological forcings are updated. The *Max.*

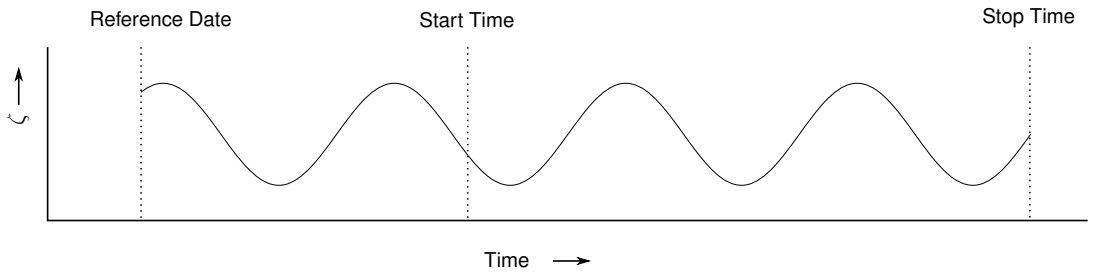


Figure 4.33: *Relation between Reference Date and the simulation start and stop time for astronomic- and harmonic-series as used in the simulation. Time-series should cover the simulation time.*

time step cannot be larger than the *User time step*, and it will automatically be set back if it is. Also, the output intervals should be a multiple of this *User time step*, see Appendix E. Finally the computational time steps will be fitted to end up exactly at each *User time step*, such that proper equidistant output time series are produced.

Nodal update interval When using astronomic boundary conditions, the nodal factors can be updated with certain intervals, see section 7.10.

Max. time step The *Max. time step* is the upper limit for the computational time step. The automatic time step can not be switched off explicitly. (If you want to enforce a fixed time step anyway, set the parameter *Max. time step (s)* to the desired step size, and the parameter *Max. Courant nr.* to an arbitrary high value.)

Initial time step the initial time step of the model; there is no data available yet during the first time step to compute the time step automatically based on a Courant condition. The computational time step then gradually increases from *Initial time step* to the CFL-number limited time step (assuming that *Initial time step* is relatively small).

Start Time The start date and time of the simulation.

Stop Time The stop date and time of the simulation. Always make sure that the model *Stop Time* is larger than the model *Start Time* to avoid errors during your calculation.

4.4.6 Processes

In the processes tab (Figure 4.34) you can specify which processes you want to incorporate into your model. You can choose whether or not to include tidal forcing, salinity, temperature and sediment/morphology by means of check boxes. In addition, you can specify which *Wave model* you want to use. Note that when ticking the sediment/morphology check box, two tabs for setting sediment and morphology parameters appear.

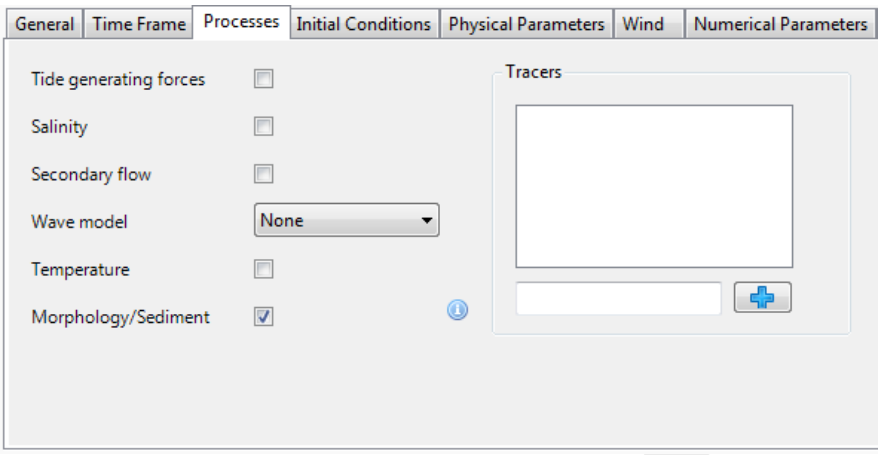


Figure 4.34: *Overview processes tab*

4.4.7 Initial conditions

When expanding the initial conditions in the *Project* window, all quantities requiring an initial state are shown (Figure 4.35). The number of quantities depends on the activated physical processes in the 'Processes' tab (see section 4.4.6). The initial conditions for each quantity can be specified as a uniform value or as a coverage (e.g. a spatially varying field).

The uniform values can edited in the 'Initial Conditions' tab, which opens upon double clicking 'Initial Conditions' in the *Project* window (Figure 4.36). In this tab you can also specify the layer distribution for the initial condition specification in case of a 3 dimensional quantity (i.e. salinity). **Note:** Please note that for 3 dimensional initial conditions currently only the option 'top-bottom' is supported.

In case of spatially varying initial conditions you can double click the quantity in the *Project* window or select it from the dropdown box in the spatial editor section of the /emphSpecial Operations ribbon (Figure 4.37). Then the spatial editor is activated, which you can use to edit spatially varying fields. For more information on how to use the spatial editor you are referred to Appendix F. In case of 3 dimensional initial conditions, you can select the layer from the quantity dropdown box in the 'Map' ribbon (Figure 4.38).

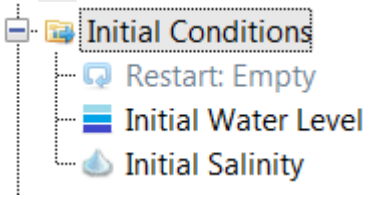


Figure 4.35: *Initial conditions in the* Project *window*

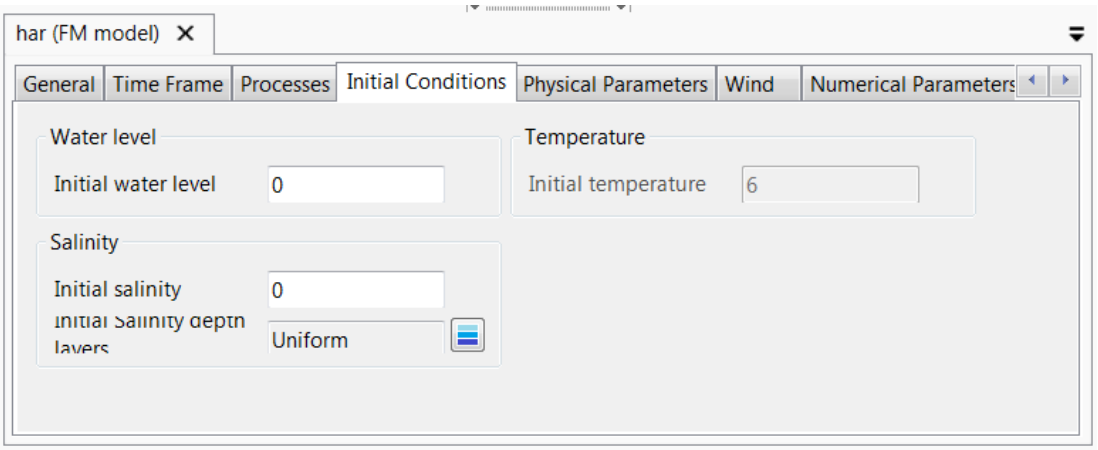


Figure 4.36: *The 'Initial Conditions' tab where you can specify the uniform values and the layer distributions of the active physical quantities.*

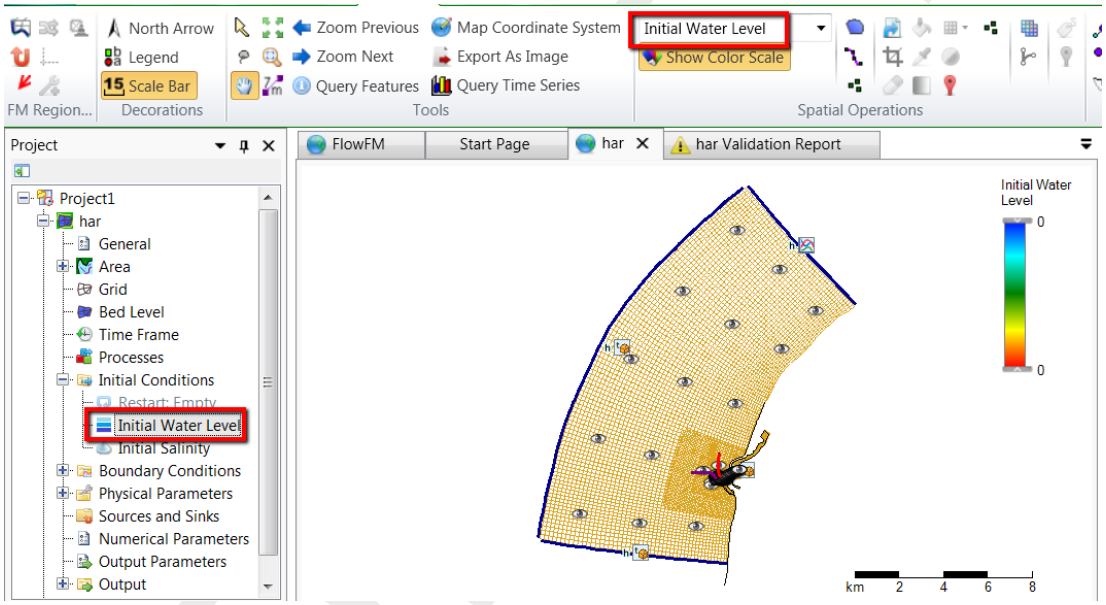


Figure 4.37: *Initial water levels activated in the spatial editor*

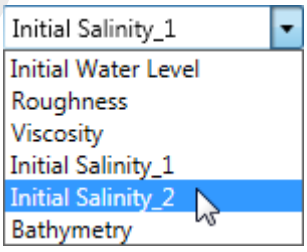


Figure 4.38: *Selecting 3 dimensional initial fields from the dropdown box in the 'Map' ribbon to edit them in the spatial editor*

Instead of defining initial conditions from scratch you can also import fields from a previous computation (using restart files). When you run a model using the Delta Shell GUI which is writing restart files, the restart states will appear in the "Output" folder in the *Project* window (Figure 4.39). For a description of the specification of restart files, please refer to paragraph

section 4.4.12. To use a restart file as initial conditions, apply the right mouse button and select “Use as initial state”. The file will now appear under “Initial Conditions” in the *Project* window (Figure 4.40). To activate the restart file utilize the right mouse button and select “Use restart”. The file will no longer be grey, but is now highlighted in black. The model will now restart from this file. Notice that the simulation still starts at the original *User Start Time*, rather than the time of the restart file. (The restart file only provides initial conditions.)

Figure 4.39: *Restart files in output states folder*

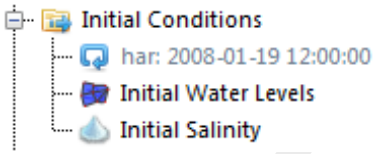


Figure 4.40: *Restart file in initial conditions attribute*

4.4.8 Boundary conditions

Boundary conditions consist of a location specification (‘support points’) and a forcing for that location.

Section 4.4.8.1 describes how support points can be specified in Delta Shell. The boundary forcing can be specified in the boundary data editor.

Section 4.4.8.2 describes the functionality of the boundary data editor. Finally, section 4.4.8.4 describes how the user can get an overview of the boundary locations and forcing in the attribute table.

4.4.8.1 Specification of boundary locations (support points)

In D-Flow FM the boundary locations are defined as ‘support points’ on a polyline (<∗.pli>). The user can add a boundary polyline (<∗.pli>) in the central map by selecting the ‘Add Boundary’ icon in ’FM Region 2D / 3D’ of the ‘Map’ ribbon (see Figure 4.41). The number of individual mouse clicks determines the number of support points on the polyline. The polyline is closed by a double click. Once the polyline is added it becomes visible in the *Project* window under ‘Boundary Conditions’ (see Figure 4.42). The polyline can be edited by the general edit operations in the ‘Map’ ribbon (i.e. add/delete/move individual geometry points or the complete geometry, see Figure 4.43). The name of the polyline (or ‘boundary’) can be edited in the Boundaries tab, which can be opened by double clicking ‘Boundaries’ in the ‘Map Tree’ (see Figure 4.44).

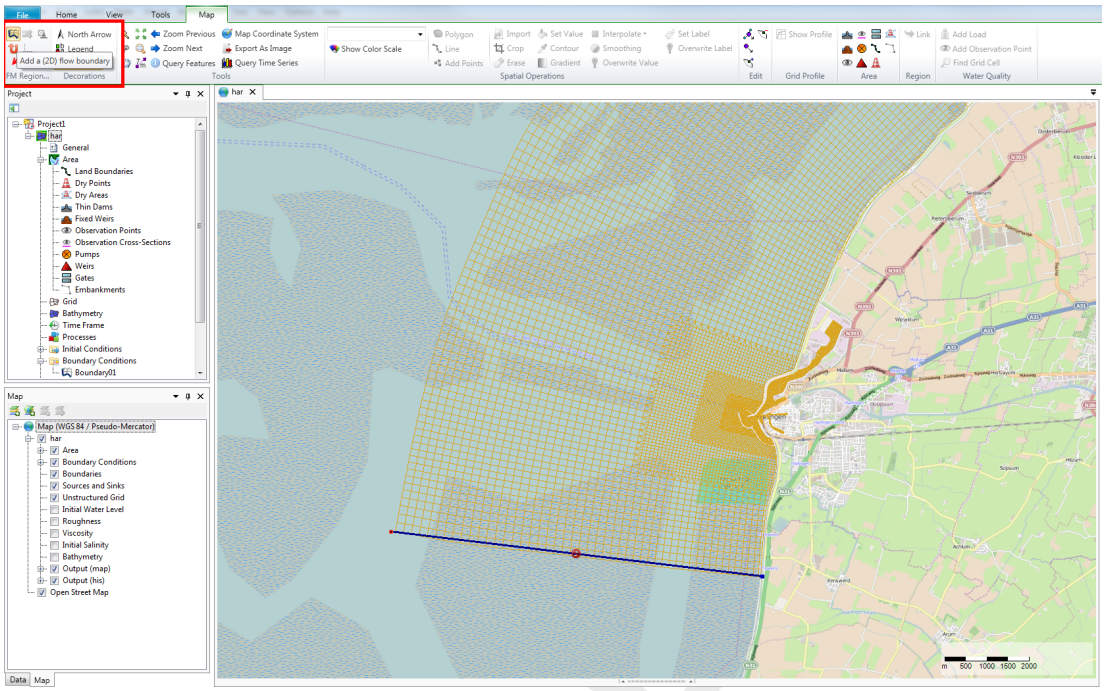


Figure 4.41: *Adding a boundary support point on a polyline in the central map. By double clicking on the polyline in the map, the boundary condition editor will open to edit the forcing data on the polyline.*

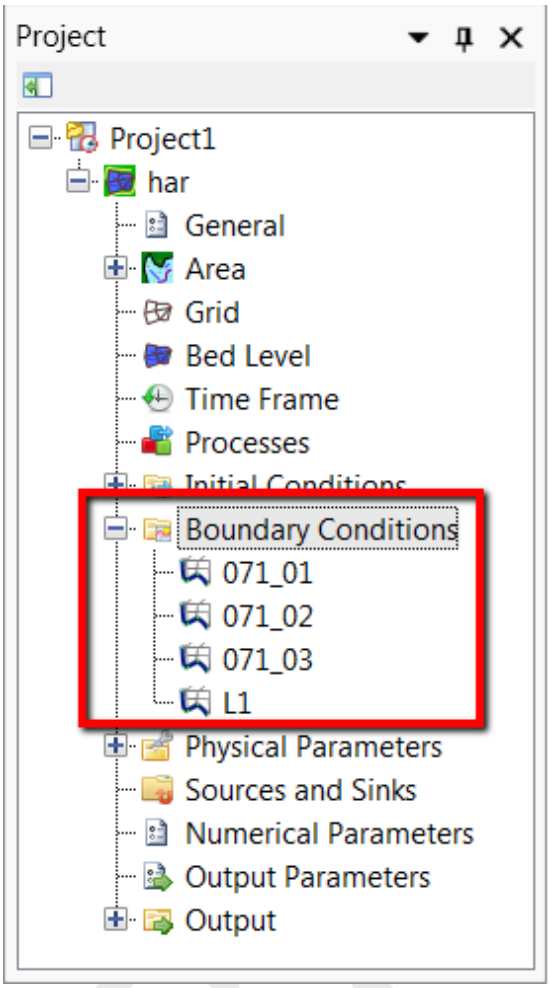


Figure 4.42: *Polyline added in* Project *window under 'Boundary Conditions'. By double clicking on the name of the polyline, the boundary condition editor will open to edit the forcing data on the polyline.*

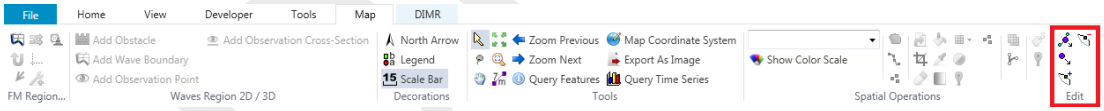


Figure 4.43: *Geometry edit options in* Map *ribbon*

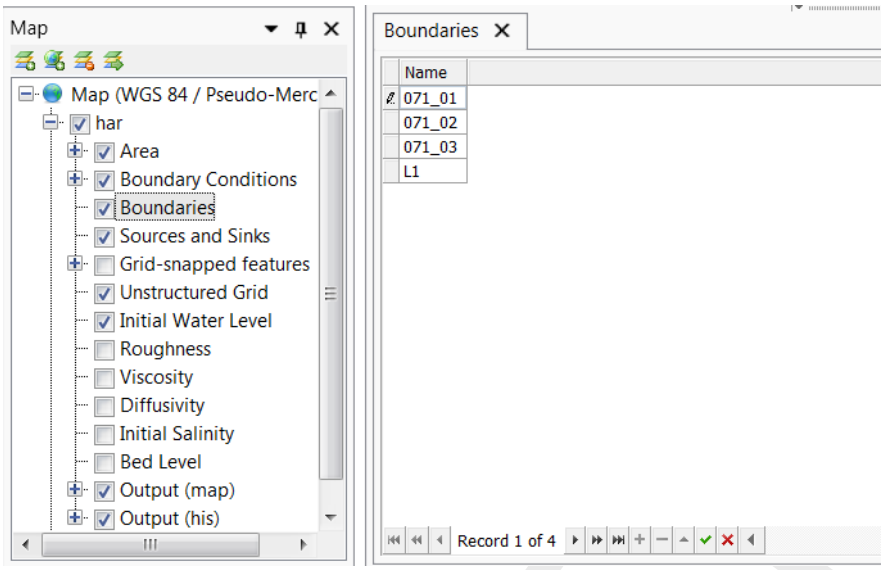


Figure 4.44: *Edit name of polyline/boundary in Boundaries tab*

4.4.8.2 Boundary data editor (forcing)

The boundary condition editor can be opened either by double clicking on the boundary name in the *Project* window (Figure 4.42) or by double clicking the boundary polyline in the map window (Figure 4.41). An overview of the boundary data editor is given in Figure 4.45. This editor can be used to specify the boundary forcing for different quantities (i.e. water level, velocity, discharge, salinity, etc.) corresponding to different processes (i.e. flow, salinity, temperature, tracers). The user can select the processes and quantities in the upper left corner. In the upper centre panel the user can select the forcing function for the selected quantity (i.e. time series, harmonic components, astronomical components or Q-h relation). The upper right corner contains a list of the support points on the polyline. The geometry view shows the location of the selected support point on the polyline (<∗.pli>). In the middle panel are some handy buttons to generate, import and export forcing data. In the lower left panel the user can specify the boundary data for the selected support point. The lower right corner shows the signal of the boundary data. The following sections describe the features of the boundary data editor in more detail.

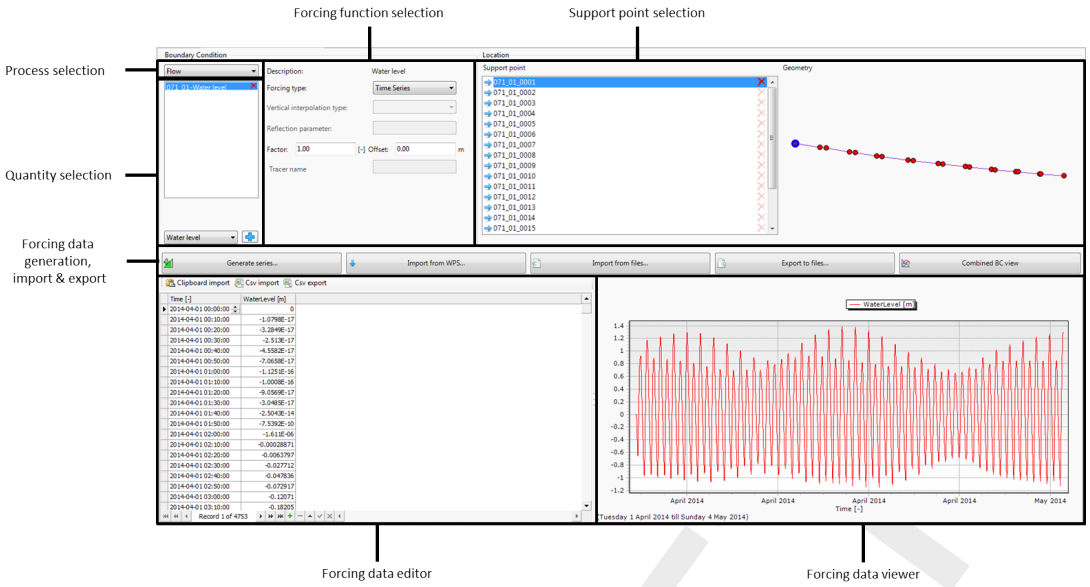


Figure 4.45: *Overview of the boundary data editor*

Process and quantity selection:

Currently, D-Flow FM supports the processes flow, salinity, temperature and tracers (**Note: tracers are not yet fully editable**). The processes available in the boundary condition editor depend on the selected processes in the processes tab (see section 4.4.6). After selecting the process from the dropdown box the user can select one of the corresponding quantities, as illustrated in Figure 4.46. For the process flow the user can choose from five principal quantities: water level, velocity, Riemann invariant, Neuman gradient and discharge. All quantities are specified per support point, except for discharges which are specified per polyline (<∗.pli>). A support point can have multiple forcing quantities of the same type (i.e. water level, velocity, Riemann, Neumann or discharge). These quantities are added up. This can be relevant to add a surge level to an astronomical water level for example. Furthermore, the user can apply normal and tangential velocities as 'add on' quantities. The following combinations of quantities are allowed:

- ◇ Water level + normal velocity
- ◇ Water level + tangential velocity
- ◇ Water level + normal velocity + tangential velocity
- ◇ Velocity (= normal) + tangential velocity
- ◇ Riemann + tangential velocity

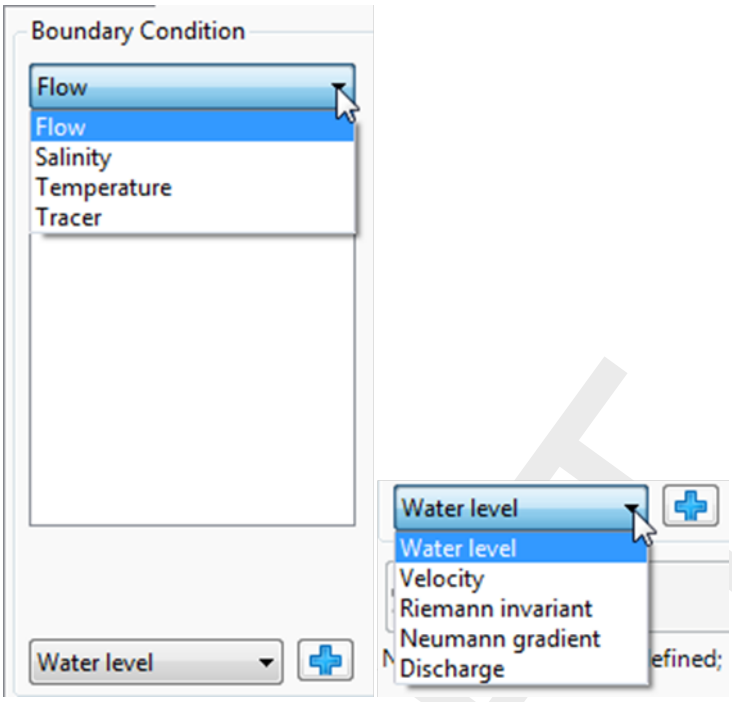


Figure 4.46: *Process and quantity selection in the boundary data editor*

Forcing function selection:

The user can select one of the following forcing functions:

- ◇ Time series
- ◇ Harmonic components
- ◇ Harmonic components + correction
- ◇ Astronomic components
- ◇ Astronomic components + correction
- ◇ Q-h relation (only for water levels)

The next section describes how data can be added for these types of forcing functions.

Add forcing data to a support point or polyline:

By default all support points on the polyline are deactivated. To add forcing data to a support point the user first needs to activate it by pressing the green 'add'-symbol in the list of support points (see Figure 4.47). Consequently, the user can specify the forcing data in the lower left panel based on the selected forcing function. Of which a preview is shown in the lower right panel. **Note: Please note that once a support point containing forcing data is made inactive, all data on the support point is lost!**

The user can choose from the forcing functions time series, harmonic components (+ correction), astronomic components (+ correction) and Q-h relation. Examples of the boundary data specifications for these different forcing functions are given below. **Note: Please note that once the user changes the forcing function of a polyline, all data on the polyline is lost!**

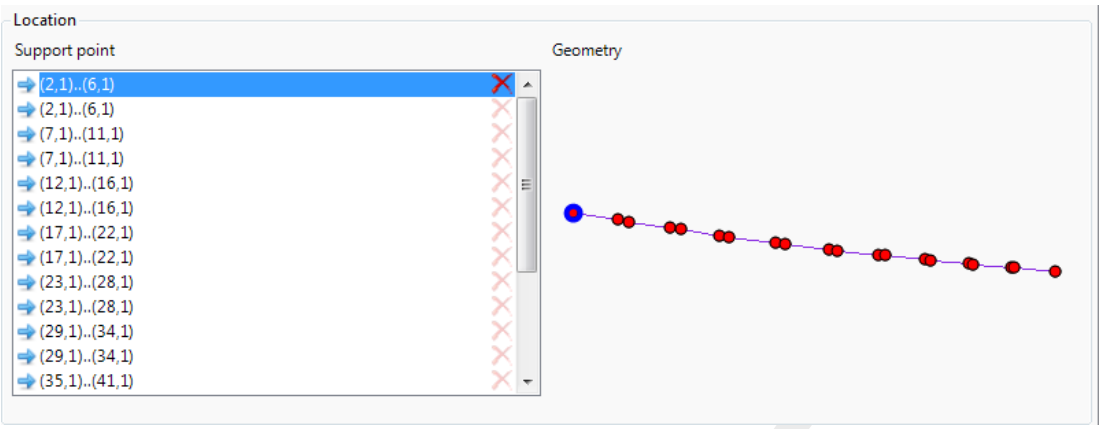


Figure 4.47: *Activate a support point*

Time series

The time format for time series is yyyy-mm-dd HH:MM:SS. There are multiple ways to specify time series for the selected quantity:

◇ Specify the time series step by step in the table (Figure 4.48): the user can add or delete rows with the “plus”- and “minus”-signs below the table.

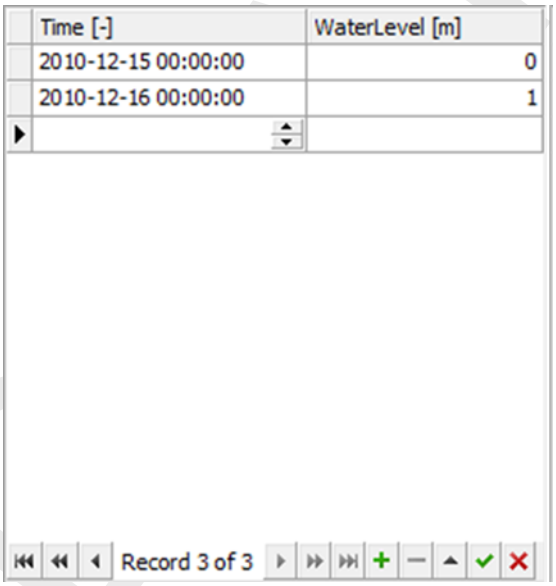


Figure 4.48: *Specification of time series in the boundary data editor (left panel)*

◇ Generate time series using the ‘Generate time series’ button (Figure 4.49): the user can specify start time, stop time and time step.

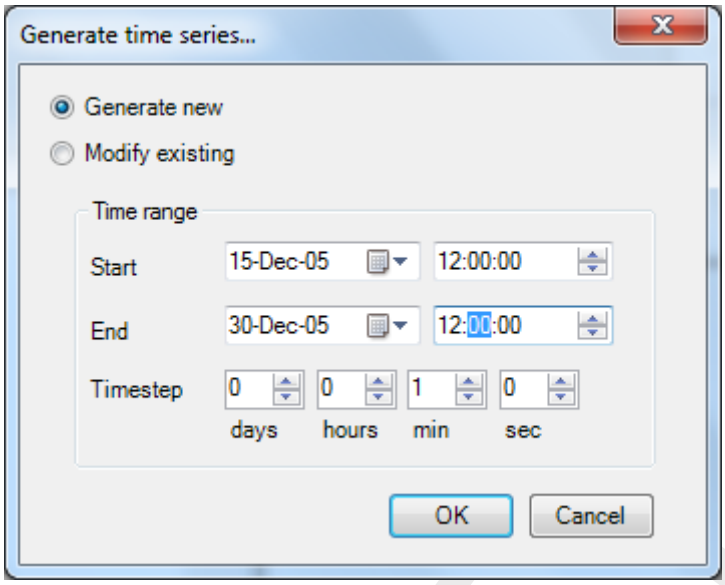


Figure 4.49: *Window for generating series of time points*

◇ Import from csv using the 'Csv import' button: a wizard will open in which the user can (1) select a csv-file (Figure 4.50), (2) specify how data should be parsed into columns (Figure 4.51) and (3) how the values should be parsed and mapped into columns (Figure 4.52).

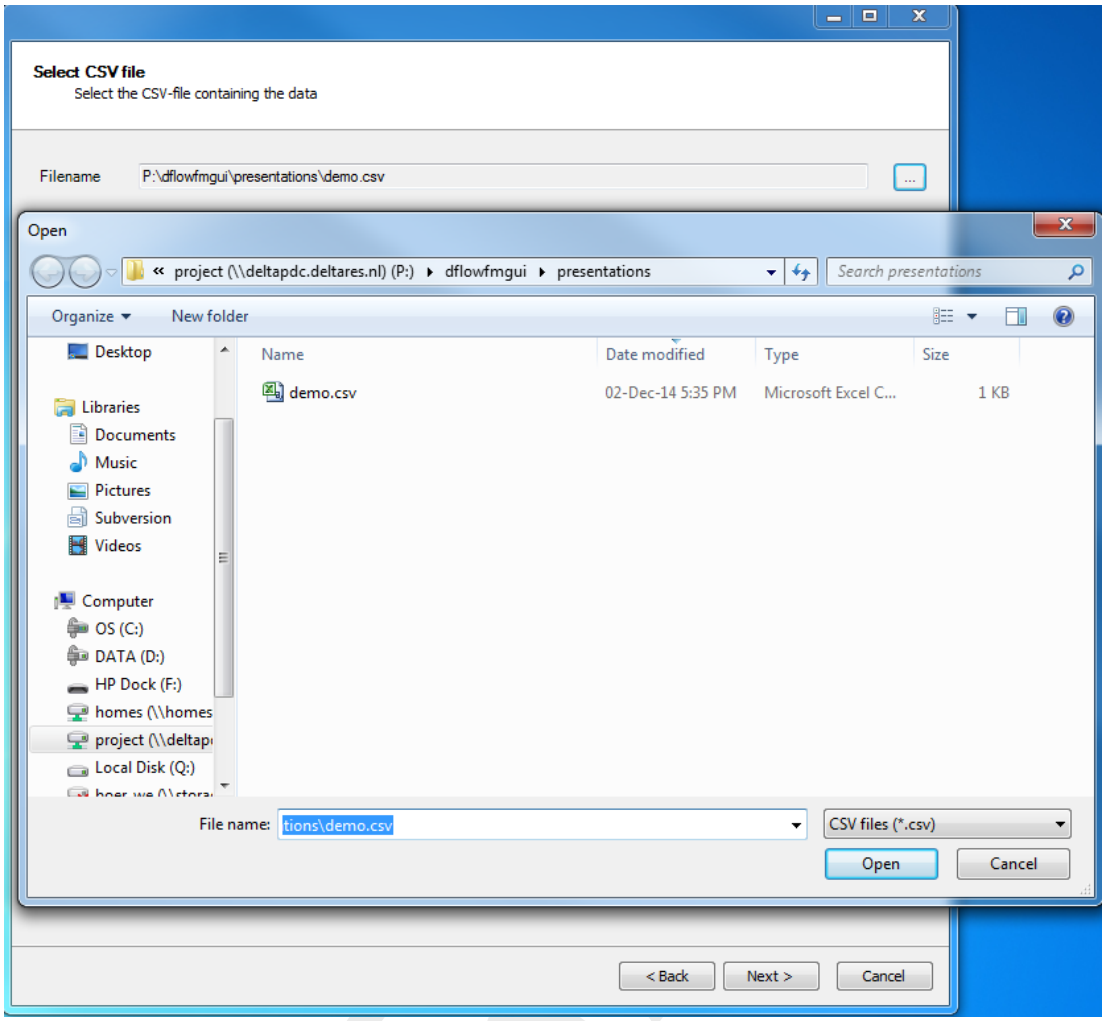


Figure 4.50: *Csv import wizard: csv file selection*

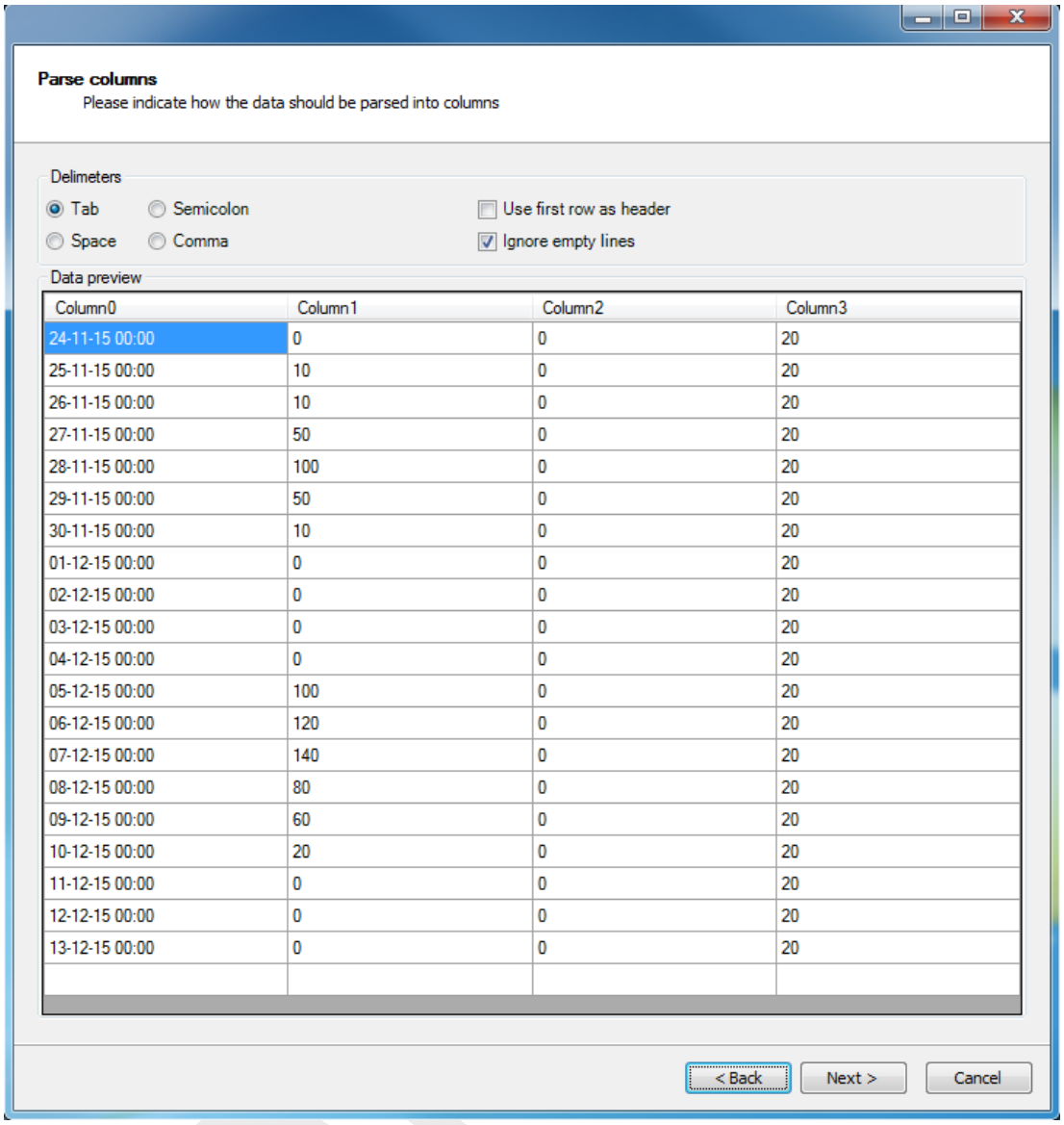


Figure 4.51: *Clipboard/csv import wizard: specification of how data should be parsed into columns*

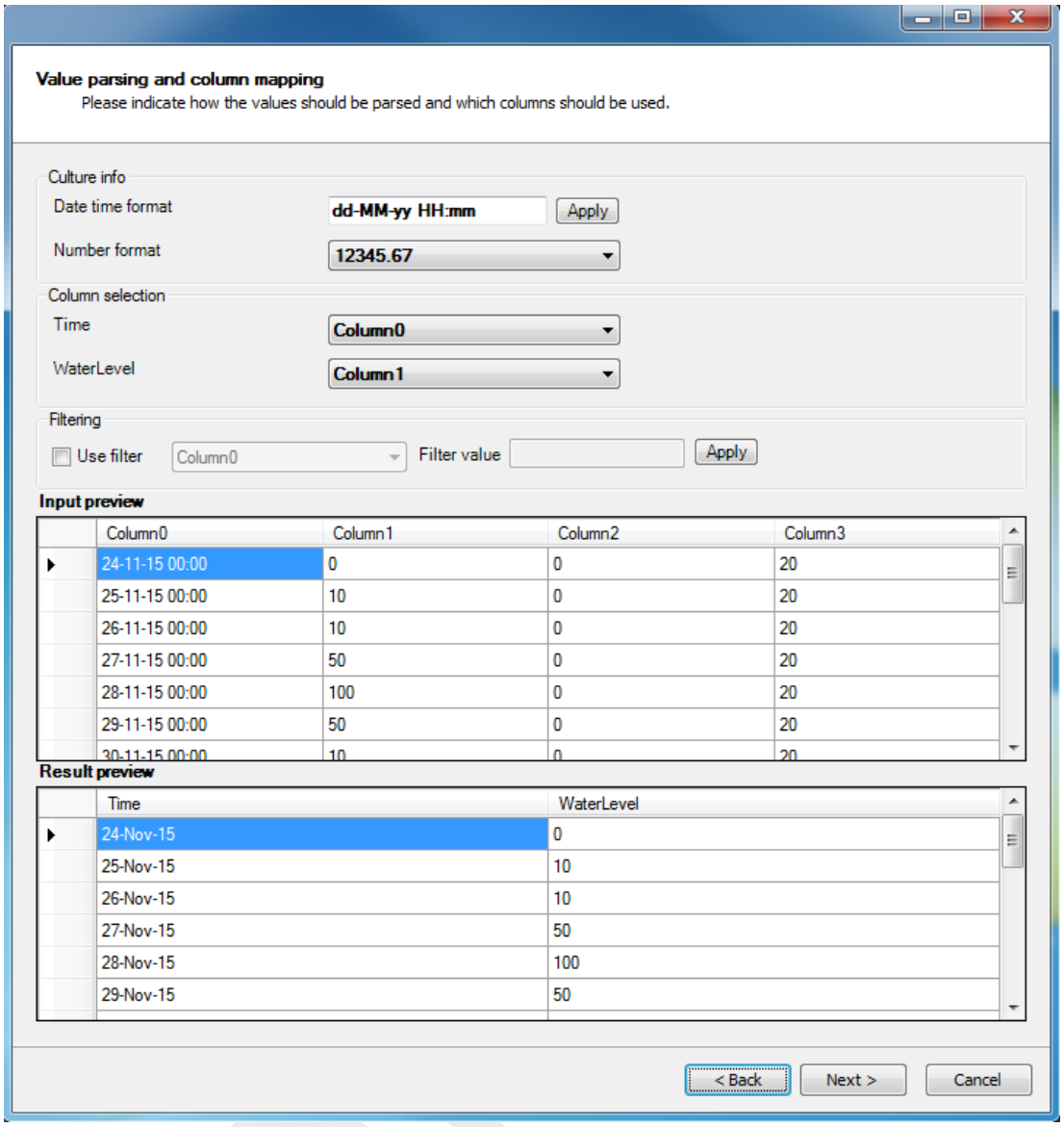


Figure 4.52: *Clipboard/csv import wizard: specification of how values should be parsed and columns should be mapped*

- Import from clipboard using the 'Clipboard import' button: a wizard will open in which the user can specify (1) how data should be parsed into columns (Figure 4.51) and (2) how the values should be parsed and mapped into columns (Figure 4.52).
- Import from Web Processing Service (WPS): with this service the user can download boundary forcing data (for now only water level time series) for a selected support point from an online database (TOPEX/Poseidon 7.2). Upon pressing the button 'Import from WPS ' a window will pop up as depicted in Figure 4.53. Here, the user can specify the time interval and time step for downloading the data. (**Note: Please note that this service is only available with an internet connection!**)

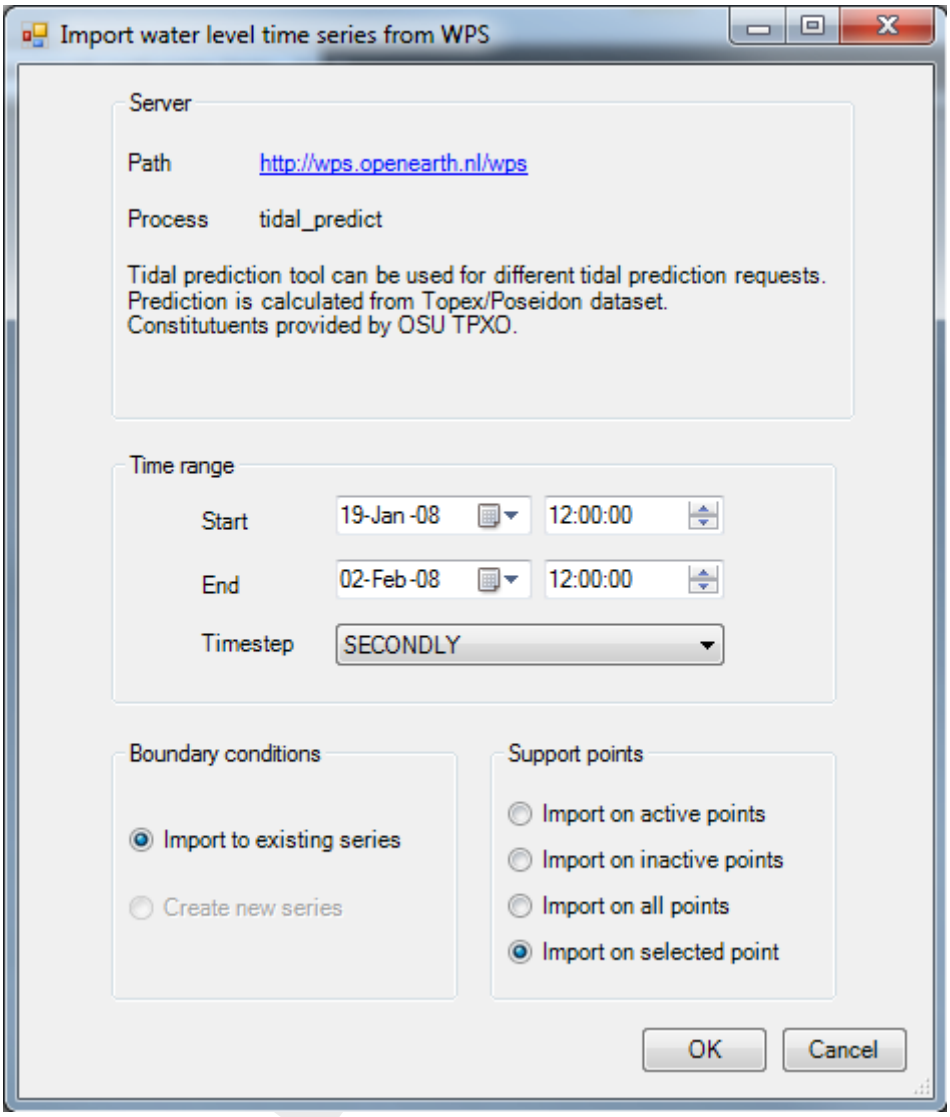


Figure 4.53: *Window for entering input to download boundary data from WPS*

◇ Import from attribute file <∗.bc>: with this button the user can import data from existing boundary conditions <∗.bc> file. The user has three options for importing:

- Overwrite where matching (replace): only overwrites the forcing data for matching support points in the <∗.bc>-file and GUI input.
- Overwrite where missing (extend): only overwrites the forcing data for matching support points in the <∗.bc>-file and in the GUI input that did not contain data.
- Overwrite all: overwrites the forcing data for all support points in the GUI (meaning that the forcing data for non-matching support points is emptied).

Harmonic components

The harmonic components are defined by a frequency, amplitude and phase (see Figure 4.54). By default the forcing data viewer shows the harmonic component for the time frame specified for the model simulation. The options to define the harmonic components are similar to the options for time series:

- ◇ Specify components step by step: the user can add or delete rows with the “plus”- and “minus”-signs below the table.
- ◇ Select (astronomical) components using the ‘Select components’ button (Figure 4.55): the user can select astronomical components which will be transformed in the corresponding frequencies.
- ◇ Import from csv using the ‘Csv import’ button: a wizard will open in which the user can (1) select a csv-file, (2) specify how data should be parsed into columns and (3) how the values should be parsed and mapped into columns.
- ◇ Import from clipboard using the ‘Clipboard import’ button: a wizard will open in which the user can specify (1) how data should be parsed into columns and (2) how the values should be parsed and mapped into columns.
- ◇ Import from attribute file $<*.bc>$: with this button the user can import data from existing boundary conditions $<*.bc>$ file. The user has three options for importing:
  - □ Overwrite where matching (replace): only overwrites the forcing data for matching support points in the bc-file and GUI input.
  - □ Overwrite where missing (extend): only overwrites the forcing data for matching support points in the bc-file and in the GUI input that did not contain data.
  - □ Overwrite all: overwrites the forcing data for all support points in the GUI (meaning that the forcing data for non-matching support points is emptied).

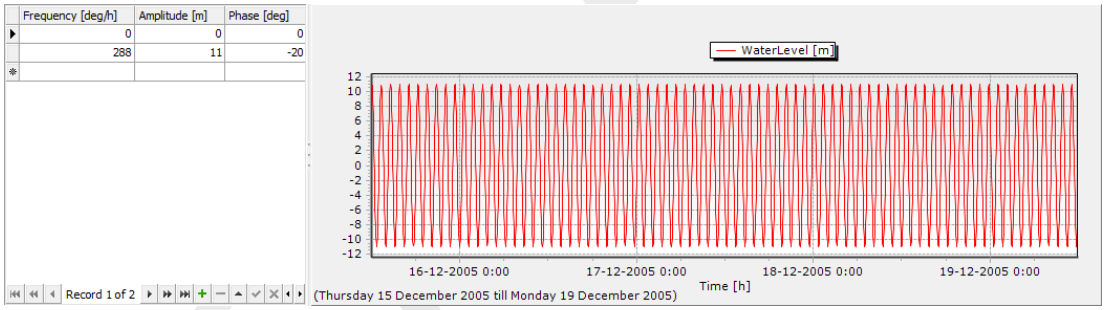


Figure 4.54: *Specification of harmonic components in boundary data editor*

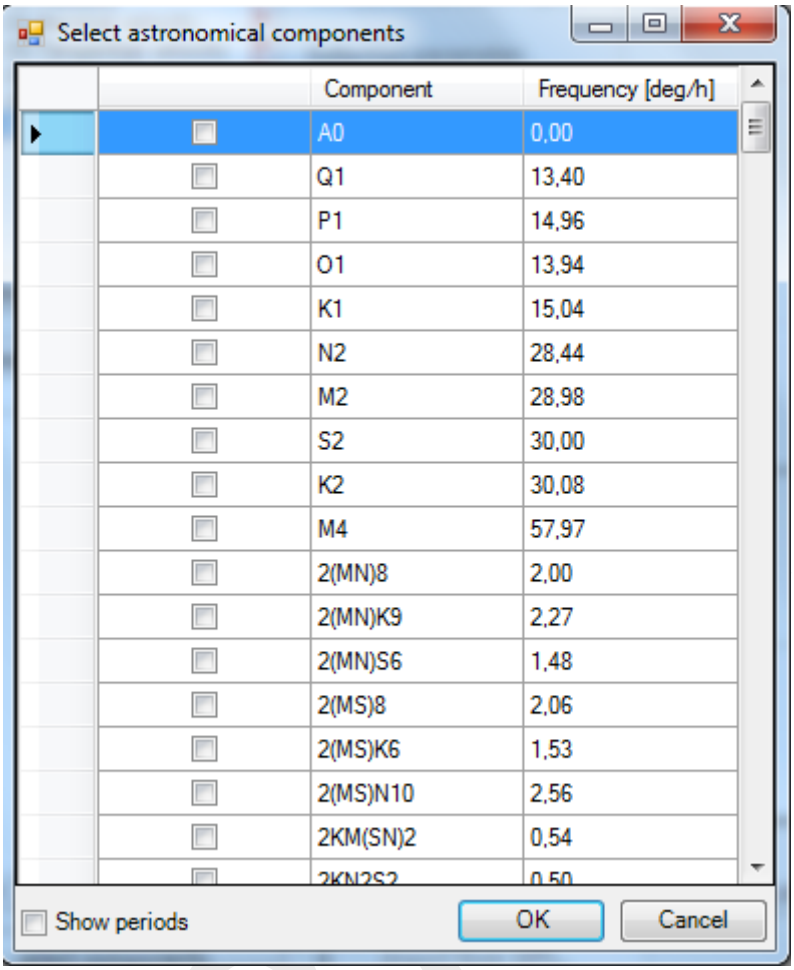


Figure 4.55: *Selection of astronomical components from list (after pressing 'select components')*

Astronomic components

Astronomical components are similar to harmonic components, with the exception that the frequency is prescribed. Instead of specifying the frequency the user can select astronomical components by name. Upon editing the component field in the table the user will get suggestions for components in a list (Figure 4.56). The most frequently used components (A0, Q1, P1, O1, K1, N2, M2, S2, K2 and M4) are put on top of the list, the other components are listed in alphabetic order. Instead of defining each component individually, the user can also make a selection of components by pressing the button 'select components' (Figure 4.55).

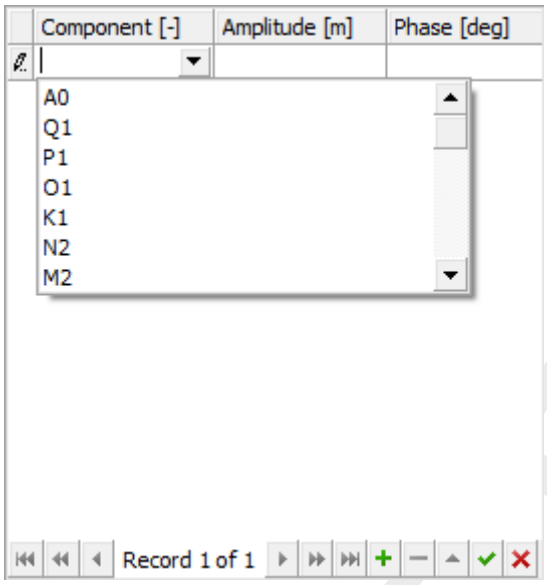


Figure 4.56: *Suggestions for astronomical components in list*

Harmonic or astronomic components with corrections

For calibration purposes the user can combine harmonic or astronomic components with corrections. The corrections are defined in terms of an amplitude (multiplication) factor and a phase difference (see Figure 4.57). This allows the user to keep track of both the original signal and the calibration coefficients. The effects of the corrections on the resulting signal are directly visualized in the forcing data viewer. **Note: Please note that the import functionality is not (yet) working properly for astronomic/harmonic boundary conditions with corrections.**

Component [-]	Amplitude [m]	Phase [deg]
A0	0.2	0
M2	1	55

Figure 4.57: *Editing harmonic/astronomic components and their corrections*

Q-h relation (only for water level)

The user can force the boundary with a Q-h relationship, but only for the quantity water level. This is a relationship between discharge and water level (see Figure 4.58). The relationship can only be prescribed per polyline, not per support point. (**Note: this functionality has not been tested extensively yet**)

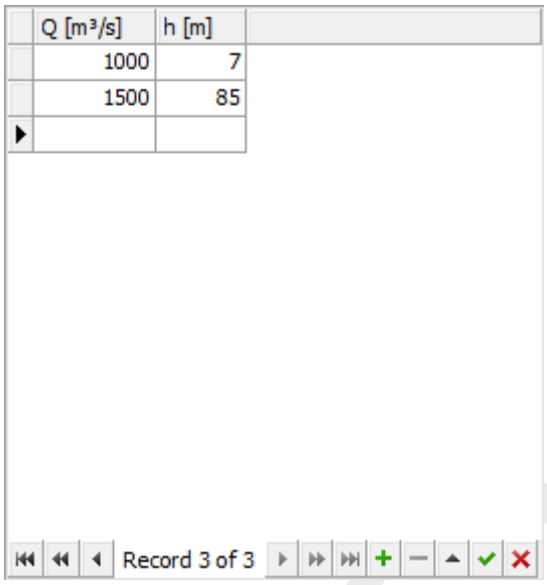


Figure 4.58: *Specification of a Q-h relationship*

Exporting boundary conditions

With the *Export to files* button the user can export all boundary forcing data for the given polyline to a $<*$.bc$>$-file.

4.4.8.2.1 3D boundary conditions

Note: The 3D-implementation is a β-functionality.

When the model is 3D (i.e. the number of layers is larger than 1), the user can specifiy 3 dimensional boundary conditions for relevant quantities such as velocity, salinity, temperature and tracer concentration. The user can choose from vertically uniform or vertically varying boundary conditions (Figure 4.59), where the latter are defined as a percentage from the bed. In the boundary condition editor the layer view will appear (Figure 4.60). Here, the user can specify the vertical positions of the boundary conditions and view their position relative to the model layers. Please note that the number and position of vertical boundary conditions does not necessarily have to match the number and/or the exact position of the model layers. The computational core will interpolate the boundary forcing position to the number of model layers.

In case of non-uniform boundary conditions over the vertical, the number of columns in the boundary forcing data editor will increase correspondingly (see Figure 4.61). In this way the user can specify the conditions for all vertical positions in the same table and view the resulting signals in the forcing data viewer.

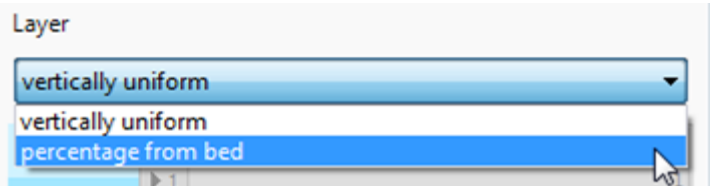


Figure 4.59: *Selection of vertically uniform or varying boundary conditions in case of a 3D model*

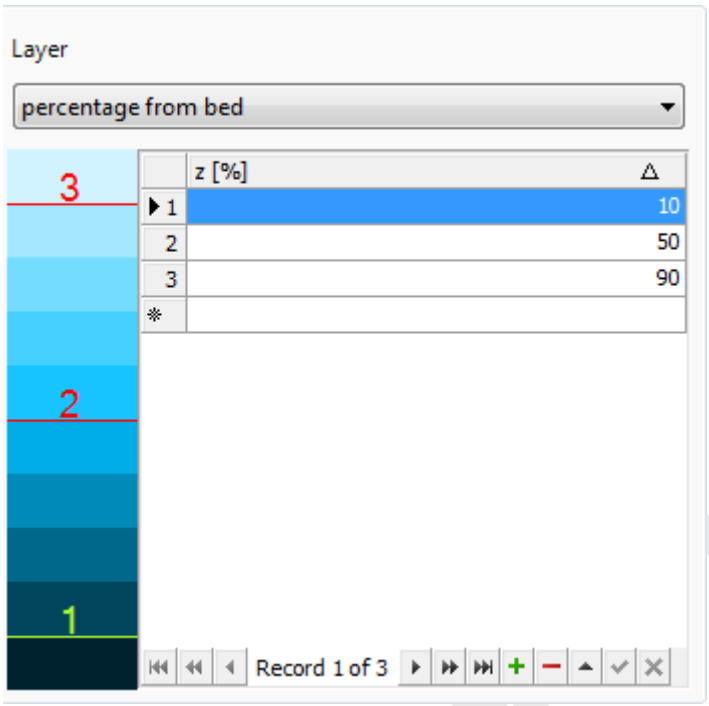


Figure 4.60: *Overview of the layer view component of the boudary conditions editor. In the table the user can edit the vertical positions of the boundary conditions as a percentage from the bed. In the view left of the table, the user can see the vertical positions of the boundary conditions (indicated by number corresponding to the table) relative to the model layers.*

Time [-]	Salinity(1) [ppt]	Salinity(2) [ppt]	Salinity(3) [ppt]
2014-04-11 12:00:00	30	25	20
2014-04-25 12:00:00	30	25	20

Figure 4.61: *Specification of boundary forcing data (in this example for salinity) at 3 positions in the vertical*

View boundary data

All boundary data of the same quantity on a support point can be (pre-)viewed in the boundary data view in the lower-right panel. If multiple signals of the same quantity have been entered, the viewer will show the active signal in red and the total signal of all datasets in grey (see Figure 4.62). In the view the user can zoom-in by dragging a box from top-left to bottom-right and zoom-out by dragging a box from bottom-right to top-left.

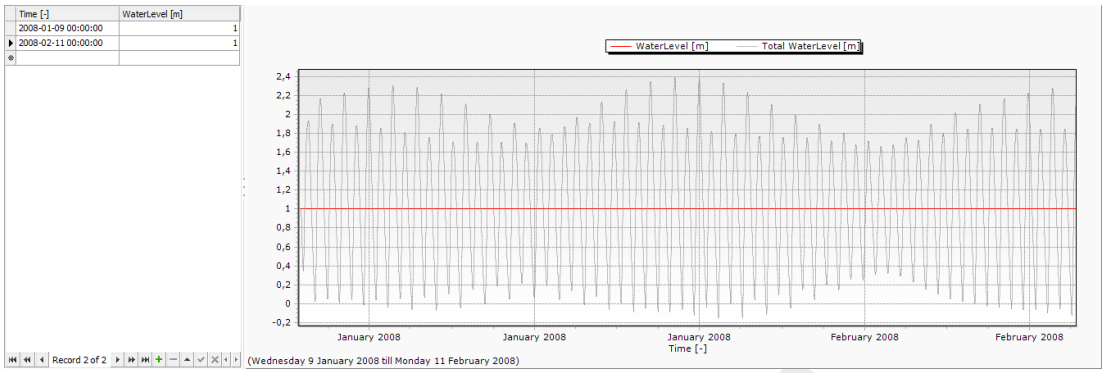


Figure 4.62: *Example of active and total signal for multiple water level data series on one support point*

To inspect multiple quantities at a support point at the same time (for example water level and salinity) the user can use the combined boundary data viewer by pressing the button 'combined BC view'. **Note: This does not work properly yet.**

4.4.8.3 Import/export boundary conditions from the *Project* window

Apart from import and export functionality per individual boundary polyline in the boundary condition editor, the GUI offers the opportunity to import and export boundary locations (<∗.pli>) and forcing (<∗.bc>) on a higher level. Hereto, you have to click the right mouse button on "Boundary Conditions" in the *Project* window and select "import" or "export" (Figure 4.63). Imports and exports on "Boundary Conditions" apply to all the boundary conditions whereas import and exports on a boundary polyline apply only to that boundary condition.

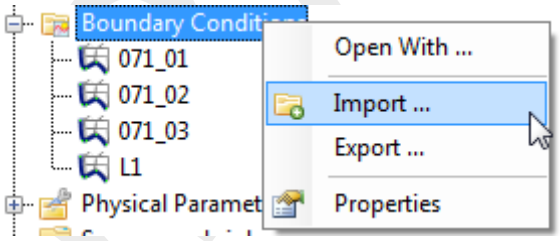


Figure 4.63: *Importing or exporting boundary features — both polylines <∗.pli> and forcing <∗.bc> — from the* Project *window using the right mouse button*

Import and export polylines

Upon importing a <∗.pli>-file with the same filename and the same polyline name(s) as the existing polyline names in the GUI, the existing polyline(s) will be replaced and all forcing data thereon will be deleted. Upon importing a polyline(s) with a different name(s), the polyline(s) will be added to the *Project* window without any forcing data on it/them. The user will be asked to import the data "as is" or to perform a coordinate transformation before the import (see Figure 4.64).

Alternatively, the user can exported created polylines to a <∗.pli>-file. Upon export the user will be asked to export the data "as is" or to perform a coordinate transformation before the export (see Figure 4.64).

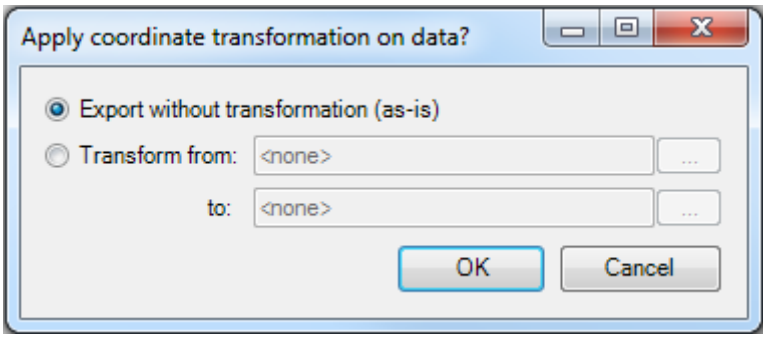


Figure 4.64: *Import or export a <∗.pli>-file as is or with coordinate transformation.*

Import and export boundary forcing data

Similar to the polylines, you can import and export boundary forcing data from/to a <∗.bc>-file. To import forcing data the existence of a polyline with at least one matching support point is a prerequisite. Upon importing <∗.bc> data you can select which quantities and forcing types from the <∗.bc>-file should be imported and with which overrwrite options (see Figure 4.65). Similarly,you can export boundary forcing data. As an additional exporting feature you can select whether you would like to export: 1) all forcing data into one file, 2) as separate files per boundary, 3) as separate files per process or 4) as separate files per quantity (see Figure 4.66).

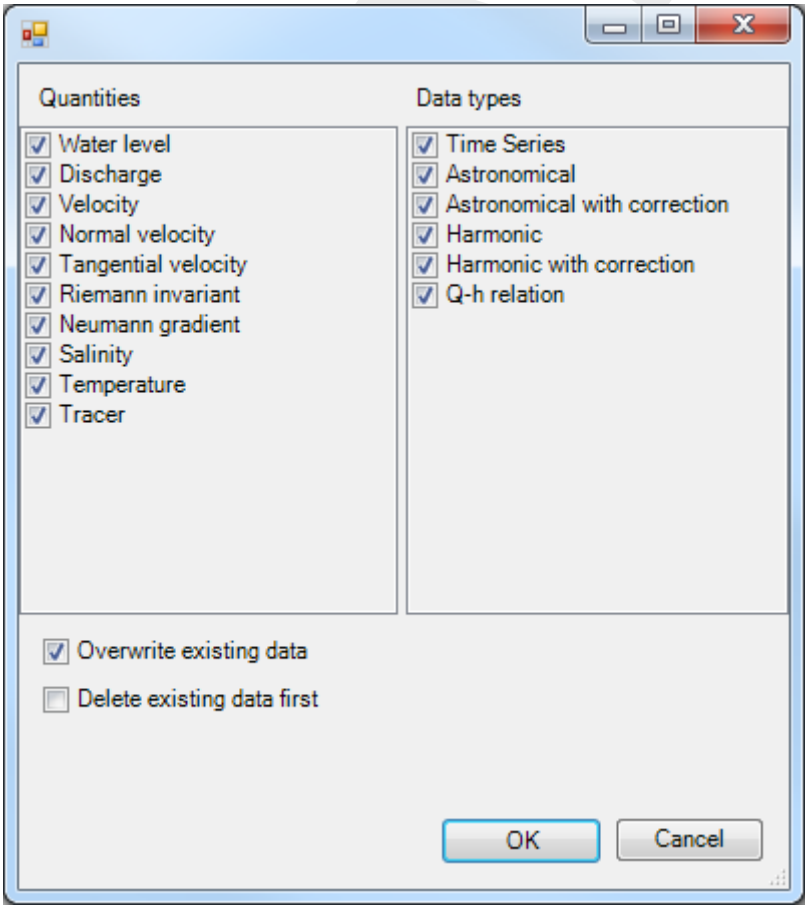


Figure 4.65: *Import or export a <∗.pli>-file as is or with coordinate transformation.*

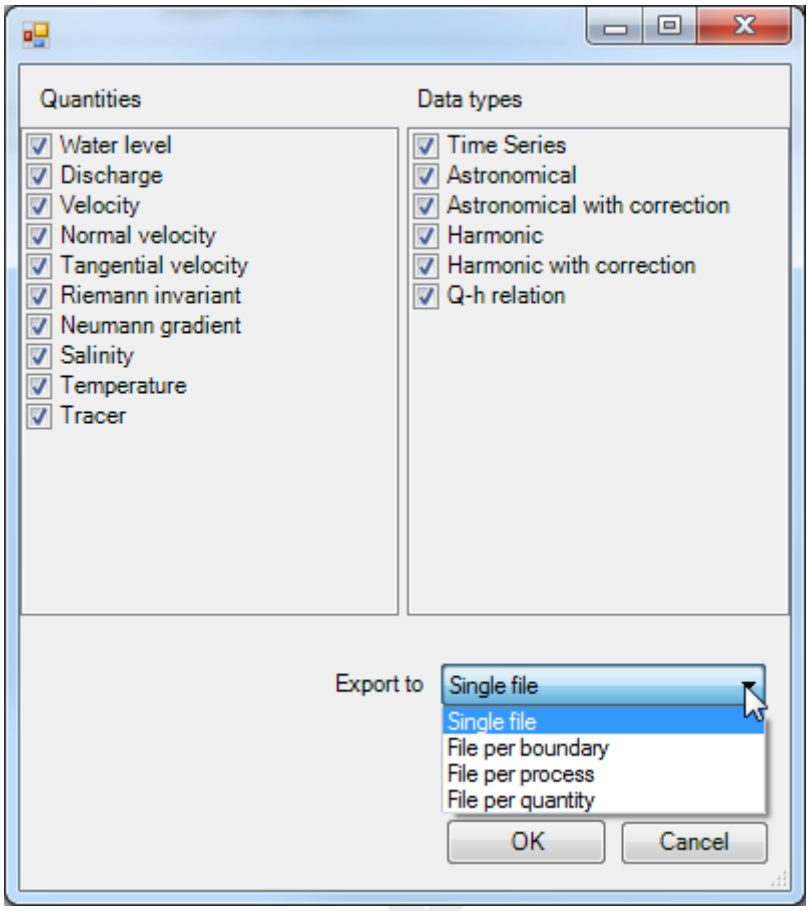


Figure 4.66: *Import or export a *.pli file as is or with coordinate transformation.*

4.4.8.4 Overview of boundary conditions in attribute table (non-editable)

The attribute table of the boundary conditions gives an overview of all specified boundary polylines and corresponding forcing (see Figure 4.67). This attribute table can be opened by double clicking 'Boundary Conditions' from the project or map tree. Most of the features in the attribute table are non-editable, except for the optional (multiplication) factor and offset per quantity per polyline. With these settings you can integrally multiply all data on a polyline with a factor and/or add an offset to it.

Boundary Conditions

Boundary	Quantity	Forcing type	Factor	Offset
071_01	WaterLevel	Time Series	1	0
071_01	Salinity	Time Series	1	0
071_02	WaterLevel	Time Series	1	0
071_02	Salinity	Time Series	1	0
071_03	WaterLevel	Harmonic	1	0
071_03	Salinity	Time Series	1	0
L1	Discharge	Time Series	1	0
L1	Salinity	Time Series	1	0

Figure 4.67: *Overview of all boundary conditions in attribute table*

4.4.9 Physical parameters

The physical parameters attribute is used to set all physical parameters of your model. When it is expanded in the *Project* window, it shows three attributes; roughness, viscosity and wind.

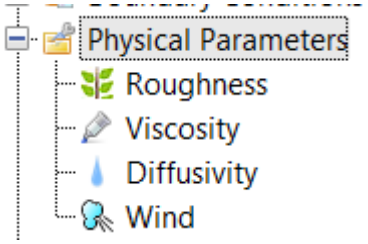


Figure 4.68: *The physical parameters in the* Project *window*

4.4.9.1 Constants

In the *Physical Parameters* tab, under *Constants*, the user can adjust the value of *Gravity* [m/s^2] and *Default water density* [kg/m^3].

4.4.9.2 Roughness

Bed roughness can be specified as a uniform value or as a coverage (e.g. a spatially varying field). The uniform values as well as the roughness formulation (i.e. Chézy, Manning, White-ColeBrook or Z_0) can be edited in the 'Physical Parameters' tab, which opens upon double clicking 'Roughness' in the *Project* window (Figure 4.69). **Note:** The latter is not yet working. In this tab you can also specify the linear friction coefficient, linear friction Umod, wall behaviour (free slip or partial slip) and wall ks for partial slip.

In case of spatially varying bed roughness you can double click the quantity in the *Project* window or select it from the dropdown box in the *Spatial Operations* ribbon (Figure 4.70). Then the spatial editor is activated, which you can use to edit spatially varying fields. For more information on how to use the spatial editor you are referred to Appendix F.

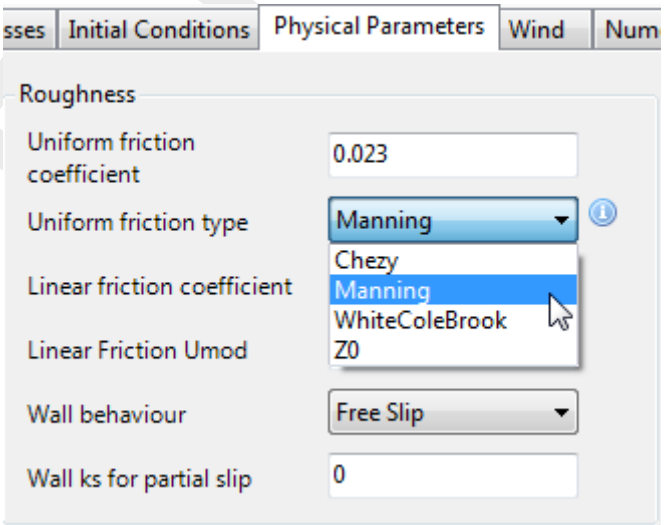


Figure 4.69: *The section of the 'Physical Parameters' tab where you can specify roughness related parameters and formulations.*

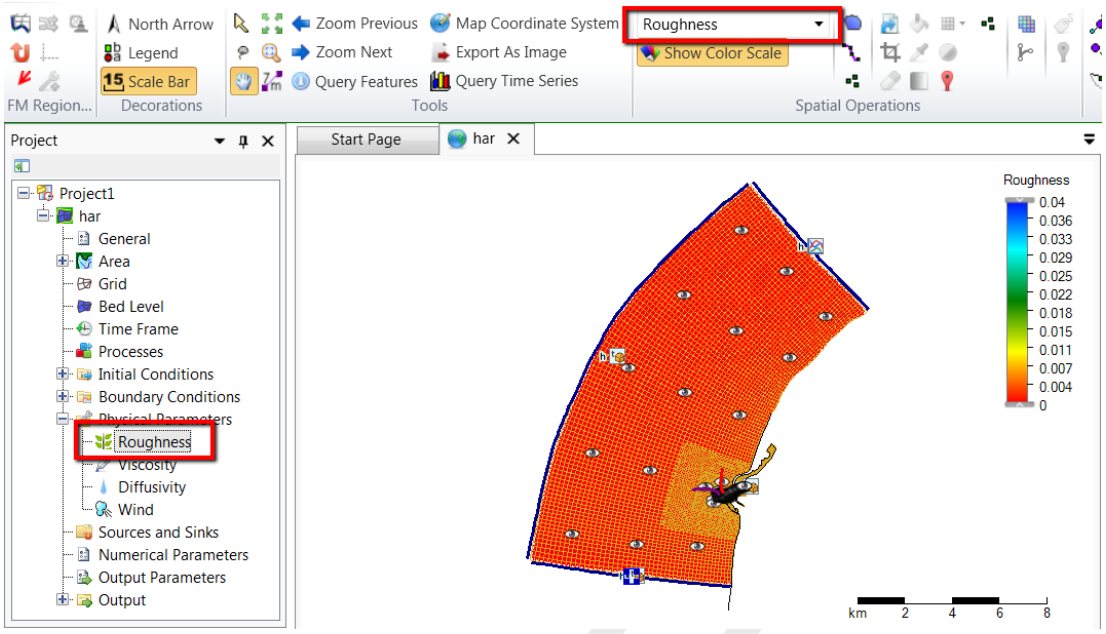


Figure 4.70: *Roughness activated in the spatial editor to create/edit a spatially varying field*

4.4.9.3 Viscosity

The eddy viscosity can be specified as a uniform value or as a coverage (e.g. a spatially varying field). In the 'Physical parameters' tab you can specify the uniform values for the horizontal and vertical (in case of 3D simulations) eddy viscosity and diffusivity (Figure 4.71).

In case of spatially varying viscosity you can double click the quantity in the *Project* window or select it from the dropdown box in the *Spatial Operations* ribbon (Figure 4.72). Then the spatial editor is activated, which you can use to edit spatially varying fields. For more information on how to use the spatial editor you are referred to Appendix F.

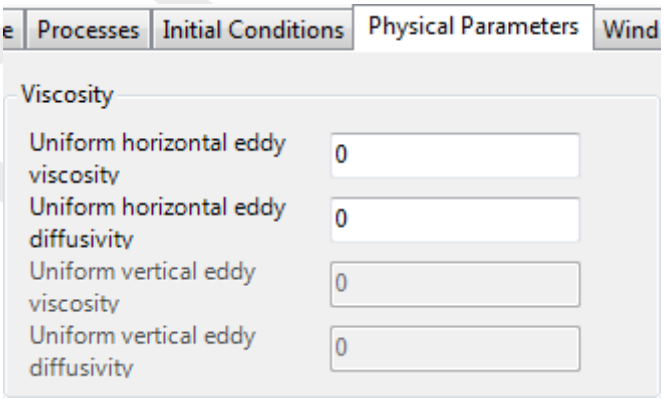


Figure 4.71: *The section of the'Physical Parameters' tab where you can specify (uniform) values for the horizontal and vertical eddy viscosity and diffusivity.*

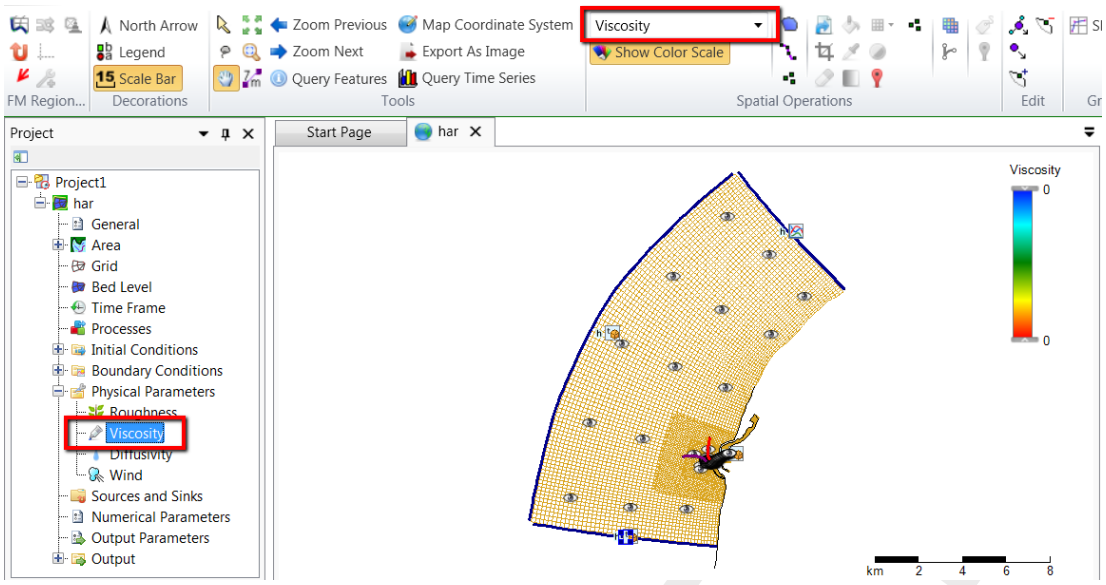


Figure 4.72: *Viscosity activated in the spatial editor to create/edit a spatially varying field*

4.4.9.4 Wind

All relevant parameters, described in chapter 11 can be adjusted in the following sub-tab.

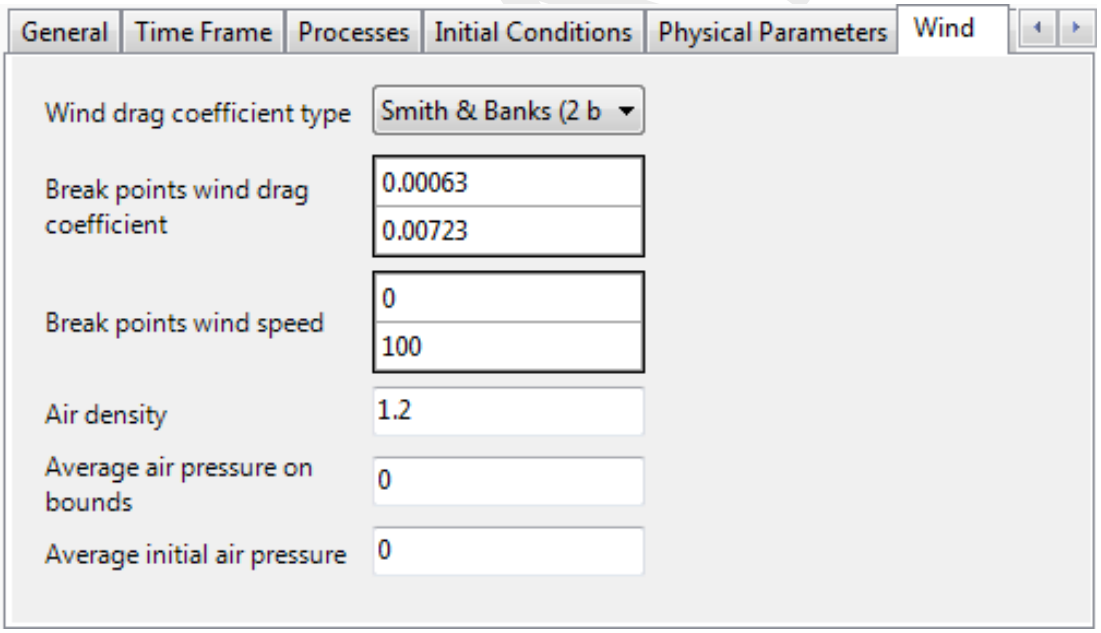


Figure 4.73: *Overview of parameters in sub-tab Wind*

4.4.9.5 Heat Flux model

The Heat flux model, described in chapter 10, needs only specification of which model to use. See the drop-down selection in Figure 4.34.

4.4.9.6 Tidal forces

The Tide generating forces, described in section 7.10, can be enabled in the *Processes* tab, see Figure 4.34.

4.4.10 Sources and sinks

Sources and sinks (or: intake/outfall facilities) can be used to add/extract a discharge to/from the model or to redistribute water and constituents (such as temperature and salinity) within the model. Sources and sinks consists of a location (defined by a $<*$.pli$>$-file) and time series describing the discharges (defined by a $<*$.tim$>$-file). All the hydrodynamical considerations behind sources and sinks are discussed in section 7.8.

Sources and sinks locations

Sources and sinks can be added to the model using the corresponding icon from the *Map* ribbon (Figure 4.74). When the sources/sinks icon is active you can add them as polyline elements in the central map using the left mouse button. Each polyline element is closed by double clicking the left mouse button.

Note: Please note that the length of the ploy line elements is not taken into account in the handling of sources and sinks (e.g. it is modeled as an instant redistribution of water and constituents without delays and friction losses).

Polyline elements starting outside the model domain and going inward are sources and, vice versa, polyline elements starting inside the model domain and going outward are sinks. Polyline elements starting and ending within the model are intake/outfall type of discharges. The drawing direction determines the direction of the discharge indicated by an arrow (Figure 4.75). In case of a source the direction of the last polyline element determines the direction of flow momentum into the model.

Note: The 'reverse' line option — to switch the discharge direction without having to redraw the source/sink — is not implemented.

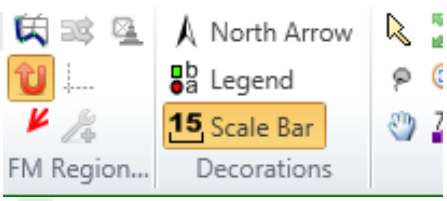


Figure 4.74: *Activate the sources and sinks editing icon in the* Map *ribbon*

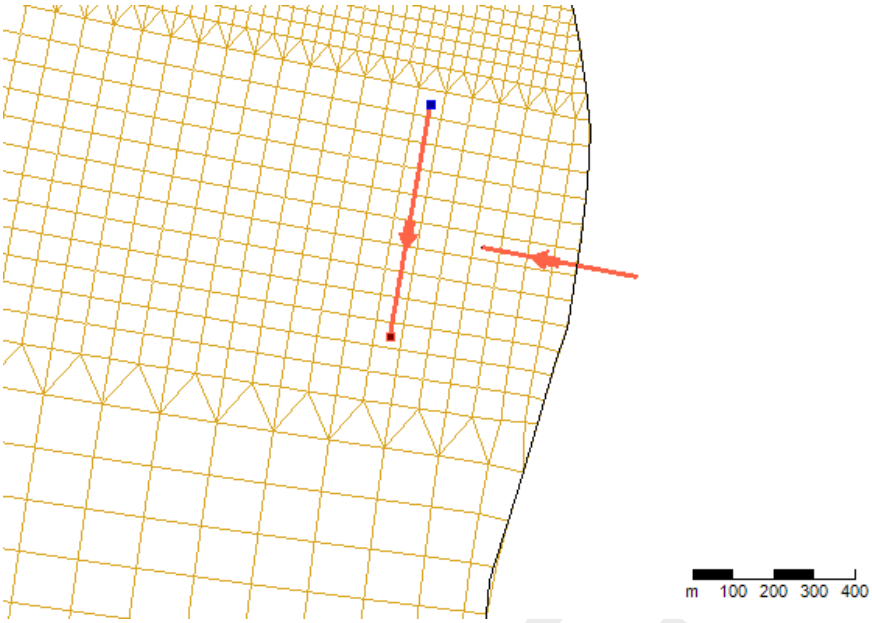


Figure 4.75: *Add sources and sinks in the central map using the 'Sources and sinks' icon.*

Sources and sinks time series

After drawing the sources/sinks locations in the central map, they appear under 'Sources and sinks' in the *Project* window (Figure 4.76). Either by double clicking the sources/sinks in the *Project* window or the line element in the central map, you can open the sources and sinks editor (Figure 4.77). In this editor you can specify the discharge time series as well as the corresponding constituents (for example salinity and temperature, depending on the active physical processes). The time series of water discharges are always defined as absolute values. For the time series of constituents the following applies:

- For sources the constituent time series are absolute values
- For sinks the constituent time series are determined by the modeled values
- For sources and sinks (intake/outfall relationships) the constituent time series are the excess values (e.g. on top of the modeled values)

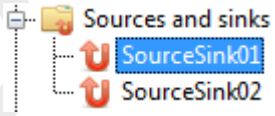


Figure 4.76: *Sources and sinks appearing in the* Project *window*

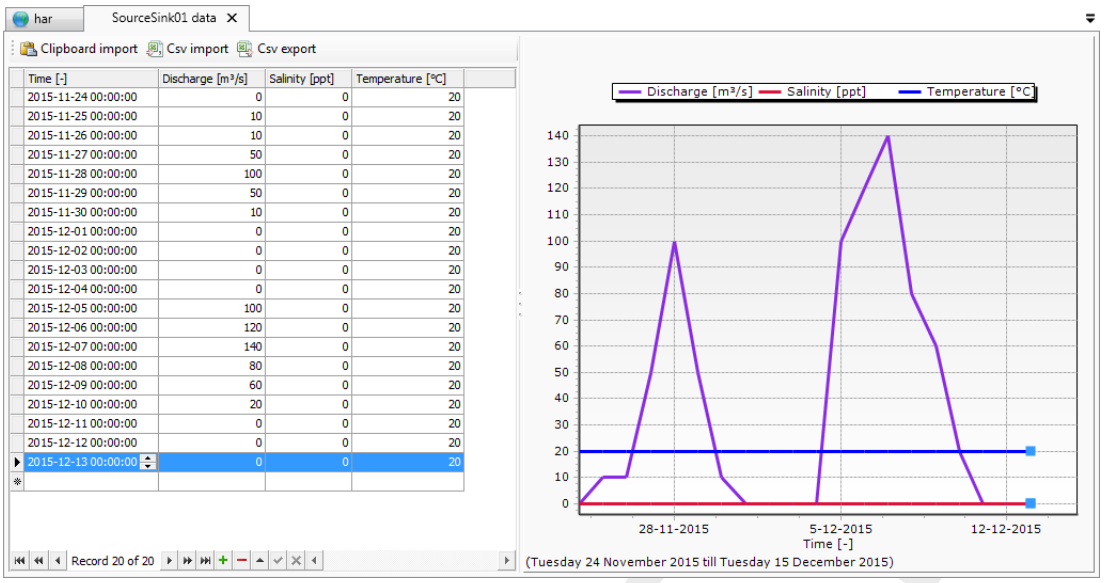


Figure 4.77: *Specifying time series for sources and sinks in the sources and sinks editor*

4.4.11 Numerical parameters

In the numerical parameters tab, all numerical parameters related to your computation can be set. The parameters that can be set are described in Table 4.1.

4.4.12 Output parameters

Model runs can produce various types of output files. The **Map** window shows the two most-used types: map output and his(tory) output (Figure 4.78).

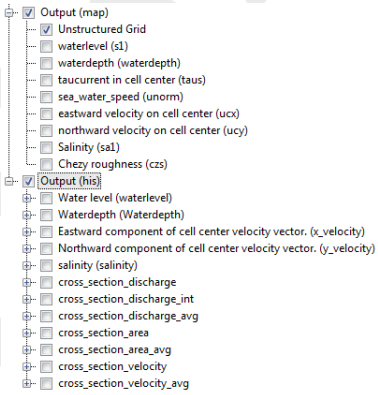


Figure 4.78: *Output parameters tab*

The history file contains output on specific locations: time series data on observation points (section 4.4.2.2), cross-sections (section 4.4.2.3) and structures (Sections 4.4.2.8 – 4.4.2.10). The map file contains flow quantities on the entire grid at specified time intervals, and can later be used for 2D and 3D visualizations of entire flow fields. The map file can typically turn out much larger than the history file, and it is therefore advised to use larger time intervals for map files than for his files.

Additionally, three more types of output can be requested: restart files, WAQ output, and timing statistics. Restart files are a special type of map file that can later be used as initial

Table 4.1: *Overview and description of numerical parameters*

Parameter	**Description**
Max Courant number	The size of the time step, Δt, is computed by the computational kernel automatically, each time step by means of the maximum tolerable Courant number. By default, this value is 0.7.
Wave velocity fraction	The wave velocity fraction is related to stability of the computation. By using this fraction, the velocity of the flow is enlarged with the wave velocity times this fraction. The value of this fraction is 0.1 by default.
Advection type	This key depicts the ID of the advection scheme. By default this value is 33.
Water depth limiter type	The limiter type for waterdepth in continuity equation: 0 means no limiter (default), 1 is the minmod method, 2 the Van Leer method, 3 the Koren method and 4 the monotone central method.
Advection velocity limiter type	The limiter type for the cell center advection velocity: 0 means no limiter, 1 the minmod method, 2 the Van Leer method, 3 the Koren method and 4 the monotone central method (default).
Salinity transport limiter type	The limiter type for salinity transport: 0 means no limiter, 1 the minmod method, 2 the Van Leer method, 3 the Koren method and 4 the monotone central method (default).
Solver type	Specification of the Poisson equation type solver for the pressure: 1 = sobekGS_OMP, 2 = sobekGS_OMPthreadsafe, 3 = sobekGS, 4 = sobekGS + Saadilud (default), 5 = parallel/global Saad, 6 = parallel/Petsc, 7 = parallel/GS.
Max degree in Gaussian elimination	The maximum degree in the Gauss elimination, part of the pressure solver. This key has the value 6 by default.
Thin dike scheme	Or: fixed weir scheme. 0: none, 1: compact stencil, 2: whole tile lifted, full subgrid weir + factor.
Thin dike contraction	Or: fixed weir contraction. This is the fixed weir flow width contraction factor, being the flow width = flow width times the fixed weir contraction.
Boundary smoothing time	Fourier smoothing time on waterlevel boundaries (s).
Linear continuity	Default 0; Set to 1 for linearizing d(Hu)/dx; link to AdvecType.
Threshold for drop losses	Apply droplosses only if local bed slope is larger than this specific value.
Theta of time integration	Compromise in explicit/implicit time integration.
Downwind cell H on Q boundaries	Specifies the way of the upstream discharge boundary: 0 is original hu on qbnd, 1 is downwind hs on qbnd

states in other runs. Restart files contain several additional flow quantities and are written at specified intervals into one file per each restart time. Typically, one selects a large restart interval in order not to waste disk space. WAQ output files are written by D-Flow FM and are intended to be used as input files to subsequent D-Water Quality runs. More details on water quality modelling can be found in chapter 17. Timing statistics can be produced both in the diagnostics file (via *Statistics output interval*, for viewing basic simulation progress), and in a separate detailed timings file (via *Timing statistics output interval*, for detailed performance analysis).

When double clicking the output parameters tab in the *Project* window, the output parameters sub-tab of the settings tab is highlighted in the central map. All parameters related to the output of your model run are specified here (Figure 4.79). The most common output parameters to set are the parameters related to the water quality files, history files, map files and restart files.

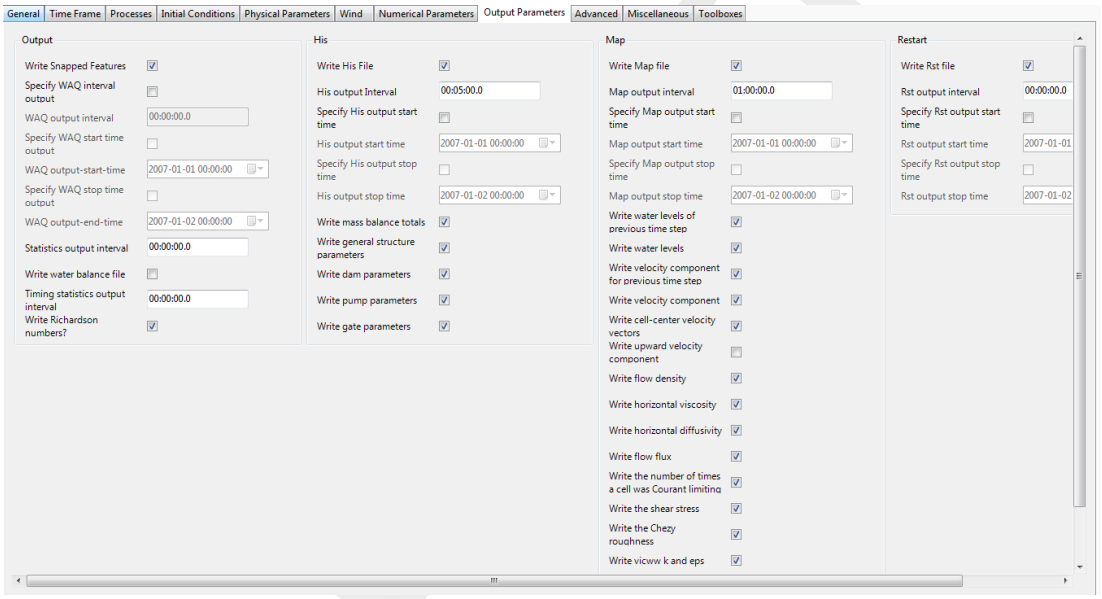


Figure 4.79: *Overview output parameters tab*

For each of the three files (water quality, history, map and restart) the input parameters are specified in the same manner (Figure 4.79). Taking his output as an example: when *Write His File* is checked, the output of history file is enabled. *His Output Interval* determines the interval at which the output data is stored in the file; the smaller the interval, the more detailed the output and the larger the file. By default, history output is written from the start until the end of the simulation. Optionally, output can be restricted to a certain time window: to specify different output start and/or stop times, check the box next to *Specify His Output Start Time* and/or *Specify His Output Stop Time* and enter the desired times next to the parameters *His Output Start Time* and *His Output Stop Time*.

When *Write Snapped Features* is activated, then shape files with snapped data will be generated for all quantities, such as fixed weirs and thin dams. For example, for fixed weirs a crest height is specified at both end of a fixed weir polyline. In between linear interpolation is applied, which can be checked via these shape files.

Below, the various output options are described in greater detail. *There is a special requirement on the output parameters for His and Restart files that the* Output Interval*,* Output Start Time *and* Output Stop Time *must be integer multiples of* User Time Step*. Optionally, the*

*interval (*Output Stop Time−Output Start Time*) should be an integer multiple of* User Time Step*.*

Write his file

His Output Interval	Time interval for history time series.
His Output Start/Stop time	Restrict history output to a specified time window.
Write mass balance totals	Enable detailed mass balance time series output in the his file.
Write (misc.) structure parameters	Enable time series output across general structures, pumps, weirs and gates in the his file.

Write map file

Map Output Interval	Time interval for map field time series.
Map Output Start/Stop time	Restrict map output to a specified time window.
Specific Map Output Times	File containing specific time values at which to produce additional map output snapshots. It the value is not integer, it is firstly set to the least integer larger than or equal to this value. If the computational time does not hit the specified time value, the output snapshot is chosen to be at the time closest to the specified time value.
Write water levels, etc.	Several optionals for enabling/disabling certain quantities output in the map file.

Write restart file

Restart interval	Time interval for restart files.
Rst Output Start/Stop time	Restrict restart output to a specified time window.

Other output options

WAQ Output Interval	Time interval for D-Water Quality files in <DFM_DELWAQ_*mdu_name**.hyd>, etc.
Simulation statistics output interval	Interval for simulation progress output (on standard out and diagnostics file).
Timing statistics output interval	Interval for detailed timings output into <*mdu_name*_timings.txt> for expert performance analysis.

Example

One example of input and output parameters (in seconds) is given in Table 4.2. Table 4.3 shows the time (after *Reference Date* in seconds) when output files are generated. We explain this example as follows.

- ◇ The history ile has output interval 18 seconds. No parameters are specified for *His Output Start Time* and *His Output Stop Time*, which means that they are automatically set equal to *Start Time* and *Stop Time* of the simulation, respectively.
- ◇ The *Map Output Interval* is 6 seconds, and *Map Output Start Time* is 15 seconds. Since the *Map Output Stop Time* is not given, it is set to equal to *Stop Time*. Moreover, we hope to have output at time given in *Specified Map Output* as 30.5 and 42.1 seconds. These two values are firstly set to 31 and 43 seconds, respectively, in the simulation. Then there will be output snapshots if the computational time hit these two integers. Otherwise, as in this example, the output snapshots will be provided when the computational time hits

the time that is greater and the closest to these integers, i.e. at 31.2 and 43.2 (as seen in Table 4.3).

◇ Three parameters are set for the output of the Rst files: the interval, start and stop time.

Input parameters		Output parameters	
Reference Date	2007-11-19 00:00:00	*His Output Interval*	00:00:18
User Time Step	00:00:00.3	*Map Output Interval*	00:00:06
Start Time	2007-11-19 00:00:03	*Map Output Start Time*	2007-11-19 00:00:15
Stop Time	2007-11-19 00:00:51	*Specific Map Output*	30.5, 42.1
		Rst Output Interval	00:00:09
		Rst Output Start Time	2007-11-19 00:00:12
		Rst Output Stop Time	2007-11-19 00:00:45

Table 4.2: *Input and output parameters of the example*

His file	3, 21, 39, 51
Map file	3, 15, 21, 27, 31.2, 33, 39, 43.2, 45, 51
Restart file	3, 12, 21, 30, 39, 45

Table 4.3: *Time (after* Reference Date *in seconds) of output files*

4.4.13 Miscellaneous

Within the miscellaneous sub-tab, various parameters in relation to waves and equatorial settings can be adjusted. Table 4.4 gives an overview and description of these parameters.

Table 4.4: *Overview and description miscellaneous parameters*

Parameter	**Description**
Time step type	Leave at default.
Turbulence model	See chapter 9.
Turbulence advection	Leave at default.
Water level threshold	Max allowed water level difference between old and new time step in any cell. Run will abort if exceeded. (0 means disabled)
Velocity threshold	Max allowed velocity difference between old and new time step in any cell. Run will abort if exceeded. (0 means disabled)
Dry cell threshold	Flooding threshold at velocity points. Used in wetting and drying.

4.4.14 Sediment

If you have activated the process sediment/morphology in the *Processes* tab (section 4.4.6), the tab *Sediment* appears. In this tab, you can add, delete and modify parameters and settings that are related to individual sediment fractions. In order to add and define a sediment fraction, the following steps can be taken:

1 Create and name a sediment fraction.
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.

After selection of the *Sediment* tab and adding a new sediment fraction, the window given by (Figure 4.80) is shown.

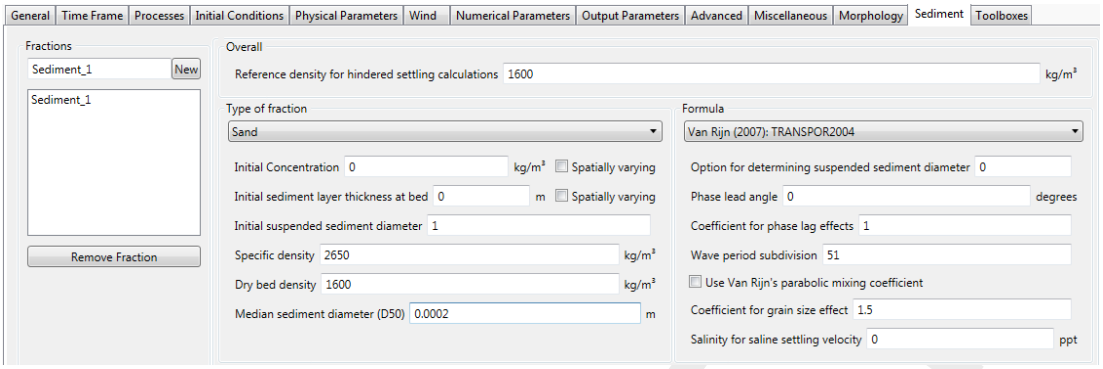


Figure 4.80: *Overview of the* Sediment *tab, showing a sediment of type 'sand'.*

A sediment fraction can be deleted by first selecting the fraction you wish to remove, and then clicking the *Remove Fraction* button.

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

Parameter	**Lower limit**	**Upper limit**	**Default**	**Unit**	**Type of sediment**
Reference density hindered settling	100	10000	1600	kg/m^3	Uniform for all fractions
Initial sediment layer at bed	0	∞	0	m	Sand, mud and bed-load
Specific density	100	4000	2650	kg/m^3	Sand, mud and bed-load
Dry bed density	0	10000	1600	kg/m^3	Sand
	0	10000	500	kg/m^3	Mud
Initial concentration	0	Inf	0	kg/m^3	Sand and mud
Median sediment diameter D_{50}	0.000063	0.002	0.0002	m	Sand
Salinity for saline settling velocity	0	391	0	ppt	Mud
Settling velocity fresh water	0	1	0.00025	m/s	Mud

(continued on next page)

Table 4.4 – continued from previous page

Parameter	Lower limit	Upper limit	Default	Unit	Type of sediment
Settling velocity saline water	0	1	0.00025	m/s	Mud
Critical shear stress erosion	0	100	0.5	N/m^2	Mud
Critical shear stress sedimentation	0	1000	1000	N/m^2	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 18.1.4.

Specific density — For sediment transport the Eckart relation is extended to include the density effect of sediment fractions in the fluid mixture, see section 18.1.3. 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 — Option to specify the initial concentration of the sediment fraction, can be specified as uniform or spatially varying.

Median sediment diameter (D_{50}) — 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 18.3.1

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

Critical bed shear stress for erosion — If the bed shear stress is smaller than the critical stress, no erosion takes place. If the bed shear stress is larger than the flux is calculated following Partheniades-Krone, see section 18.2.3, can be specified as uniform or spatially varying.

Critical bed shear stress for sedimentation — If the bed shear stress is larger than the critical stress, no sedimentation takes place. If the bed shear stress is smaller than the flux is calculated following Partheniades-Krone, see section 18.2.3, can be specified as uniform or spatially varying.

Sediment erosion rate — Erosion parameter M in the formulation of Partheniades-Krone, see section 18.2.3.

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 18.6.4.

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. In Appendix F, a detailed description on how to work with this spatial editor is provided. Note that you can no longer specify a uniform value for a variable that is selected as spatially varying.

4.4.15 Morphology

If you have activated the process sediment/morphology in the *Processes* tab (section 4.4.6), the tab *Morphology* appears. In this tab, you can modify parameters and settings that are related to individual sediment fractions. After selection of the *Morphology* tab, the window given by (Figure 4.81) is shown.

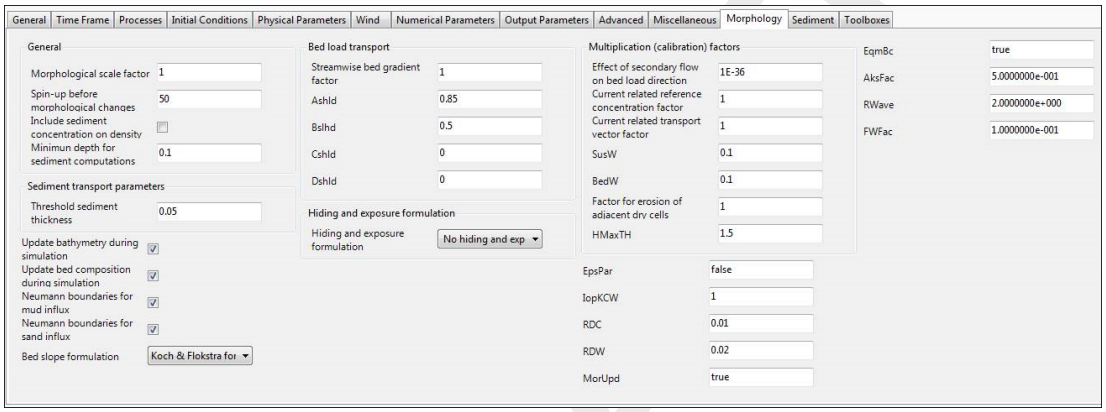


Figure 4.81: *Default view of the* Morphology *tab.*

With the feedback of bottom 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 18.6 for details.

General

Update bathymetry during FLOW simulation

If you want to take into account the feedback of bottom changes on the hydrodynamics, tick off this option.

Remark:

- ◇ The use of this update option only affects the updating of the depth values (at ζ and velocity points) used by flow calculations at subsequent time-steps; the quantity of sediment available at the bed will still be updated, regardless of the state of this flag.

Include effect of sediment on fluid density

You can include or neglect the effect of sediment on the fluid density by setting this option accordingly.

For coarser non-cohesive material you can specify that, at all open inflow boundaries, the flow should enter carrying all “sand” or “mud” sediment fractions at their equilibrium concentration profiles. This means that the sediment 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.

Equilibrium sand concentration profile at inflow boundary

Tick off to use this option. When not activated the inflow concen-

trations specified in Data Group *Boundaries* → *Transport conditions* will be used.

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 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 interval before morphological changes — Specify a time interval (in minutes after the start time) after which the morphological bottom 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 the available bottom sediments will not be taken into account.

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 18.6.2.

Sediment transport parameters

The following parameters are only relevant for non-cohesive sediments.

van Rijn's reference level factor — For non-cohesive sediment (e.g. sand), we follow the method of Van Rijn (1993) for the combined effect of waves and currents, see section 18.3. The reference height formulation contains a proportionality factor called *van Rijn's reference level factor*.

Because of the more complex, partly explicit — partly implicit, erosive flux terms used for "sand" type sediments it is not possible to use the simple source limitation technique used for cohesive sediments. Instead, you must specify a *Threshold sediment thickness*.

Threshold sediment thickness — At each time-step the thickness of the bottom sediments is calculated. If the remaining sediment thickness is less than the user-specified threshold *and erosive conditions are expected* then the source and sink sediment flux terms, see Eq. ((18.25)), are reduced in the following manner:

Estimated ripple height factor — In case of waves, the wave related roughness is related to the estimated ripple height, see section 18.3.3.

Multiplication (calibration) factors

The following parameters are only relevant for non-cohesive sediments.

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 would occur in the wet cell is assigned to the adjacent dry cells.

Current-related reference concentration factor: The reference concentration is calculated in accordance with Van Rijn *et al.* (2000), see section 18.3.3.

Only Van Rijn (1993) and Van Rijn *et al.* (2004) compute explicitly a wave-related transport component.

$$S_{\text{total}} = \text{BED} \cdot S_{\text{bedload current}} + \text{BEDW} \cdot S_{\text{bedload waves}} + \text{SUSW} \cdot S_{\text{suspended waves}} \quad (4.1)$$

$$\frac{dDPS}{dt} = S_{\text{total out}} - S_{\text{total in}} + \text{SUS} \cdot (\text{Entrainment} - \text{Deposition}) \quad (4.2)$$

where $S_{\text{bedload current}}$, $S_{\text{bedload waves}}$, $S_{\text{suspended waves}}$, Entrainment, and Deposition depend on the sediment transport formula used. In most cases it holds $S_{\text{bedload waves}} = 0$ and $S_{\text{suspended waves}} = 0$.

Current-related transport vector magnitude factor: —
Wave-related suspended transport factor: The wave-related suspended sediment transport is modelled using an approximation method proposed by Van Rijn (2001), see section 18.5.1.
Wave-related bedload transport factor: —

Domain:

Parameter	Lower limit	Upper limit	Default	Unit
Include sediment concentration on density	yes or no		no	none
Update bathymetry during simulation	yes or no		yes	none
Update bed composition during simulation	yes or no		no	none
Neumann boundaries for sand/mud influx	yes or no		yes	none
Morphological scale factor	0.0	10000.0	1.0	-
Spin-up interval	0.0		50.0	min
Minimum depth for sediment calculation	0.1	10.0	0.1	m
Threshold sediment thickness	0.005	10.0	0.05	m
Van Rijn's reference level	0.4	2.0	1.0	-
Estimated ripple height factor	1.0	5.0	2.0	-
Factor for erosion of adjacent dry cells	0.0	1.0	0.0	-
Current-related reference concentration factor	0.0	100.0	1.0	-
Current-related transport vector magnitude factor	0.0	100.0	1.0	-
Wave-related suspended transport factor	0.0	100.0	1.0	-
Wave-related bedload transport factor	0.0	100.0	1.0	-

4.5 Save project, MDU file and attribute files

To save your Delta Shell 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 Delta Shell project can be achieved in two ways. Navigate the menu ribbons to *File* and click *Import*. The import wizard appears, allowing you to select what you want to import (Figure 4.82).

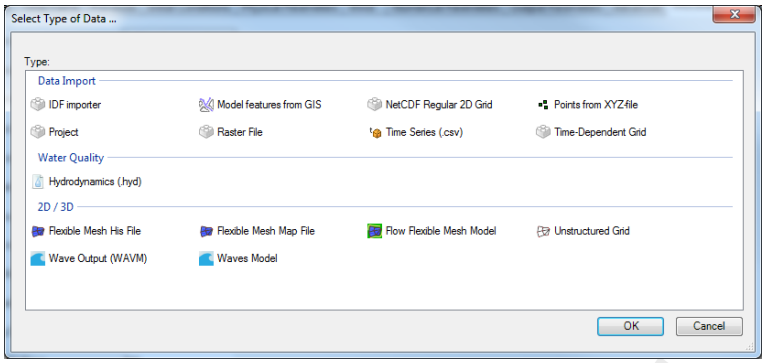


Figure 4.82: *Model/data import wizard*

Alternatively, you can also right mouse click on the name of your project in the *Project* window and select *Import*.

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.

5 Running a model

5.1 Running a simulation

After defining the input for the D-Flow FM hydrodynamic simulation, the computation can be executed either via Delta Shell or using batch scripts. Via Delta Shell, the status of the computation and possible messages are displayed in a separate window. When using a batch script, all messages are written to the diagnostics file (section E.1) and you can continue working in the current window. Not all functionality is available when using Delta Shell to start a calculation. Use a batch script (see section 5.4) in the following cases:

1 Using MPI to run in parallel
2 Using some queueing mechanism on a cluster
3 Running some unattended simulations, while continuing to work in Delta Shell.

Note that currently we have two different names of the D-Flow FM executables, for Windows `dflowfm-cli.exe` and for Linux `dflowfm`.

5.2 Parallel calculations using MPI

5.2.1 Introduction

This section describes parallel computing with D-Flow FM based on the *Message Passing Interface* system (MPI). This can be run both on computing clusters with distributed memory as well as shared memory machines with multiple processors and/or multiple CPU cores. The goal of parallelization of D-Flow FM is twofold. We aim for much faster computations on shared- or distributed-memory machines and the ability to model problems that do not fit on a single machine. A less powerful, yet possibly attractive performance improvement is offered by D-Flow FM's OpenMP-based parallelization (section 5.5.1).

Technical backgrounds on the parallel algorithms in D-Flow FM are described in the Technical Reference Manual D-Flow FM TRM (2015).

Workflow of a parallel run

A parallel run divides the work between multiple processes. To this end we partition the model and let separate processes solve the submodels and generate partitioned output. Given a whole model, the workflow is as follows:

1 partition the model (mesh and model definition file),
2 submit the parallel job to a queue on a computing cluster, and
3 visualize the results from partitioned output files.

5.2.2 Partitioning the model

In D-Flow FM a model is defined by the model definition file, the mesh file and external forcing/boundary condition files, et cetera. The latter are shared by all submodels and do *not* need to be partitioned, they should only be available to all processes. So, partitioning the model concerns partitioning of:

- ◇ the mesh. This is achieved through the graphical user interface or by a command line option. Mesh files for every subdomain will be created;
- ◇ the model definition file. The partitioned model definition files will contain references to the subdomain mesh, and all other information equals its sequential counterpart.

An efficient approach to partition both the mesh and MDU files is via the command line, using

```
> dflowfm --partition:ndomains=n:icgsolver=i <mdu-file>
```

This command reads the name of the mesh file from `mdu-file`, and generates `n` subdomain mesh files by the METIS software package (See D-Flow FM TRM (2015) and references mentioned therein). Then, it creates `n` subdomain MDU files where the parallel Krylov solver `icgsolver` is set to `i`. Here, `i` can be 6, the PETSc solver(recommended for Linux), or, 7, the parallel CG with MILU block preconditioning (recommended for Windows).

For example, to partition the MDU file <example.mdu>, which specifies the mesh file as <exampel_net.nc>, to eight subdomain files on a Windows machine, one can use:

```
> dflowfm --partition:ndomains=8:icgsolver=7 example.mdu
```

The mesh file is partitioned into eight subdomain mesh files, with names <example_000j_net.nc>, `j=0,1,...,7`. In other words, they are:

```
example_0000_net.nc  example_0003_net.nc  example_0006_net.nc
example_0001_net.nc  example_0004_net.nc  example_0007_net.nc
example_0002_net.nc  example_0005_net.nc
```

Then, eight subdomain mdu-files are also created, with names <example_0000.mdu> to <exampel_0007.mdu>. The different items in, e.g. <example_0000.mdu> with respect to the original mdu-file are:

```
[geometry]
NetFile       = example_0000_net.nc

[numerics]
Icgsolver     = 7
```

If the user wants to manually partition the mesh instead of applying METIS, then he has to provide a polygon file <userpol.pol> which determines the mesh partition. In this situation, following command can partition both the MDU and mesh files:

```
> dflowfm  --partition:icgsolver=i <mdu-file> <userpol.pol>
```

5.2.2.1 More about the mesh partitioning

The mesh can be automatically partitioned with the METIS software package, or manually by supplying polygons that define the subdomains. They both produce a cell coloring of the unpartitioned mesh. In each subdomain, the cells are assigned the same color, and augmented with ghost cells. These information are saved in the resulting partitioning mesh file, e.g. <example_NNNN_net.nc>, where _NNNN is a subdomain index.

Regarding partitioning manually with user-supplied partitioning polygons, the partitioning obeys the following rules:

- ◇ if the polygons have a z-value specified, it is considered a subdomain number,
- ◇ if the polygons have no z-value specified, its order determines the corresponding subdomain number,
- ◇ if a cell is not inside at least one polygon, it is assigned to subdomain 0,
- ◇ if a cell is inside only one polygon, it is assigned to the subdomain defined by that polygon,
- ◇ if a cell is inside more than one polygon, it is assigned to the subdomain with the highest number.

In other words, the polygons may be overlapping and the largest subdomain number is taken in the overlapping regions. If the polygons have no z-value, the polygon order determines the corresponding subdomain number, i.e. the first polygon corresponds to subdomain 1 et cetera and there is no polygon defining subdomain 0.

Both types of mesh partitioning are available through Delta Shell or on the command line.

Partitioning the mesh with METIS via Delta Shell

We will firstly focus on the METIS partitioner. Partitioning the mesh from within Delta Shell is achieved by the following steps. In the *Project* window, select the model you want to run by means of clicking on the desired model (Figure 6.1). A right-mouse click will open the context menu, then select *Export...*. In the window **Select Type of Data...**, choose *Partition exporter* and the partitioning dialog will appear (Figure 5.1).

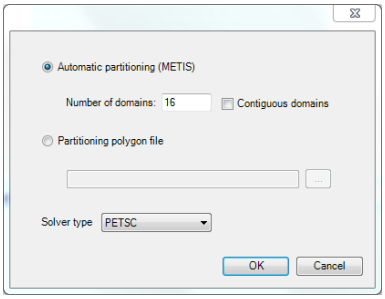


Figure 5.1: *Partioning exporter dialog*

Enter the desired amount of subdomains, and typically leave the *contiguous* option switched off and the solver type at its default. After pressing *OK*, a file dialog will appear. Enter the name of the MDU file, *without* any trailing '_000x' partition numbers: these will be added automatically.

Partitioning the mesh with the graphical user interface is achieved by the following steps: You are prompted for Contiguous domains are not necessary for parallel computations in D-Flow FM and often METIS produces contiguous subdomains without enforcing it. Still, some users may want to explicitly enforce contiguous domains. If you want to do so, make sure that your unpartitioned mesh is contiguous. Not being so may cause errors, Note that there is *no* polygon defining subdomain 0. Parts of the mesh not confined by any polygon are assumed to be in subdomain 0. In other words, there are at least $N - 1$ polygons defining N subdomains. In that case, regenerate the cell colors/domain numbers again by selecting *Operations* $\rightarrow$ *Generate domain numbers (polygon or METIS)*. Note that you will not be asked to specify the number of subdomains. The cell coloring/domain numbering is now based on the (modified) polygons and not produced by the METIS partitioner. Manual partitioning with user-specified polygons will be explained in the next section, The entered mesh filename is a *basename* that will be used to derive the partitioning filenames, e.g. <example_net.nc> will produce:

Partitioning the mesh from the command line

Apart from using the graphical user interface, it is possible to perform the partitioning on the command line. The two types of partitioning can be carried out via the following commands.

The command that uses METIS partitioner reads:

```
> dflowfm --partition:ndomains=n <meshfile>
```

where `ndomains=n` specifies that `n` subdomains are to be generated. For example, partitioning <example_net.nc> results in subdomain mesh files <example_000j_net.nc>, `j=0,1,...,n-1`.

An advanced command, which enables more options, is:

```
> dflowfm --partition:ndomains=n[:method=0|1][:genpolygon=0|1][:contiguous=0|1]
 <meshfile>
```

where the partition method can be chosen via setting `method=0`, the Recursive Bisection method (default), or `method=1`, the multilevel K-Way method. We refer to Karypis (2013) for more details about these two methods. Option `genpolygon` specifies if the command generates a partition polygon file (`genpolygon=1`), or not (`genpolygon=0`, default). Option `contiguous` enforces the contiguous partition when specifying both `contiguous=1` and `method=1`. (Only the K-Way method enables the contiguous partition.) It is not switched on by default. Comparing to the previous command, this advanced command additionally generates a partition polygon file <example_part.pol> when `genpolygon=1` is specified.

Note: Backwards compatibility: when using the legacy partitioning script `generate_parallel_mdu.sh` make sure to include the non-default option `genpolygon=1` in the above command, such that the required polygon file is produced.

Note: When partition a mesh file, e.g. <example_net.nc>, by default a separate file <DFM_interpreted_idomain_example_net.nc> is generated, which includes partition domain information and cell information. One can switch off generating this file by adding in the MDU file ->`[output]`-> `Writepart_domain = 0`.

To manually partition a mesh, a user-specified polygon file <userpols.pol> has to be provided. The corresponding command reads:

```
> dflowfm --partition <meshfile> <userpol.pol>
```

This generates files the same as before.

5.2.3 Partitioning the MDU file

Having partitioned the mesh, the model definition file needs to be partitioned, as every submodel requires its own definition file with references to

- ◇ the partitioned mesh file, e.g. <example_0000_net.nc>,
- ◇ an appropriate parallel Krylov solver, can be
  - 6: PETSc solver, recommended (for Linux), or
  - 7: parallel CG with MILU block preconditioning (for Windows),
- ◇ a unique snapshot directory,
- ◇ optionally, a partitioned restart file, and
- ◇ optionally, a partitioning polygon file, e.g. <example_part.pol>.

The `generate_parallel_mdu.sh` script partitions a sequential model definition file automatically:

```
> generate_parallel_mdu.sh <mdu-file> <nprocs> [partpol-file] <Icgsolver>
```

with

`mdu-file`	sequential model definition file,
`nprocs`	number of subdomains/parallel processes,
`partpol-file`	partitioning polygon file (optionally),
`Icgsolver`	parallel Krylov solver, can be 6 or 7.

Note that the partitioned mesh filenames (and partitioned restart filenames) are derived from the mesh filename (and the restart filename) specified in the sequential model definition file.

5.2.3.1 Remaining model input

A parallel run of a D-Flow FM model needs only partitioned <.mdu> and <_net.nc> files. All other model input is the same as for a standalone run, e.g., meteo forcings, boundary conditions, observation stations and more. These are generally copied to the working directory by the parallel job submission script.

5.2.4 Running a parallel job

To run a parallel job with D-Flow FM model on a cluster you have to prepare the submission script. The submission script should be prepared with respect to the specific options that job scheduler on your cluster requires.

The simple example of the D-Flow FM submission script on the cluster with the Grid Engine:

```
#!/bin/bash
#$ -V
#$ -q test
#$ -cwd
#$ -N My_DflowFM_JOB
#$ -m bea
#$ -M my.email@provider.net

export LD_LIBRARY_PATH=$DFLOWFM/lib:$LD_LIBRARY_PATH
export PATH=$DFLOWFM/bin:$PATH

mpiexec -np 4 dflowfm --autostartstop YOUR_MDU_FILE.mdu > out.txt 2> err.txt
```

In this simplify example above we submit the D-Flow FM simulation that was partitioned into 4 domains and is going to use only 1 node. The options used above are:

- ◇ -V Specify that all environment variables active within the qsub utility be exported to the context of the job.
- ◇ -q Specify the queue 'test' to be used for this job, if absent default queue is used.
- ◇ -cwd Execute the job from the current working directory.
- ◇ -N Specify the name of the job.
- ◇ -m Specifies which message type should be emailed (b=beginning of job, e=end of job, a=abort of job.
- ◇ -M Specifies the email address to send the notification.

In order to submit more complicated, e.g. multi-node simulations, additional options that are scheduler depended have to be added.

5.2.5 Visualizing the results of a parallel run

The map and history output files (as introduced in section 4.4.12) deserve special attention in parallel runs.

The history file — with time series for observation points, structures and more — is written only by process #0, and all model-global data has already been aggregated into that single file: <*mdu_name*_0000_his.nc>.

The map file — with full-grid output of flow fields — is written for each domain separately as <*mdu_name*_000X_map.nc>. This saves communication overhead during the parallel run. The partitioned map files contain duplicate points, since each file also contains the domain's ghost nodes. For postprocessing these map files, two options are now available:

1 Direct plotting of the set of all map files in Delft3D-QUICKPLOT: the partitioned file series will be recognized automatically, and the partion results will be drawn on top of each other. For water levels this gives good results.

2 Merging the partioned map files into a single global map file with the DFMOUTPUT tool. The resulting map file can then be loaded again in Delft3D-QUICKPLOT and other post-processing utilities.

5.2.5.1 Plotting all partitioned map files with Delft3D-QUICKPLOT

When opening one of the partitioned map files into Delft3D-QUICKPLOT, it will automatically detect that the map file is part of a series. An additional select list *Domain* appears, see Figure 5.2. Select either "all partitions", or a partition of your choice, and proceed with the plotting as normal (section 6.3).

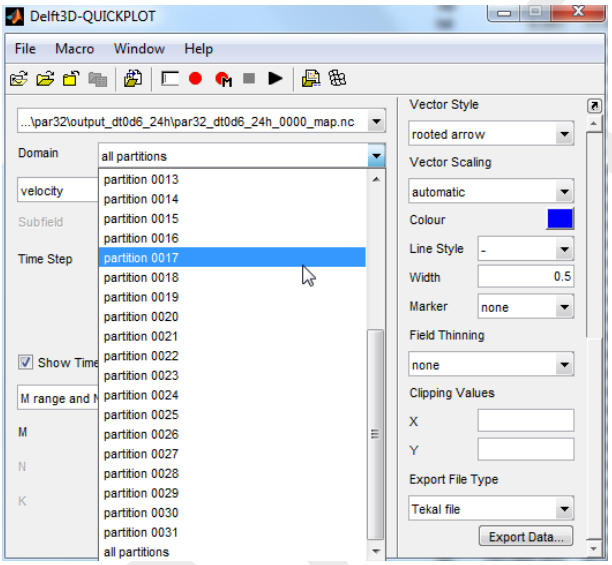


Figure 5.2: *Domain selector in Delft3D-QUICKPLOT for partitioned map files.*

5.2.5.2 Merging multiple map files into one

The partitioned map files of a parallel model run can be merged into a single global map file with the DFMOUTPUT tool. It cuts off ghost nodes, and concatenates all grid points, taking care of correct global renumbering. Usage:

```
> dfmoutput mapmerge [--infile FILE1 [FILE2 FILE3...]] [--outfile DSTFILE]
```

where `FILE1/2/3` are the input files, e.g., <*mdu_name*_0000_map.nc>, . . . , <*mdu_name*_0031_map.nc> and `DSTFILE` is an optional output file name (the default is <*mdu_name*_merged_map.nc>).

Remark:

◇ Since a restart file is a special type of map file, partitioned restart files can also be merged using the above command.

The built-in help gives a list of more advanced options:

```
> dfmoutput mapmerge --help
Merge multiple map files from parallel run into one.

Optional switches:
```

```
   --infile FILE1 [FILE2...], -i FILE1 [FILE2...]
          default value
          One or more input files.
   --listfile LISTFILE, -F LISTFILE
          Pass contents of LISTFILE as input files.
   --outfile DSTFILE, -o DSTFILE
          Write output to file DSTFILE.
 Default: <model>_merged_map.nc
   --force, -f
          default value .false.
          Force overwriting of existing output file.
   --help, -h
          Print this help message
   --version, -v
          Print version

 Examples:
   dfmoutput mapmerge --infile model_0000_map.nc model_0001_map.nc
```

5.3 Running a scenario using Delta Shell

In the *Project* window, select the model you want to run by means of clicking the first attribute of the desired model (Figure 6.1).

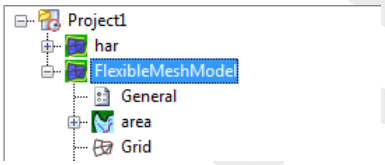


Figure 5.3: *Selecting the model you want to run in the* Project *window*

Starting the calculation can be achieved in two ways. You can navigate the menu ribbons; go to “Home” and in the group Run click on the button “Run Current”. To run all models that are opened in the *Project* window, click on “Run All” (Figure 5.4).

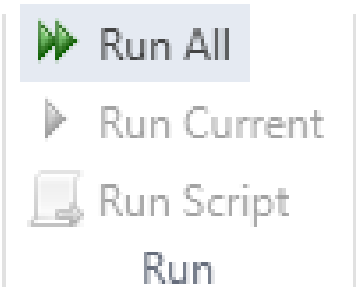


Figure 5.4: *Group Run in Home ribbon*

Alternatively, you can right mouse click the first attribute in the *Project* window of the model you want to run. Next, click “Run Model” to start the calculation. When you select the first of the model you want to run, the properties window (“View” “Properties”) shows several properties of the model you selected. If you set “ShowModelRunConsole” on true, the model run console of the computational core will be showed during the calculation, providing you with additional information during the model run (Figure 5.5).

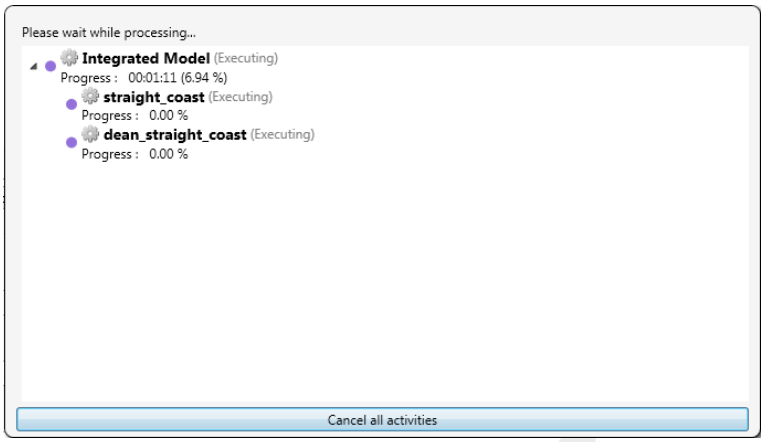


Figure 5.5: *Run console Delta Shell*

When you cancel the run by clicking “Cancel all activities”, model results are stored up to the point where you cancel the run.

5.4 Running a scenario using a batch script

Separate scripts are needed for Windows (with the extension <∗.bat>) and Linux (with the extension <∗.sh>). See section 5.7 for the command-line arguments.

In this section we refer to the variable `%DFLOWFM%` for Windows and `$DFLOWFM` for Linux as a variable that stores path to the directory that contains the dflowfm-cli package.

The easiest Windows script (assuming you have downloaded the Windows dflowfm-cli package, assuming you are in the directory of a configured test-case):

```
set PATH=%DFLOWFM%\bin;%PATH%
dflowfm-cli.exe --autostartstop YOUR_MDU_FILE.mdu
```

The easiest Linux script (assuming you have downloaded the Linux dflowfm-cli package, assuming you are in the directory of a configured test-case):

```
export LD_LIBRARY_PATH=$DFLOWFM/lib:$LD_LIBRARY_PATH
export PATH=$DFLOWFM/bin:$PATH
dflowfm --autostartstop YOUR_MDU_FILE.mdu
```

5.5 Run time

The actual run time of a model can vary considerably depending on a variety of factors such as:

- ◇ The problem being solved, characterised by the number of active grid points, the number of layers in the vertical or the number of processes taken into account.
- ◇ The length of the simulation in time and the time step being used.
- ◇ The hardware configuration that is used and the work load of the processor.

For this reason, only some general considerations are given to determine the run time of a hydrodynamic simulation. On a PC or a workstation without separate I/O-processors the CPU time is the sum of the processor time and the I/O time.

The *processor time* required for a simulation is primarily determined by:

- ◇ The model definition, i.e., the number of active grid points and the number and type of the processes taken into account.
- ◇ The length of the simulated period in terms of the number of time steps executed.

The *I/O time* is determined by:

- ◇ The number of times the computed data are written to history, map, restart files and other communication files for water quality or wave model couplings.
- ◇ The number of observation points, cross-sections and the number of output parameters.

The simulation performance is defined as the CPU time per grid point per time step per constituent:

$$\text{simulation performance} = \frac{\text{CPU time}}{\text{Dnt} \cdot \text{Ndx}} \quad \text{[system seconds]}$$

where:

Dnt	is the number of time steps executed
Ndx	is the number of flow nodes

The simulation performance is written to the diagnostic file at the end of the simulation.

5.5.1 Multi-core performance improvements by OpenMP

D-Flow FM has built-in support for multi-core parallellism using OpenMP[1]. This speeds up calculations by employing multiple processor cores in a single (shared-memory) computer, e.g., a modern-day notebook. OpenMP-parallellism in D-Flow FM does not scale as well as MPI-parallellism (section 5.2), but it comes for free (not any change to model input necessary) and can give a welcome performance improvement (approximately double speed on an Intel quadcore CPU). It is strongly advised to limit the number of OpenMP-threads to one less than the number of physical cores in your machine, thus also ignoring any hyperthreading. An example on Linux for an i7 quadcore CPU machine:

```
export OMP_NUM_THREADS=3
dflowfm --autostartstop YOUR_MDU_FILE.mdu
```

5.6 Files and file sizes

For estimating the required disk space the following files are important:

- ◇ history file
- ◇ map file
- ◇ restart file

[1] http://www.openmp.org

5.6.1 History file

The size of the history file is determined by:

- ◇ The number of monitoring points (observation points + cross-sections): H1.
- ◇ The number of quantities stored: H2.
- ◇ The number of additional process parameters, such as salinity, temperature, constituents and turbulence quantities, taken into account in the simulation: H3.
- ◇ The number of time the history data is written to the history file: H4.

You can estimate the size of a history file (in bytes) from the following equation:

size history file = H1 · (H2 + H3) · H4 · 8 bytes.

As a first approximation you can use H2 = 8.

Example

For a 2D simulation with density driven currents (salinity and temperature), a simulated period of 12 hrs 30 min, a time integration step of 5 minutes, 30 monitoring points and each time step being stored, the size of the history file will be of the order of 384 kBytes. For the same model but now with 10 layers in the vertical the file size will increase to about 4 MBytes. These estimates show that history files are rather small. Unless the number of monitoring points is excessively large the history files are typically much smaller than the map output files.

5.6.2 Map file

The size of the map file is determined by:

- ◇ The size of the model, i.e. the number of grid cells multiplied by the number of layers (Ndxi · Kmax): M1n, and the number of flow links (open grid cell edges) multiplied by the number of layers (Lnx · Kmax): M1l.
- ◇ The number of quantities stored on grid cells and flow links: M2n, M2l, respectively.
- ◇ The number of process parameters taken into account, such as salinity, temperature, constituents and turbulence quantities: M3.
- ◇ The number of time steps for which the map file is written: M4.

Remark:

- ◇ For a more refined estimate you should distinguish between parameters that depend or not on the number of layers used (such as the water level). For a 3D simulation the latter quantities can be neglected, for a 2D simulation they must be accounted for. As a first estimate we double the number of quantities M2 in a 2D simulation.

As a first approximation you can use M2n = 5, M2l = 5 for a 3D simulation and M2n = 8, M2l = 5 for a 2D simulation.

You can estimate the size of a map file (in bytes) from the following equation:

size map file =[M1n · (M2n + M3) + M1l · M2l] · M4 · 8 bytes.

Example

For a 2D simulation with 6800 grid cells and 13000 flow links, simulation results stored for a period of 7 days, and the file is written with an interval of 60 minutes the size of the map file will be about 161 MBytes. For larger models the map file can easily become excessively large, as result the map file is less frequently written, for instance every 2 or 3 hours.

5.6.3 Restart file

A restart file is a special type of map file, where only one time snapshot per file is saved (i.e, M4 = 1). No grid or flow geometry information is stored in a restart file, except for the flow cell/link information (denoted by M5). Moreover, the restart files obtained after a parallel run contain some necessary information about parallelization (denoted by M6). Similarly to the equation of size map file above, one can write the estimating equation as follows:

size rst file = [M1n · (M2n + M3) + M1l · M2l + M5 + M6] · 8 bytes,

where M6 = 0 for a sequential run.

5.7 Command-line arguments

A complete model schematisation can be run from the command line using the D-Flow FM Command Line Interface (CLI), `dflowfm-cli.exe` (`dflowfm` on Linux). A basic non-interactive run is started by:

```
> dflowfm-cli --autostartstop \emph{mdu\_name}.mdu
```

In the box below, a full list of command-line options and arguments is shown:

```
> dflowfm-cli --help
Usage: dflowfm-cli [OPTIONS] [FILE]...
Options:
  --autostart MDUFILE
      Auto-start the model run, and wait upon completion.

  --autostartstop MDUFILE
      Auto-start the model run, and exit upon completion.

  --noautostart MDUFILE
      Disable any AutoStart option in the MDU file (if any).

  --partition:OPTS [POLFILE] NETFILE
      Partitions the unstructured grid in NETFILE into multiple files.

      POLFILE is an optional polygon file which defines the partitions.
      Only used when ndomain in OPTS is undefined or 0.

      OPTS is a colon-separated list opt1=val1:opt2=val2:...
          ndomains  = N     Number of partitions.
          method    = [01]  Partition method: Recursive Bisection(0), K-Way(1).

          genpolygon= [01]  Generate partition polygon(1) or not(0).
          contiguous= [01]  Enforce contiguous grid cells in each domain.
                            Only available when K-Way is enabled (method=1).
```

```
   -t N, --threads N
       Set maximum number of OpenMP threads.
 N must be a positive integer.


   --refine:OPTS NETFILE
       Refine the unstructured grid in NETFILE from commandline.
       OPTS is a colon-separated list opt1=val1:opt2=val2:...
           hmin=VAL
           dtmax=VAL
           maxlevel=M
           connect=[01]
           directional=[01]
           outsidecell=[01]

   -q, --quiet
       Minimal output: Only (fatal) errors are shown.

   --verbose:[level_stdout[:level_dia]], e.g., --verbose:INFO:DEBUG
       Set verbosity level of output on standard out and in diagnostics file.
       where level is in: {DEBUG|INFO|WARNING|ERROR|FATAL}
       Levels are optional, default is INFO on screen, DEBUG in dia file.

   -h, --help
       Display this help information and exit.

   -v, --version
       Output version information and exit.
```

5.8 Restart a simulation

D-Flow FM allows to restart a simulation, not from the original starting time, but from a user-specified time with all the information at that time. In other words, for a model which has a long spinup time from t_{start}, instead of restarting from t_{start}, one can restart another simulation of the same model from a later time t_{rst}, where $t_{\mathrm{start}} \leq t_{\mathrm{rst}} < t_{\mathrm{stop}}$. And the results for times $t_{\mathrm{rst}} \leq t \leq t_{\mathrm{stop}}$ are the same as in the original simulation run.

This can be achieved by following steps:

1. In order to obtain restart files <_rst.nc>, this needs to be enabled in the output parameters (see section 4.4.12 for more details about how to set output parameters).
2. Run the original model from t_{start} to t_{stop}, resulting in restart files.
3. To restart the simulation from time t_{rst}, in the MDU file modify `TStart` to t_{rst}, *and* fill in the name of corresponding restart file in `RestartFile` of the `[restart]`-section. Moreover, place the corresponding restart file relative to the directory of this MDU file.

To restart a parallel simulation, one can use any of the following methods:

Method 1 On each subdomain use its own restart file.

Method 2 Merge all the subdomain restart files into a single global restart file (see section 5.2.5.2), and then use it for all the subdomains. This means to put the name of this merged file as `RestartFile` in all subdomain MDU files. This method is supported when restarting with the same, or a different domain partitioning. Moreover, such a merged restart file can also be used to restart a sequential run.

The above two methods require taking care of the name of the restart file in subdomain MDU files. D-Flow FM automatically fills in the correct names, when partition an MDU file to subdomain MDU files (see section 5.2.2), in the following way:

For Method 1 When <*mduname*_YYMMDD_HHMMSS_rst.nc> is filled in `RestartFile` of the original MDU file, partition this MDU file gives subdomain MDU files with `RestartFile` as <*mduname*_000X_YYMMDD_HHMMSS_rst.nc> for each subdomain <000X>.

For Method 2 If the string word "merged" is contained in the name of `RestartFile` in the original MDU file, then this file name is kept to all the subdomain MDU files after partitioning.

It is also possible to use a map file as a restart file, following the above approaches. Notice that in this case, one needs to specify the `RestartDateTime` in MDU file as well. However, we strongly recommend to use <_rst.nc> file instead of a map file.

D-Flow FM also supports restarting a 3D model simulation with σ-layers. **Note:** The 3D-implementation is a beta functionality.

5.9 Frequently asked questions

This chapter aims to help you with common questions that may arise while using D-Flow FM.

1 **Question**
My model does not run/crashes. What's wrong?
Answer
The diagnostics file is the starting point for finding out what went wrong. See section E.1 for a detailed description of the contents of this file, and the order of model run output. Globally, ask yourself the following questions:

- ◇ Was the MDU file found?
- ◇ If yes, was the model successfully loaded? Common mistakes are missing boundary or meteorological forcings file.
- ◇ If yes, was the time loop successfully started? Possible errors are non-writable output files.
- ◇ If yes, does the dia file contain any messages from during the time loop? Possible errors are solver convergence errors.
- ◇ If not, did the run end successfully?

2 **Question**
I get a warning that my network is non-orthogonal. Can I loosen the orthogonality treshold?
Answer
Unfortunately, no. Orthogonality is very important for accuracy: advised orthogonality values for your grid are around 0.01, preferrably lower. The current treshold is already very high at a value of 0.5. Use RGFGRID to improve your grid orthogonality (and smoothness).

6 Visualize results

6.1 Introduction

A model run will produce two types of output:

1 a graph or history (<∗.his>-file) for a specific quantity on a location
2 a map (<∗.map>-file) for a specific quantity

Both are stored in files within the project, as described in section 5.6.

D-Flow FM provides basic visualization of the model and the model results. Advanced and tailor-made visualization is possible by the export of the his- and/or map-files, and inspection with dedicated visualization applications. Some are provided and described below.

6.2 Visualization with Delta Shell

When your model run has finished, a new folder called “Output” has appeared at the bottom of the attributes of your model in the *Map* window. Inside this folder, all output quantities of the his-, and map-files can be found, as well as a folder called “States”, in which you find all restart files written during the model run. Output folders have also appeared in the *Map* window; “Output (map)” and “Output (his)”. Both the results of your map and his files can be viewed in the central map by means of enabling the desired quantities from the *Map* window (Figure 6.1).

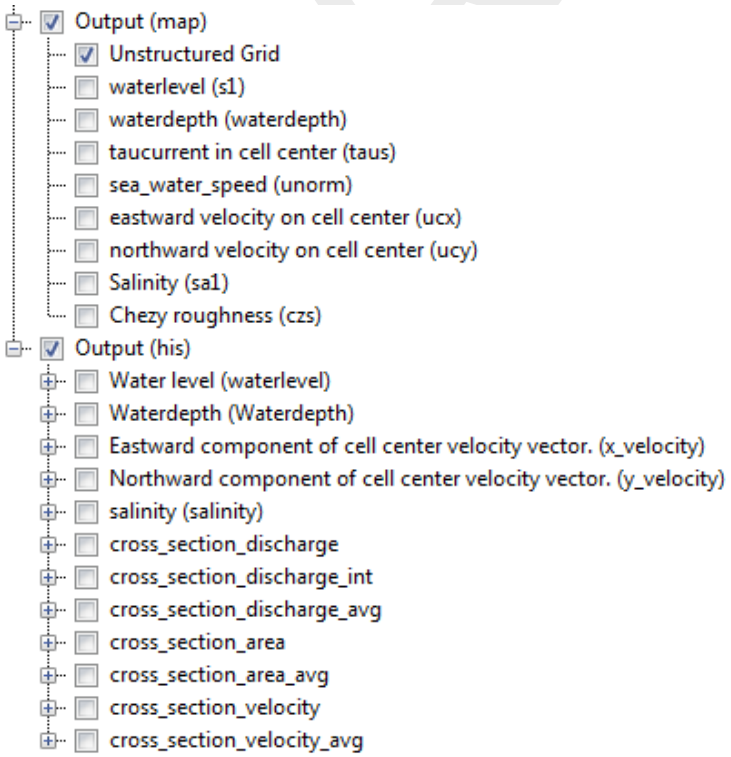


Figure 6.1: *Example of setting output (in)visible in the* Map *window*

The time navigator can be used to slide through the different time steps in the output files. If your model is relatively large, the drawing performance of the interface can be improved

dramatically by enabling QuadTree visualizations in the properties window of the layer you want to visualize. To this end, select the layer you want to visualize in the ...

6.3 Visualization with Quickplot

The interface of the Delft3D-QUICKPLOT allows to open the NetCDF output files from a D-Flow FM simulation. In the interface you can select data fields, make a selection of time steps, stations or specify a preferred figure presentation options. After selection of a certain options you can visualize your data by using the “Quick View” button. To add another plot to an existing figure the “Add to Plot” button should be used.

When plotting the map output files from a D-Flow FM simulation, by default the presentation type “markers” will be selected. To smoothly visualize your results it is recommended to change presentation type into “polygons” and then select the option “Fill Polygons” (see the example on the Figure 6.2).

Figure 6.2: *Useful map visualization options in the Delft3D-QUICKPLOT*

See the Delft3D-QUICKPLOT User Manual for full details and a description of the routines and their use.

6.4 Visualization with Muppet

The interface of the Muppet allows to “Add Dataset” from a NetCDF output file from a D-Flow FM simulation. It is possible to create a timeseries for a selected variable in from the history files. Additionally Muppet offers the option to visualize the map output files from a D-Flow FM simulation (see Figure 6.3).

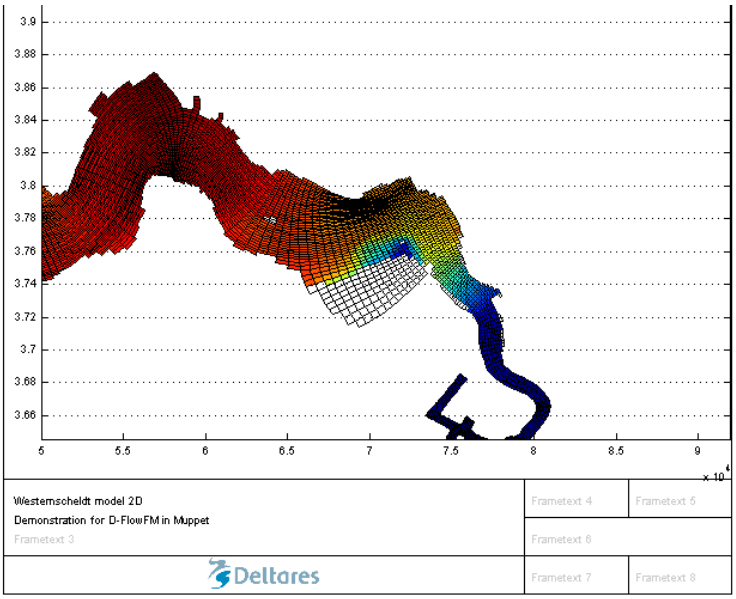


Figure 6.3: *Example of the Muppet visualization of the D-Flow FM map output file*

In the Muppet interface it is possible to specify figure settings, plot descriptions, labels and many more.

6.5 Visualization with Matlab

In the OpenEarthTools you can find two example scripts that allow you to load and visualize the D-Flow FM output. Note that in the Matlab scripts for the D-Flow FM the UGRID notation is used.

The <plotMap.m> script plots a D-Flow FM unstructured map and optionally the handles h are returned. By modifying the script you can change the plotted variable, layout or the plot style options.

The <plotNet.m> script plots a D-Flow FM unstructured net, optionally the handles h are returned. This script can visualize nodes, links and cell circumcenters of a network. By modifying the script you can choose the preferred plotting settings and variables to plot (by default nodes, edges and faces are plotted).

6.6 Visualization with Python

Currently there are no examples of Python scripts for the D-Flow FM output visualization in the OpenEarthTools. However, if such a need arises it is possible to load netcdf Python libraries, and create your own simple visualization of the variables present in the NetCDF output files.

7 Hydrodynamics

7.1 Introduction

Increasing awareness of environmental issues has focused the attention of scientists and engineers on the problem of predicting the flow and dispersion of contaminants in water systems. Reliable information on water flow, waves, water quality, sediment transport and morphology can be obtained from appropriate mathematical models. In general the first step in such modelling activities concerns the simulation of the flow itself. Whether the problem is related, for example, to the stability of a hydraulic structure, to salt intrusion, to the dispersion of pollutants or to the transport of silt and sediment, flow simulations usually form the basis of the investigations to be carried out.

The *Delft3D Flexible Mesh Suite* is the integrated modelling system of Deltares for the aquatic environment. D-Flow Flexible Mesh, the flow module of this system, provides the hydrodynamic basis for other modules such as water quality, ecology, waves and morphology. For steady and non-steady modelling of the far-field water quality and ecology, it is coupled with the far-field water quality module D-Water Quality. For the interaction between waves and currents the flow module may be coupled with the short-waves model D-Waves. To control structures, the flow module is coupled to the D-Real Time Control module.

D-Flow FM is flexible by using an unstructured grid in the horizontal plane. In the vertical direction D-Flow FM offers two different vertical grid systems: a so-called σ co-ordinate system (σ-model) introduced by Phillips (1957) for ocean models and the Cartesian z-co-ordinate system (Z-model).

This section gives some background information on the conceptual model of the D-Flow FM module. Most of the concepts and algorithms are applicable to both the σ-model and Z-model.

Note: The 3D-implementation is a β-functionality.

7.2 General background

7.2.1 Range of applications of D-Flow FM

The hydrodynamic module D-Flow FM simulates two-dimensional (2DH, depth-averaged) or three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and/or meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). The flow model can be used to predict the flow in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. It aims to model flow phenomena of which the horizontal length and time scales are significantly larger than the vertical scales.

If the fluid is vertically homogeneous, a depth-averaged approach is appropriate. D-Flow FM is able to run in two-dimensional mode (one computational layer), which corresponds to solving the depth-averaged equations. Examples in which the two-dimensional, depth-averaged flow equations can be applied are tidal waves, storm surges, tsunamis, harbor oscillations (seiches) and transport of pollutants in vertically well-mixed flow regimes.

Three-dimensional modelling is of particular interest in transport problems where the horizontal flow field shows significant variation in the vertical direction. This variation may be generated by wind forcing, bed stress, Coriolis force, bed topography or density differences. Examples are dispersion of waste or cooling water in lakes and coastal areas, upwelling and

downwelling of nutrients, salt intrusion in estuaries, fresh water river discharges in bays and thermal stratification in lakes and seas.

7.2.2 Physical processes

The numerical hydrodynamic modelling system D-Flow FM solves the unsteady shallow water equations in two (depth-averaged) or in three dimensions. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe. In D-Flow FM models with structured grid are considered as a simplified form of an unstructured grid. In Cartesian co-ordinates, the free surface level and bathymetry are related to a flat horizontal plane of reference, whereas in spherical co-ordinates the reference plane follows the Earth curvature.

The flow is forced by tide at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Source and sink terms are included in the equations to model the discharge and withdrawal of water.

The D-Flow FM model includes mathematical formulations that take into account the following physical phenomena:

- ◇ Free surface gradients (barotropic effects).
- ◇ The effect of the Earth rotation (Coriolis force).
- ◇ Water with variable density (equation of state).
- ◇ Horizontal density gradients in the pressure (baroclinic effects).
- ◇ Turbulence induced mass and momentum fluxes (turbulence closure models).
- ◇ Transport of salt, heat and other conservative constituents.
- ◇ Tidal forcing at the open boundaries.
- ◇ Space and time varying wind shear-stress at the water surface.
- ◇ Space varying shear-stress at the bed.
- ◇ Space and time varying atmospheric pressure on the water surface.
- ◇ Time varying sources and sinks (e.g. river discharges).
- ◇ Drying and flooding of tidal flats.
- ◇ Heat exchange through the free surface.
- ◇ Evaporation and precipitation.
- ◇ Tide generating forces.
- ◇ Effect of secondary flow on depth-averaged momentum equations.
- ◇ Lateral shear-stress at wall.
- ◇ Vertical exchange of momentum due to internal waves.
- ◇ Influence of waves on the bed shear-stress (2D and 3D).
- ◇ Wave induced stresses (radiation stress) and mass fluxes.
- ◇ Flow through hydraulic structures.
- ◇ Wind driven flows including tropical cyclone winds.

7.2.3 Assumptions underlying D-Flow FM

In D-Flow FM the 2D (depth-averaged) or 3D non-linear shallow water equations are solved. These equations are derived from the three dimensional Navier-Stokes equations for incompressible free surface flow. The following assumptions and approximations are applied:

- ◇ In the σ co-ordinate system the depth is assumed to be much smaller than the horizontal length scale. For such a small aspect ratio the shallow water assumption is valid, which means that the vertical momentum equation is reduced to the hydrostatic pressure relation. Thus, vertical accelerations are assumed to be small compared to the gravitational acceleration and are therefore not taken into account.
- ◇ The effect of variable density is only taken into account in the pressure term (Boussinesq approximation).
- ◇ In the σ co-ordinate system, the immediate effect of buoyancy on the vertical flow is not considered. In D-Flow FM vertical density differences are taken into account in the horizontal pressure gradients and in the vertical turbulent exchange coefficients. So the application of D-Flow FM is restricted to mid-field and far-field dispersion simulations of discharged water.
- ◇ For a dynamic online coupling between morphological changes and flow the 2D sediment and morphology feature is available.
- ◇ In a Cartesian frame of reference, the effect of the Earth curvature is not taken into account. Furthermore, the Coriolis parameter is assumed to be uniform unless specifically specified otherwise.
- ◇ In spherical co-ordinates the inertial frequency depends on the latitude.
- ◇ At the bed a slip boundary condition is assumed, a quadratic bed stress formulation is applied.
- ◇ The formulation for the enhanced bed shear-stress due to the combination of waves and currents is based on a 2D flow field, generated from the velocity near the bed using a logarithmic approximation.
- ◇ The equations of D-Flow FM are capable of resolving the turbulent scales (large eddy simulation), but usually the hydrodynamic grids are too coarse to resolve the fluctuations. Therefore, the basic equations are Reynolds-averaged introducing so-called Reynolds stresses. These stresses are related to the Reynolds-averaged flow quantities by a turbulence closure model.
- ◇ In D-Flow FM the 3D turbulent eddies are bounded by the water depth. Their contribution to the vertical exchange of horizontal momentum and mass is modelled through a vertical eddy viscosity and eddy diffusivity coefficient (eddy viscosity concept). The coefficients are assumed to be proportional to a velocity scale and a length scale. The coefficients may be specified (constant) or computed by means of an algebraic, k-τ or k-ε turbulence model, where k is the turbulent kinetic energy, τ is the turbulent time scale and ε is the dissipation rate of turbulent kinetic energy.
- ◇ In agreement with the aspect ratio for shallow water flow, the production of turbulence is based on the vertical (and not the horizontal) gradients of the horizontal flow. In case of small-scale flow (partial slip along closed boundaries), the horizontal gradients are included in the production term.
- ◇ The boundary conditions for the turbulent kinetic energy and energy dissipation at the free surface and bed assume a logarithmic law of the wall (local equilibrium).
- ◇ The eddy viscosity is an-isotropic. The horizontal eddy viscosity and diffusivity coefficients should combine both the effect of the 3D turbulent eddies and the horizontal motions that cannot be resolved by the horizontal grid. The horizontal eddy viscosity is generally much larger than the vertical eddy viscosity.
- ◇ For large-scale flow simulations, the tangential shear-stress at lateral closed boundaries can be neglected (free slip). In case of small-scale flow partial slip is applied along closed boundaries.
- ◇ For large-scale flow simulations, the horizontal viscosity terms are reduced to a bi-harmonic

operator along co-ordinate lines. In case of small-scale flow the complete Reynold's stress tensor is computed. The shear-stress at the side walls is calculated using a logarithmic law of the wall.

- ◇ In the σ co-ordinate system, D-Flow FM solves the so-called long wave equation. The pressure is hydrostatic and the model is not capable of resolving the scales of short waves. Therefore, the basic equations are averaged in analogy with turbulence introducing so called radiation stresses. These stresses are related to the wave quantities of Delft3D-WAVE.
- ◇ It is assumed that a velocity point is set dry when the actual water depth is below half of a user-defined threshold. If the point is set dry, then the velocity at that point is set to zero. The velocity point is set wet again when the local water depth is above the threshold. The hysteresis between drying and flooding is introduced to prevent drying and flooding in two consecutive time steps.
  The drying and flooding procedure leads to a discontinuous movement of the closed boundaries at tidal flats.
- ◇ A continuity cell is set dry when all surrounding velocity points at the grid cell faces are dry or when the actual water depth at the cell centre is below zero (negative volume).
- ◇ The flux of matter through a closed wall and through the bed is zero.
- ◇ Without specification of a temperature model, the heat exchange through the free surface is zero. The heat loss through the bed is always zero.
- ◇ If the total heat flux through the water surface is computed using a temperature excess model the exchange coefficient is a function of temperature and wind speed and is determined according to Sweers (1976). The natural background temperature is assumed constant in space and may vary in time. In the more advanced heat flux formulation the fluxes due to solar radiation, atmospheric and back radiation, convection, and heat loss due to evaporation are modeled separately.
- ◇ The effect of precipitation on the water temperature is accounted for.

7.3 Hydrodynamic processes

D-Flow FM solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. In the vertical momentum equation the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. In 3D models the vertical velocities are computed from the continuity equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on an ustructured finite volume grid.

In the horizontal direction D-Flow FM uses orthogonal unstructured grids. Two coordinate references are supported:

1 Cartesian co-ordinates
2 Spherical co-ordinates

The boundaries of a river, an estuary or a coastal sea are in general curved and are not smoothly represented on a structured grid. The boundary becomes irregular and may introduce significant discretization errors. To reduce these errors unstructured grids are used. The unstructured grids also allow local grid refinement in areas with large horizontal gradients.

In the vertical direction D-Flow FM offers two different vertical grid systems: the σ coordinate system (σ-model) and the Cartesian z-co-ordinate system (Z-model). In the σ model, the vertical grid consists of layers bounded by two σ planes, which are not strictly horizontal but follow the bed topography and the free surface. Because the σ-model is boundary fitted both to the bed and to the moving free surface, a smooth representation of the topography is obtained. The number of layers over the entire horizontal computational area is constant,

irrespective of the local water depth. The distribution of the relative layer thickness is usually non-uniform. This allows for more resolution in the zones of interest such as the near surface area (important for e.g. wind-driven flows, heat exchange with the atmosphere) and the near bed area (sediment transport). Please note that in D-Flow FM, unlike Delft3D, the σ coordinate is equal to zero on the bed is 1 on the water surface.

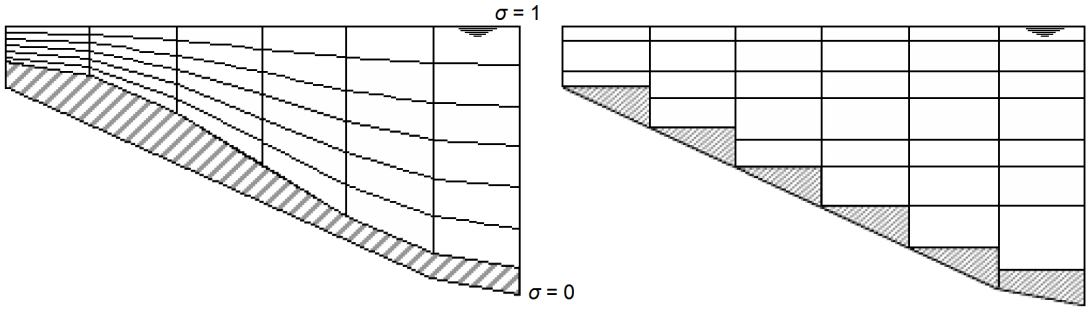


Figure 7.1: *Example of σ-model (left) and Z-model (right).*

Although the σ-grid is boundary fitted (in the vertical), it will not always have enough resolution around the pycnocline. The co-ordinate lines intersect the density interfaces that may give significant errors in the approximation of strictly horizontal density gradients (Leendertse, 1990; Stelling and Van Kester, 1994). Therefore, Z-model was introduced in D-Flow FM for 3D simulations of weakly forced stratified water systems. The Z-model has horizontal co-ordinate lines that are (nearly) parallel with density interfaces (isopycnals) in regions with steep bed slopes. This is important to reduce artificial mixing of scalar properties such as salinity and temperature. The Z-model is not boundary-fitted in the vertical. The bed (and free surface) is usually not a co-ordinate line and is represented as a staircase (zig-zag boundary).

7.3.1 Topological conventions

A computational cell in a D-Flow FM grid (sometimes referred to as a 'network') consists of corner nodes and edges connecting the corner nodes. Such a grid cell should contain at least three corner nodes and at most six corner nodes. The following topological conventions are used:

- ◇ netnodes: corners of a cell (triangles, quadrangles, ...),
- ◇ netlinks: edges of a cell, connecting netnodes,
- ◇ flownodes: the cell circumcentre, in case of triangles the exact intersection of the three perpendicular bisectors and hence also the centre of the circumscribing circle,
- ◇ flowlinks: a line segment connecting two flownodes.

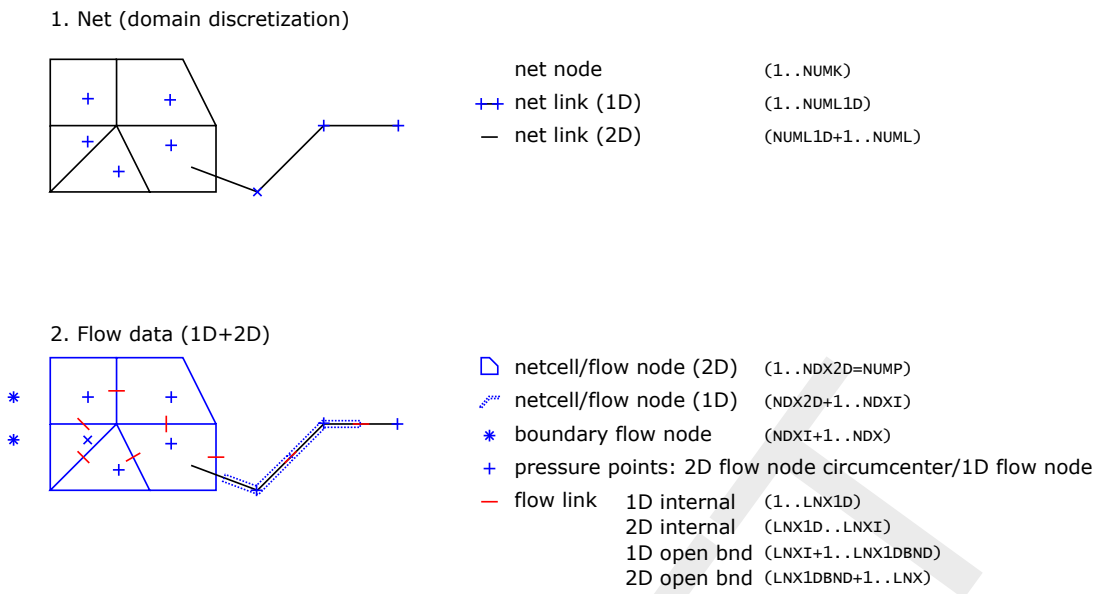


Figure 7.2: *Flexible mesh topology*

This mesh topology is illustrated in Figure 7.2. The 'center' of a cell can be defined in multiple ways. To illustrate this, two conventional cell center definitions for a triangle are highlighted in Figure 7.3. The two displayed cell centers have different properties:

1 the circumcenter is the location within the triangle which is the center point of a circle that intersects the triangle at each corner node of the triangle; as a consequence, the orthogonal projection of the center point to each face of the triangle divides each face into two exactly equidistant pieces,
2 the mass center (or centroid) is the center of gravity; as a consequence, a line through a corner node and the mass center divides a face into two exactly equidistant pieces under an angle not necessarily equal to 90°.

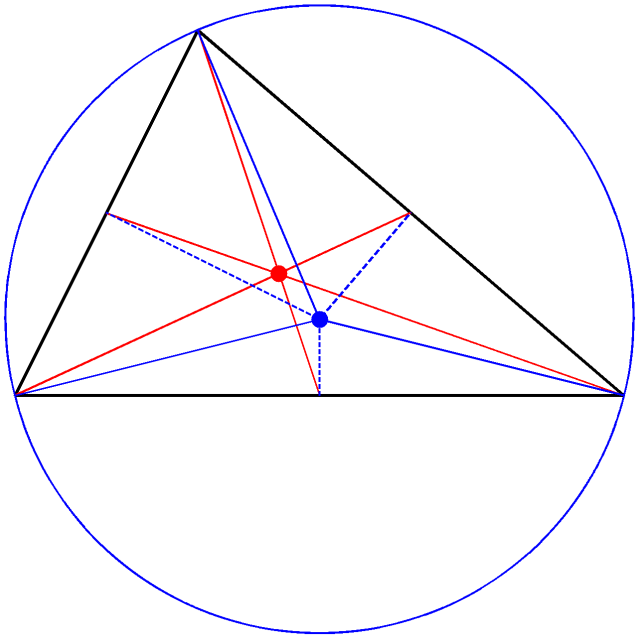


Figure 7.3: *Two conventional definitions of the cell center of a triangle: the circumcenter and the mass center.*

D-Flow FM utilizes the **circumcenter** as the basis of the definition of the elementary flow variables 'water level' and 'flow velocity'. The water level is defined at the circumcenter, whereas the face normal flow velocity is defined at the orthogonal projection of the circumcenter onto the cell face, i.e., the midpoint of the cell face.

Important properties of the mesh are the *orthogonality* and *smoothness*. The *orthogonality* is defined as the cosine of the angle φ between a flowlink and a netlink. Ideally 0, angle $\varphi = 90^\circ$. The *smoothness* of a mesh is defined as the ratio of the areas of two adjacent cells. Ideally 1, the areas of the cells are equal to each other. A nearly ideal setup is shown in Figure 7.4.

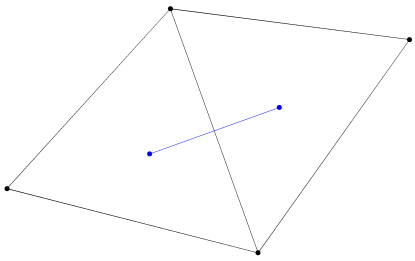


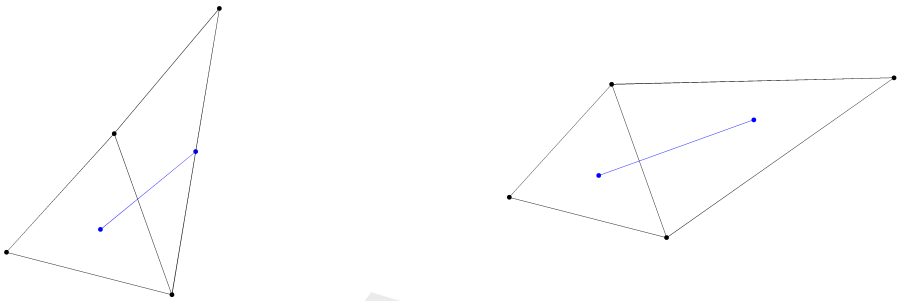
Figure 7.4: *Perfect orthogonality and nearly perfect smoothness along the edge connecting two triangles. Black lines/dots are network links/nodes, blue lines/dots are flow links/nodes.*

It is quite easy (and therefore dangerous) to generate meshes that violate the orthogonality

and smoothness requirements. In Figure 7.5, two different setups of two gridcells are shown with different mesh properties.

The left picture of Figure 7.5 shows how orthogonality can be detoriated by skewing the right triangle with respect to the left triangle. While having the same area (perfect smoothness), the mutually oblique orientation results in poor orthogonality. In this particular case, the centre of the circumscribing circle is in principle located outside the right triangle. Such a triangle is denoted as an 'open' triangle, which is bad for computations.

The opposite is shown in the right picture of Figure 7.5 in which the right triangle has strongly been elongated, disturbing the smoothness property. However, the orthogonality is nearly perfect. Nonetheless, both meshes need to be improved to assure accurate model results.



(a) *Perfect smoothness, but poor orthogonality.* ***(b)*** *Perfect orthogonality, but poor smoothness*

Figure 7.5: *Poor mesh properties due to violating either the smoothness or the orthogonality at the edge connecting two triangles. Black lines/dots are network links/nodes, blue lines/dots are flow links/nodes.*

7.3.2 Conservation of mass and momentum

In this section, we will present in detail the governing equations for mass and momentum conservation. These equations are indicated by a continuity equation and momentum equations.

7.3.2.1 Continuity equation

D-Flow FM solves the depth-averaged continuity equation, derived by integration the continuity equation, for incompressible fluids ($\nabla \bullet \boldsymbol{u} = 0$) over the total depth, taken into account the kinematic boundary conditions at water surface and bed level, and is given by:

$$\frac{\partial h}{\partial t} + \frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial y} = Q \tag{7.1}$$

with U and V the depth averaged velocities. Q is representing the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation:

$$Q = \int_0^h (q_{in} - q_{out})\, dz + P - E \tag{7.2}$$

with q_{in} and q_{out} the local sources and sinks of water per unit of volume [1/s], respectively, P the non-local source term of precipitation and E non-local sink term due to evaporation. We remark that the intake of, for example, a power plant is a withdrawal of water and should be modelled as a sink. At the free surface there may be a source due to precipitation or a sink due to evaporation.

7.3.2.2 Momentum equations in horizontal direction

The momentum equations in x- and y-direction are given by:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + F_x + \frac{\partial}{\partial z}\left(\nu_V \frac{\partial u}{\partial z}\right) + M_x \quad (7.3)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + F_y + \frac{\partial}{\partial z}\left(\nu_V \frac{\partial v}{\partial z}\right) + M_y \quad (7.4)$$

Where ν_V is the vertical eddy viscosity coefficient. Density variations are neglected, except in the baroclinic pressure terms, $\partial P/\partial x$ and $\partial P/\partial y$ represent the pressure gradients.

The forces F_x and F_y in the momentum equations represent the unbalance of horizontal Reynolds stresses.

M_x and M_y represent the contributions due to external sources or sinks of momentum (external forces by hydraulic structures, discharge or withdrawal of water, wave stresses, etc.).

The effects of surface waves on the flow as modelled in D-Flow FM are described in section 15.2.

7.3.2.3 Vertical velocities

The vertical velocity w in the adapting σ co-ordinate system is computed from the continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} + \frac{\partial w}{\partial z} = h\left(q_{in} - q_{out}\right) \quad (7.5)$$

At the surface the effect of precipitation and evaporation is taken into account. The vertical velocity w is defined at the iso σ-surfaces. w is the vertical velocity relative to the moving σ-plane. It may be interpreted as the velocity associated with up- or downwelling motions.

7.3.3 The hydrostatic pressure assumption

Under the shallow water assumption, the vertical momentum equation is reduced to a hydrostatic pressure equation. Vertical accelerations due to buoyancy effects and due to sudden variations in the bed topography are not taken into account. So:

$$\frac{\partial P}{\partial z} = -\rho g h \quad (7.6)$$

For water of constant density and taking into account the atmospheric pressure, it includes gradients of the free surface level, called barotropic pressure gradients. The atmospheric pressure is included in the system for storm surge simulations. The atmospheric pressure gradients dominate the external forcing at peak winds during storm events. Space and time varying wind and pressure fields are especially important when simulating storm surges.

In case of a non-uniform density the pressure gradients includes not only barotropic pressure gradient, but also vertical pressure gradient, the so called baroclinic pressure gradient. The baroclinic pressure gradient is the result of variable distribution of density and temperature in the vertical direction.

In the horizontal gradient a vertical derivative is introduced by the σ co-ordinate transformation. In estuaries and coastal seas the vertical grid may deteriorate strongly in case of steep

bed slopes. In order to avoid artificial flow the numerical approximation of the baroclinic pressure terms requires a special numerical approach. The treatment of D-Flow FM to avoid the artificial mixing due to σ co-ordinates are discussed in section 7.5, see also Stelling and Van Kester (1994).

7.3.4 The Coriolis force

The Coriolis parameter f depends on the geographic latitude ϕ and the angular speed of rotation of the earth, Ω ($f = 2\Omega \sin \phi$). For a grid the user should specify the space varying Coriolis parameter, using a suitable projection. This can be done by selecting *Coordinate System* in RGFGRID, and selection of the option for *Spherical Coordinate*. The parameters for translation and rotation can be given as shown in Figure 7.6.

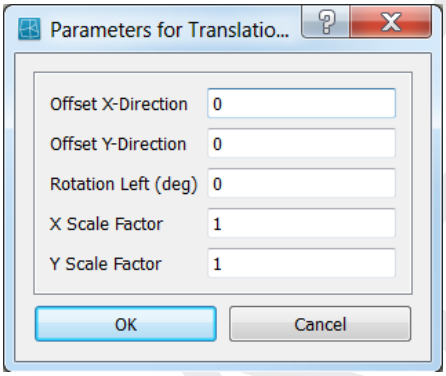


Figure 7.6: *Input for map projection for specifying Coriolis parameter on the grid.*

7.3.5 Diffusion of momentum

The forces F_x and F_y in the horizontal momentum equations represent the unbalance of horizontal Reynolds stresses. The Reynolds stresses are modelled using the eddy viscosity concept, (for details e.g. Rodi (1984)). This concept expresses the Reynolds stress component as the product between a flow as well as grid-dependent eddy viscosity coefficient and the corresponding components of the mean rate-of-deformation tensor. The meaning and the order of the eddy viscosity coefficients differ for 2D and 3D, for different horizontal and vertical turbulence length scales and fine or coarse grids. In general the eddy viscosity is a function of space and time.

For 3D shallow water flow the stress tensor is an-isotropic. The horizontal eddy viscosity coefficient, ν_H, is much larger than the vertical eddy viscosity ν_V ($\nu_H \gg \nu_V$). The horizontal viscosity coefficient may be a superposition of three parts:

1 a part due to "sub-grid scale turbulence",
2 a part due to "3D-turbulence" see Uittenbogaard *et al.* (1992) and
3 a part due to dispersion for depth-averaged simulations.

In simulations with the depth-averaged momentum and transport equations, the redistribution of momentum and matter due to the vertical variation of the horizontal velocity is denoted as dispersion. In 2D simulations this dispersion is not simulated as the vertical profile of the horizontal velocity is not resolved. Then this dispersive effect may be modelled as the product of a viscosity coefficient and a velocity gradient. The dispersion term may be estimated by the Elder formulation.

If the vertical profile of the horizontal velocity is not close to a logarithmic profile (e.g. due to stratification or due to forcing by wind) then a 3D-model for the transport of matter is recommended.

The horizontal eddy viscosity is mostly associated with the contribution of horizontal turbulent motions and forcing that are not resolved by the horizontal grid ("sub-grid scale turbulence") or by (a priori) the Reynolds-averaged shallow-water equations. in 3D, in the vertical direction, ν_V is referred to as the three-dimensional turbulence and in it is computed following a 3D-turbulence closure model.

Therefore, in addition to all turbulence closure models in D-Flow FM a constant (space and time) background mixing coefficient may be specified by the user, which is a background value for the vertical eddy viscosity in the momentum Equation (7.3) and Equation (7.4) consequently.

The horizontal and vertical eddy viscosities can be set by user defined value under `Physical Parameters` shown in Figure 7.7.

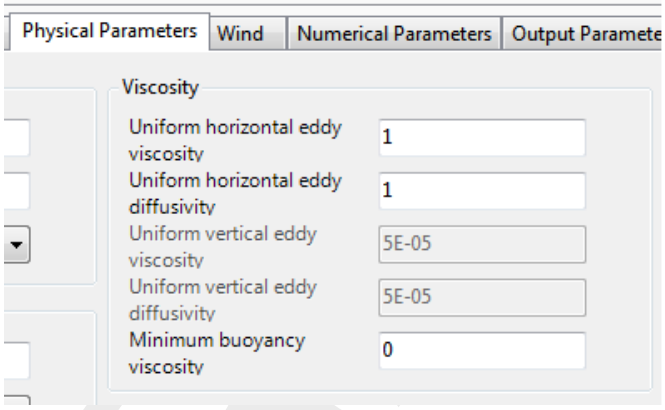


Figure 7.7: *Input parameters for horizontal and vertical eddy viscosities.*

7.3.6 Conveyance in 2D

Bed friction often plays a major role in the discharge capacity and expected maximum water levels of channels and gullies. If we model a trapezoidal channel with sloping sidewalls on a grid with 6 grid cells across the width of the channel, a typical cross section using the standard bed representation with uniform depth appears per cell (Figure 7.8a). In D-Flow FM, we allow for representation of a locally sloping bed as shown in Figure 7.8b.

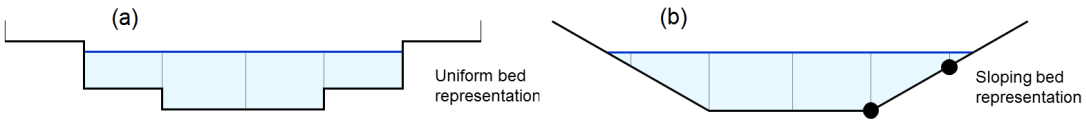


Figure 7.8: *Bed representation with uniform depth levels (a), and locally sloping bed (b).*

The most left and the most right cell are not yet wet in the uniform bed representation. In the sloping bed representation, these outer cells are partly wet, yielding a more accurate description of the total wet cross sectional area. The user can select whether to apply this

more accurate description or not. This can only be done only in combination with a net-node based bathymetry description, i.e. using the keyword `Ibedlevtype = 3` in the `.mdu` file.

For the bed friction in 2D models, one implicitly assumes a fully developed vertical velocity profile, using a logarithmic function of the water depth for the White-Colebrook bed friction formulation, or a one-sixth power function of the water depth for the Manning formulation. In a sloping cell, the local water depth is varying over the width of the cell. In the deeper part flow velocities will be higher than in the shallower part. Bed stresses will vary over the width of a cell with water depth and with the velocity. Integrating the stresses over the width of a cell one can derive the resulting total stress.

The bed friction term is not only a function of the normal velocity component in the direction of the flow link itself, but also depends on the tangential velocity component and with that on the total velocity. For each of the four components water depth, normal velocity, total velocity and Chézy parameter, we assume a linear variation over the width (Figure 7.9).

If we have in the `.mdu` file `Conveyance2D = 3`, the 2D analytic conveyance description using these four linearly varying components is applied. This option shows best grid convergence behaviour. Good grid convergence implies that the converged answer can be achieved on a coarser grid, thus saving computational costs.

If one sets `Conveyance2D = 2`, the tangential velocity component is assumed zero. This method is only applicable on curvilinear grids that are aligned with the flow direction.

If one sets `Conveyance2D = 1`, both the normal and tangential velocity component are assumed constant over the width. Effectively one obtains the so called 'lumped' bed friction approach, with hydraulic radius $R = A/P$, A being the wet cross sectional area and P the wet perimeter. This method works equally well as methods 2 and 1, provided that there is sufficient resolution of a gully in the grid. It is found that when a gully is resolved by more than about 10 or 12 cells, it provides almost identical answers as method 2, while saving some 10 % computational overhead compared to method 2.

Setting `Conveyance2D = -1`, the hydraulic radius is based on a uniform bed level at the velocity point taken as the average bed level of the two surrounding net nodes (depth points in WAQUA terms). This option is identical to the combination of WAQUA option `dpuopt = mean` i.c.m. `dpsopt = max`.

Setting `Conveyance2D = 0`, the hydraulic radius is based on a uniform bed level at the velocity point taken as the average bed level of the two surrounding water level points. This option is not advisable because cell bed levels are taken as the minimum value of the bed levels of attached link. So a min-max operator is invoked, which is not suitable for accuracy.

7.4 Hydrodynamics boundary conditions

In section 4.4.8, the boundary conditions are discussed from the viewpoint of the user interface. In the user interface, the user can specify the locations at which particular boundary conditions are to be imposed. Using section 4.4.8 as a backdrop, the present section discusses the underlying files and fileformats and the way these are interpreted by the computational kernel. Three types of boundary conditions are discussed in this section, namely open boundaries (in section 7.4.1), vertical boundaries (in section 7.4.2) and closed boundaries (in section 7.4.3).

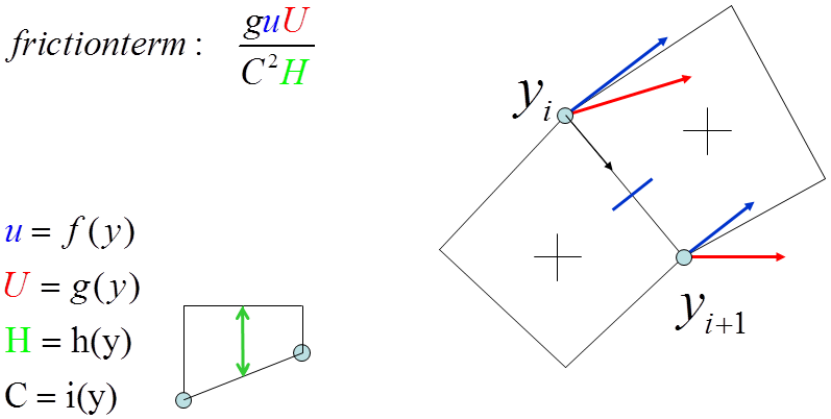


Figure 7.9: *A shematic view of the linear variation over the width for calculating the flow parameters.*

7.4.1 Open boundary conditions

The proper prescription of an open boundary condition along a certain (part of the) rim of the grid can be achieved by considering four elements of the model:

1. a polyline file (extension `.pli`), containing the *locations* at which the boundary conditions should be imposed,
2. a boundary conditions file (extension `.bc`), containing the key *physical information*, such the time dependent information of the quantity under consideration and the physical nature of the quantity itself,
3. an external forcing file (extension `.ext`), in which the connection is laid between the polyline file and the boundary conditons file,
4. the prescription of the single external forcing file, containing the connection between location and physical information, in the master definition file (extension `.mdu`).

These four elements are subsequently discussed in the following.

7.4.1.1 The location of support points

The flow engine needs the specification of support points for the boundary conditions (also see section 4.4.8.1). By default, these support points are a means to construct a series of virtual cell centers along the boundary rim of the grid. Figure 7.10 provides an image of this concept.

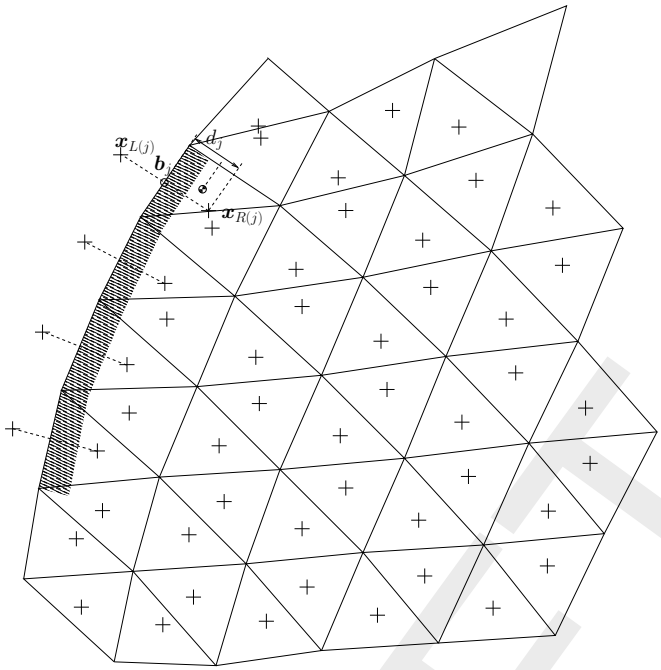


Figure 7.10: *Virtual boundary 'cells' near the shaded boundary; $\boldsymbol{x}_{Lj}$ is the virtual 'cell' center near boundary face j; $\boldsymbol{x}_{R(j)}$ is the inner-cell center; $\mathbf{b}_j$ is the point on face j that is nearest to the inner-cell center*

The support points are stored as one single polyline per boundary condition, marking the rim along which the boundary conditions should hold. The polyline should be drawn in the vicinity of the rim. The user can specify the size of this 'vinicity' by means of the MDU-file keyword `OpenBoundaryTolerance`. The keyword specifies the search tolerance factor between the boundary polyline and the grid cells. The unit of this keyword is the cell size unit (i.e., not metres). By default, this value is 3, which loosely means that in the vinicity of $3\Delta x$ of the grid rim is searched of a boundary condition polyline.

The actual location of a specific boundary location point can be computed in three different ways, dependent on the user's choice for the keyword `izbndpos` in the MDU-file:

1 `izbndpos = 0`: construction of the boundary condition point by means of orthogonal mirroring of the closest cell center,
2 `izbndpos = 1`: construction of the boundary condition point as the orthogonal projection of the closest cell center onto the grid rim,
3 `izbndpos = 2`: construction of the boundary condition point as the actual location of the support points spanning the polyline.

Only the option `izbndpos = 0` is discussed; the other two options are not yet fully operational. The mirroring of the closest cell center is conducted as follows. First, the orthogonal distance from the boundary cell center to the actual rim of the grid is computed: d_j in Figure 7.10. Second, the cell center of the outside virtual cell is defined at a distance d_j outside of the grid. However, the flat area of the cell, say A , at the rim can give rise to an adaptation of this distance. If $\frac{1}{2}\sqrt{A} > d_j$, then the center of the virtual cell is located at the a distance $\frac{1}{2}\sqrt{A}$ away from the grid.

7.4.1.2 Physical information

In the bc-file, multiple types of boundary conditions can be prescribed. In this section, the boundary conditions for the flow motion are briefly reflected on.

Water level

A water level signal is applied at the cell center of the virtual cell outside the grid (ghost cells or mirror cells). Water levels can be imposed as a timeseries or as a harmonic signal. In case of a harmonic signal, the period of the signal can be given as an astronomic component acronym.

If a timeseries is applied to a the first support point of a polyline named arbitraryname, prescribed in some polyline file, then the header of the bc-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = timeseries
Time-interpolation   = linear
Quantity             = time
Unit                 = minutes since YYYY-MM-DD
Quantity             = waterlevelbnd
Unit                 = m
 [two-column data]
```

The data is to be inserted as a two-column array containing the time (in minutes) and the water level itself (in meters w.r.t. the reference level). In case of harmonic components, the header of the bc-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = harmonic
Quantity             = harmonic component
Unit                 = minutes
Quantity             = waterlevelbnd amplitude
Unit                 = m
Quantity             = waterlevelbnd phase
Unit                 = degrees
 [three-column data]
```

The data is to be inserted as a three-column array containing the period (in minutes), the amplitude (in meters) and the phase (in degrees). If the period is T minutes, the amplitude is A meters and the phase is φ degrees, then the signal that is applied reads

$$h(t) = B + A\ \cos(2\pi t/T - \varphi). \tag{7.7}$$

The parameter B can be prescribed by an additional signal with a period specified equal to 0 minutes. As an example, the data series:

```
 0.0  0.5  0.0
745.0  2.0  0.0
```

represents the signal $h(t) = 0.5 + 2.0\ \cos(2\pi t/745)$, with the time t in minutes.

Discharge

A discharge boundary condition is applied at the face-center of the virtual boundary cell. For this, the face-normal velocity is used in combination with the face-center water depth. The face-based water depth in the evaluation of the flow area can optionally be set to a downwind approximation (for an inflowing discharge boundary) with the option `jbasqbnddownwindhs = 1` (default value).

Discharges can be imposed as a timeseries or as a harmonic signal. In case of a harmonic signal, the period of the signal can be given as an astronomic component acronym.

If a timeseries is applied to a the first support point of a polyline named `arbitraryname`, prescribed in some polyline file, then the header of the `bc`-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = timeseries
Time-interpolation   = linear
Quantity             = time
Unit                 = minutes since YYYY-MM-DD
Quantity             = dischargebnd
Unit                 = m3/s
 [two-column data]
```

The data is to be inserted as a two-column array containing the time (in minutes) and the water level itself (in meters w.r.t. the reference level). In case of harmonic components, the header of the `bc`-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = harmonic
Quantity             = harmonic component
Unit                 = minutes
Quantity             = dischargebnd amplitude
Unit                 = m3/s
Quantity             = dischargebnd phase
Unit                 = degrees
 [three-column data]
```

The data is to be inserted as a three-column array containing the period (in minutes), the amplitude (in cubic meters per second) and the phase (in degrees).

Velocity

A velocity boundary condition is applied at the face-center of the virtual boundary cell. Values provided are interpreted as face-normal velocities. Velocities can be imposed as a timeseries or as a harmonic signal. In case of a harmonic signal, the period of the signal can be given as an astronomic component acronym.

If a timeseries is applied to a the first support point of a polyline named `arbitraryname`, prescribed in some polyline file, then the header of the `bc`-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = timeseries
Time-interpolation   = linear
Quantity             = time
Unit                 = minutes since YYYY-MM-DD
Quantity             = velocitybnd
Unit                 = m/s
 [two-column data]
```

The data is to be inserted as a two-column array containing the time (in minutes) and the water level itself (in meters w.r.t. the reference level). In case of harmonic components, the header of the `bc`-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = harmonic
Quantity             = harmonic component
Unit                 = minutes
Quantity             = velocitybnd amplitude
Unit                 = m/s
Quantity             = velocitybnd phase
Unit                 = degrees
 [three-column data]
```

The data is to be inserted as a three-column array containing the period (in minutes), the amplitude (in meters per second) and the phase (in degrees).

Water level gradient

Besides the option to prescribe actual water levels as a boundary condition, D-Flow FM facilitates the prescription of water level *gradients*. Such a Neumann-type boundary condition for the water level can be assigned through the keyword `neumannbnd`. The value of the water level gradient is applied at the face-center.

Water level gradients can be imposed as a timeseries or as a harmonic signal. In case of a harmonic signal, the period of the signal can be given as an astronomic component acronym. If a timeseries is applied to a the first support point of a polyline named `arbitraryname`, prescribed in some polyline file, then the header of the `bc`-file is:

```
[forcing]
Name                 = arbitraryname_0001
Function             = timeseries
Time-interpolation   = linear
Quantity             = time
Unit                 = minutes since YYYY-MM-DD
Quantity             = neumannbnd
```

```
Unit                    = -
 [two-column data]
```

The data is to be inserted as a two-column array containing the time (in minutes) and the water level itself (in meters w.r.t. the reference level). In case of harmonic components, the header of the bc-file is:

```
[forcing]
Name                    = arbitraryname_0001
Function                = harmonic
Quantity                = harmonic component
Unit                    = minutes
Quantity                = neumannbnd amplitude
Unit                    = -
Quantity                = neumannbnd phase
Unit                    = degrees
 [three-column data]
```

The data is to be inserted as a three-column array containing the period (in minutes), the amplitude (in meters per second) and the phase (in degrees). The water level gradient is interpreted positive in the outward-normal direction.

Riemann invariant

At a Riemann boundary we do not allow any outgoing perturbation with respect to some reference boundary state to reflect back from the boundary. This is achieved by prescribing the incoming Riemann invariant. Using the convention of a positive inward normal at the boundary, this can be put as $u_b + 2\sqrt{gH_b}$, with u_b the velocity at the boundary and H_b the total water depth at the boundary. In this expression, we take the boundary values u_b and H_b as the reference boundary state. While applying Riemann boundaries, directional effects are disregarded.

Using linearization and the assumption of a flow field that is initially at rest, the Riemann boundary is rewritten such that is takes the form:

$$\zeta = 2\zeta_b - \sqrt{\frac{H}{g}}u - \zeta_0 \tag{7.8}$$

with ζ the surface level elevation, H the total water depth, g the gravitational acceleration, u the velocity (positive inward) and ζ_0 the initial surface level elevation. Instead of prescribing a combination of the velocity and the water level, we prefer to prescribe only the water level at the boundary, i.e. ζ_b. The value for ζ_b is supposed to be provided by the user (as well as, obviously, the initial surface level elevation ζ_0).

A water level for Riemann boundary can be imposed as a timeseries or as a harmonic signal. In case of a harmonic signal, the period of the signal can be given as an astronomic component acronym. If a timeseries is applied to a the first support point of a polyline named arbitraryname, prescribed in some polyline file, then the header of the bc-file is:

```
[forcing]
Name                    = arbitraryname_0001
```

```
Function               = timeseries
Time-interpolation     = linear
Quantity               = time
Unit                   = minutes since YYYY-MM-DD
Quantity               = riemannbnd
Unit                   = m
 [two-column data]
```

The data is to be inserted as a two-column array containing the time (in minutes) and the water level for Riemann boundary (in meters). In case of harmonic components, the header of the bc-file is:

```
[forcing]
Name                   = arbitraryname_0001
Function               = harmonic
Quantity               = harmonic component
Unit                   = minutes
Quantity               = riemannbnd amplitude
Unit                   = m
Quantity               = riemannbnd phase
Unit                   = degrees
 [three-column data]
```

The data is to be inserted as a three-column array containing the period (in minutes), the amplitude (in meters per second) and the phase (in degrees).

Suppose, as an example, that we have:

- ◇ a flow domain with a bathymetry at a bed level equal to 0 m w.r.t. the reference level,
- ◇ an initial water level equal to 10 m w.r.t. the reference level,
- ◇ a local initial disturbance of the initial water level,
- ◇ and an initial flow field at rest,

and that we aim to prevent reflections at the boundary. In that case, it follows from Equation (7.8) that $\zeta_b = 10$ m w.r.t. the reference level is to be prescribed. Remark that this application only holds for small disturbances of ζ from ζ_b.

Discharge-water level dependency

If a relation between the discharge and the local water level is known on beforehand, then this relation can be provided to the flow model as a table by means of the keyword qhtable. This table, provides the water level ζ as a function of the computed discharge Q.

If a Qh-table is applied to a the first support point of a polyline named arbitraryname, prescribed in some polyline file, then the header of the bc-file is:

```
[forcing]
Name                   = arbitraryname_0001
Function               = qhtable
Quantity               = qhbnd discharge
Unit                   = m3/s
Quantity               = qhbnd waterlevel
```

```
Unit                    = m
 [two-column data]
```

The data is to be inserted as a two-column array containing the discharge (in cubic meters per second) and the water *level* (in meters w.r.t. the reference level).

The user is able to apply a weighting parameter to compromise between the water level computed by the Qh-relation and the water level computed at the previous time step level. This parameter is accessible as the keyword `Qhrelax` in the MDU-file. By default, this parameter is 0.01. As a consequence, the newly computed water level consists of the Qh-relation result for 1 % and for 99 % of the previous time step water level.

7.4.1.3 Example

Recalling the four elementary actions from the beginning of section 7.4.1, the administration in files can be illustrated by means of an example. Suppose, we have a channel that is geometrically modelled by means of the grid shown in Figure 7.11. The domain is 10000 m long and 500 m wide. The bottom left corner coincides with the origin of the geometrical frame of reference.

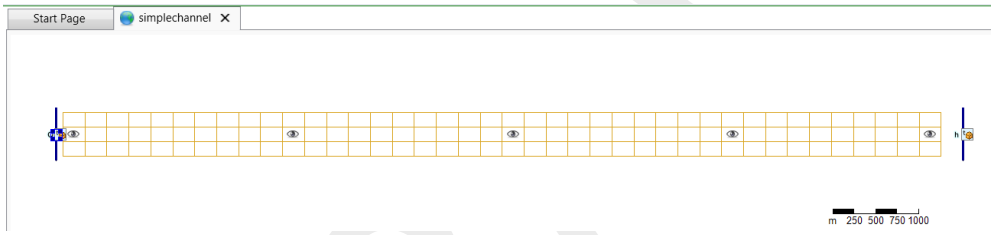


Figure 7.11: *Delta-Shell view of a simple channel covered by a straightforward Cartesian grid. Boundary conditions are prescribed at the left hand side and the right hand size of the domain.*

The domain shown in Figure 7.11 contains two boundaries: on the left hand, a discharge boundary condition is present to present flow entering the domain, on the right hand, a water level boundary condition is set. Having two boundaries, we have two polyline files, in this example: `left.pli` and `right.pli`.

The contents of `left.pli` are:

```
boundaryleft
    2     2
    -80    -50
    -80    550
```

whereas the contents of `right.pli` are:

```
boundaryright
    2     2
```

```
  10250     -50
  10250     550
```

Notice that both polyline files contain the name of the polyline, namely `boundaryleft` and `boundaryright`, respectively. In this example, both the polylines contain *two* support points. For each of these support points, timeseries can be prescribed. In this example, we restrict ourselves to homogeneous boundary conditions. This means that we have to prescribe physical information for the first support points, i.e. for `boundaryleft_0001` and `boundaryright_0001`.

The physical information should be provided in the `bc`-file. In this example, we use the following `bc`-file:

```
[forcing]
Name                = boundaryleft_0001
Function            = timeseries
Time-interpolation  = linear
Quantity            = time
Unit                = minutes since 2001-01-01
Quantity            = dischargebnd
Unit                = m3/s
  0.000000    2500.0
120.000000    3000.0
240.000000    2500.0
360.000000    2000.0
480.000000    2500.0
600.000000    3000.0
720.000000    2500.0
840.000000    2000.0
960.000000    2500.0
1080.000000    3000.0
1200.000000    2500.0
1320.000000    2000.0
1440.000000    2500.0

[forcing]
Name                = boundaryright_0001
Function            = timeseries
Time-interpolation  = linear
Quantity            = time
Unit                = minutes since 2001-01-01
Quantity            = waterlevelbnd
Unit                = m
  0.000000    2.50
1440.000000    2.50
```

This file couples the timeseries for the discharge to the support point named `boundaryleft_0001`. Likewise, the water level boundary, being constant in time, is coupled to the support point named `boundaryright_0001`.

The final specification of the boundary conditions is wrapped up in the external forcing file, with extension `.ext`. In this file, the connection is laid between the quantity of the boundary condition, the name of the polyline file (in which the name of the polyline itself is given) and the forcing file (in which the physical information is provided). In our example, the file `simplechannel.ext` has the following contents:

```
[boundary]
quantity     = dischargebnd
locationfile = left.pli
forcingfile  = simplechannel.bc

[boundary]
quantity     = waterlevelbnd
locationfile = right.pli
forcingfile  = simplechannel.bc
```

The final step is to let the model know that the external forcings file `simplechannel.ext` is the one that should be used. This is to be achieved in the MDU-file:

```
[external forcing]
ExtForceFile                          =
ExtForceFileNew                       = simplechannel.ext
```

Notice that the name is specified at the keyword `ExtForceFileNew`. The other keyword, `ExtForceFile`, should be kept empty, unless *deprecated* `.tim`-files and/or `.cmp`-files are used to prescribe the physical information for the boundaries.

7.4.1.4 Miscellaneous

In the previous sections, the most essential information on the application of boundary conditions is described. Some remaining aspects are discussed in this section.

Artificial boundary layers

Advection terms at the offshore boundary may generate an artificial boundary layer along the boundary. The advection terms containing normal gradients have to be switched off. This is done by utilizing the keyword `jacstbnd` in the MDU-file. By default this keyword `jacstbnd = 0`, keeping the functionality inactive. The keyword can be set to `jacstbnd = 1` to do otherwise.

Smoothing parameter boundary conditions

The solution of the shallow water equations is uniquely determined by a set of initial and boundary conditions. The boundary conditions represent the external forcing and determine the steady state solution. The deviation between the initial condition and the steady state solution generates a transient (mass spring system analogy).

In D-Flow FM, the initial conditions for the water level and velocities are obtained from:

- ◇ The results of a previous run (warm start).
- ◇ User-prescribed (space varying or uniform) input fields (cold start).

The initial values are usually inconsistent with the boundary conditions at the start time of the simulation. This will generate a transient solution consisting of waves with eigen frequencies of the model domain. These waves may be reflected at the boundaries and generate a standing wave system. The waves should be dissipated completely by bottom friction and viscosity

terms or leave the domain through the open boundaries. The damping of the transient solution determines the spin-up time of the numerical model.

To reduce the amplitude of the transient wave and the spin-up time of a model, D-Flow FM has an option to switch on the boundary forcing gradually by use of a smoothing period (parameter T_{smo}). With $F_i(t)$ the initial value at the boundary, $F_b(t)$ the boundary condition signal and $F_b^{smo}(t)$ the boundary conditiona fter smoothing, the boundary forcing is given by:

$$F_b^{smo}(t) = \alpha F_i(t) + (1 - \alpha)F_b(t), \tag{7.9}$$

with:

$$\alpha = \frac{T_{smo} - t}{T_{smo}} \tag{7.10}$$

if $t < T_{smo}$. In case $t \geq T_{smo}$, then the smoothing parameter is set to zero: $\alpha = 0$.

Smoothing is possible both for a warm and a cold start. If the initial conditions are consistent with the boundary conditions at the start time of the simulation then the smoothing time should be set to zero.

Secondary boundary conditions

In section 7.4.1.2, several types of boundary conditions are discussed. In addition, two types of boundary conditions can be applied on top of the canonical types: *normal* velocities and *tangential* velocities. The associated keyword are `normalvelocitybnd` and `tangentialvelocitybnd`, respectively.

7.4.2 Vertical boundary conditions

Vertical boundary conditions close the system of shallow water equations at the bed level and the free surface level. Please refer to the Delft3D-FLOW User Manual, Section 9.4.1.1.

7.4.3 Shear-stresses at closed boundaries

A closed boundary is situated at the transition between land and water. At a closed boundary, two boundary conditions have to be prescribed. One boundary condition has to do with the flow normal to the boundary and the other one with the shear-stress along the boundary. A closed sidewalls is always considered as impermeable. For the shear stress along the boundary, the possible conditions to be prescribed are free-slip (zero tangential shear-stress), partial-slip and full-slip.

For large-scale simulations, the influence of the shear-stresses along closed boundaries can be neglected. Free slip is then applied for all closed boundaries. For simulations of smallscale flow (e.g. laboratory scale), the influence of the side walls on the flow may no longer be neglected. This option has been implemented for closed boundaries and dry points *but not for thin dams*. The reason is that the shear stress at a thin dam is dependent on the side (double valued).

Along the side walls, the tangential shear stress is calculated based on a logarithmic law of the wal. The friction velocity u_* is determined by the logarithmic law for a rough wall, with side wall roughness y_0 and the velocity in the first grid point near the side wall. Let Δy_s be the grid size normal to the sidwall, then:

$$|\vec{u}_{\text{sidewall}}| = \frac{u_*}{\kappa} \ln\left(1 + \frac{\Delta y_s}{2y_0}\right) \tag{7.11}$$

The choice for the way tangial shear stress are computed can be inserted through the key `irov` in the MDU-file (under `[physics]`):

- ◇ the case `irov = 0` treats the side walls as free-slip walls (default),
- ◇ the case `irov = 1` treats the side walls as partial-slip walls,
- ◇ the case `irov = 2` treats the side walls as no-slip walls.

If the choice for partial-slip walls is made, then a specific wall roughness value should be prescribed in the MDU-file. For this, the keyword `wall_ks` should be used (under `[physics]` in the MDU-file). The computational engine interpretes this value as Nikuradse roughness k_s. The value for y_0 is computed as $y_0 = k_s/30$.

7.5 Artificial mixing due to sigma-coordinates

The σ-transformation is boundary-fitted in the vertical. The bottom boundary and free surface are represented smoothly. The water column is divided into the same number of layers independent of the water depth. In a σ-model, the vertical resolution increases automatically in shallow areas.

For steep bottom slopes combined with vertical stratification, σ-transformed grids introduce numerical problems for the accurate approximation of horizontal gradients both in the baroclinic pressure term and in the horizontal diffusion term. Due to truncation errors artificial vertical mixing and artificial flow may occur, Leendertse (1990) and Stelling and Van Kester (1994). This artificial vertical transport is sometimes called "creep".

Let z_b be the position of the bed and H the total water depth. If we consider the transformation from Cartesian co-ordinates to σ co-ordinates, defined by:

$$x = x^* \, , \, y = y^* \, , \, \sigma = \frac{z - z_b}{H} \quad (H = \zeta - z_b) \tag{7.12}$$

as result $\sigma = 0$ at the bed level and $\sigma = 1$ at the free surface. The horizontal pressure gradient reads:

$$\frac{\partial p}{\partial x} = \frac{\partial p^*}{\partial x^*}\frac{\partial x^*}{\partial x} + \frac{\partial p^*}{\partial \sigma}\frac{\partial \sigma}{\partial x} = \frac{\partial p^*}{\partial x^*} - \frac{1}{H}\left(\frac{\partial z_b}{\partial x} + \sigma\frac{\partial H}{\partial x}\right)\frac{\partial p^*}{\partial \sigma}. \tag{7.13}$$

In case of vertical stratification near steep bottom slopes, small pressure gradients at the left-hand side may be the sum of relatively large terms with opposite sign at the right-hand side.

Small truncation errors in the approximation of both terms result in a relatively large error in the pressure gradient.

This artificial forcing produces artificial flow.

The truncation errors depend on the grid sizes Δx and Δz.

Observations of this kind has led to the notion of "hydrostatic consistency", see also Figure 7.12. In the notation used by Haney (1991) this consistency relation is given by:

$$\left|\frac{\sigma}{H}\frac{\partial H}{\partial x}\right| < \left|\frac{\partial \sigma}{\partial x}\right| \tag{7.14}$$

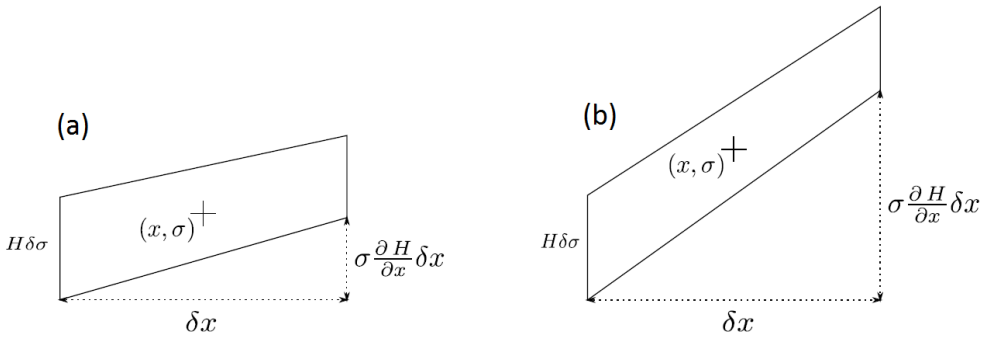


Figure 7.12: *Example of a hydrostatic consistent and inconsistent grid; (a)* $H\delta\sigma > \sigma\frac{\partial H}{\partial x}\delta x$*, (b)* $H\delta\sigma < \sigma\frac{\partial H}{\partial x}\delta x$

From this equation, it can be seen that by increasing the number of σ-levels the consistency condition will eventually be violated.

Similarly, for the horizontal diffusion term, the transformation from Cartesian co-ordinates to σ co-ordinates leads to various cross derivatives. For example, the transformation of a simple second order derivative leads to:

$$\frac{\partial^2 c}{\partial x^2} = \frac{\partial^2 c^*}{\partial x^{*2}} + \left(\frac{\partial \sigma}{\partial x}\right)^2 - \frac{\partial^2 c^*}{\partial \sigma^2} + 2\frac{\partial \sigma}{\partial x} - \frac{\partial^2 c^*}{\partial x^* \partial \sigma} + \frac{\partial^2 \sigma}{\partial x^2} - \frac{\partial c^*}{\partial \sigma} \tag{7.15}$$

For such a combination of terms it is difficult to find a numerical approximation that is stable and positive, see Huang and Spaulding (1996). Near steep bottom slopes or near tidal flats where the total depth becomes very small, truncations errors in the approximation of the horizontal diffusive fluxes in σ-co-ordinates are likely to become very large, similar to the horizontal pressure gradient.

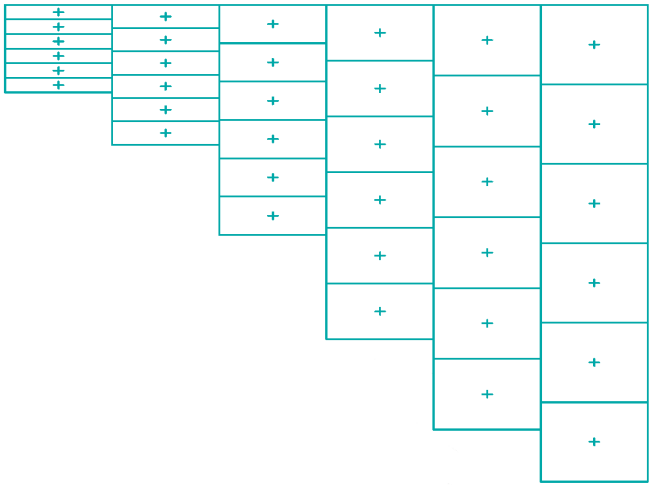


Figure 7.13: *Finite Volume for diffusive fluxes and pressure gradients*

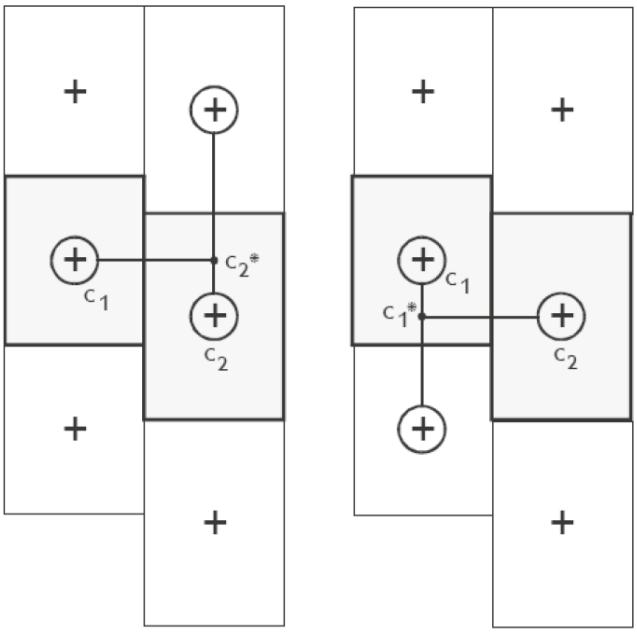


Figure 7.14: *Left and right approximation of a strict horizontal gradient*

In D-Flow FM the stress tensor is redefined in the σ co-ordinate system assuming that the horizontal length scale is much larger than the water depth (Blumberg and Mellor, 1985) and that the flow is of boundary-layer type. The horizontal gradients are taken along σ-planes. This approach guarantees a positive definite operator, also on the numerical grid (Beckers *et al.*, 1998).

If the same approach is used for the horizontal diffusion operator in the transport equation:

$$\frac{\partial^2 c}{\partial x^2} \approx \frac{\partial^2 c^*}{\partial x^{*2}} \tag{7.16}$$

Horizontal diffusion will lead to vertical transport of matter through vertical stratification interfaces (pycnocline) which is nonphysical. A more accurate, strict horizontal discretization is needed.

In D-Flow FM an option is available that minimises artificial vertical diffusion and artificial flow due to truncation errors. A method has been implemented which gives a consistent, stable and monotonic approximation of both the horizontal pressure gradient and the horizontal diffusion term, even when the hydrostatic consistency condition equation is not fulfilled. This "anti-creep" option is based upon a Finite Volume approach; see Figure 7.13. The horizontal diffusive fluxes and baroclinic pressure gradients are approximated in Cartesian co-ordinates by defining rectangular finite volumes around the σ-co-ordinate grid points. Since these boxes are not nicely connected to each other, see Figure 7.14, an interpolation in z co-ordinates is required to compute the fluxes at the interfaces.

Since the centres of the finite volumes on the left-hand side and right-hand side of a vertical interval are not at the same vertical level, a z-interpolation of the scalar concentration c is needed to compute strictly horizontal derivatives. The values obtained from this interpolation are indicated by c_1^* and c_2^* respectively in Figure 7.14. (Stelling and Van Kester, 1994) apply

a non-linear filter to combine the two consistent approximations of the horizontal gradient,

$$
\begin{array}{l}
s_1 = \left(c_2^* - c_1\right)/\Delta x \text{ and } s_2 = \left(c_2 - c_1^*\right)/\Delta x \\
\texttt{If } s_1 \times s_2 < 0 \texttt{ Then} \\
\quad \frac{\Delta c}{\Delta x} = 0 \\
\texttt{Else} \\
\quad \frac{\Delta c}{\Delta x} = sign\left(s_1\right) \times \min\left(\left|s_1\right|, \left|s_2\right|\right) \\
\texttt{Endif}
\end{array}
\tag{7.17}
$$

If an interval has only grid boxes at one side, the derivative is directly set to zero. The horizontal fluxes are summed for each control volume to compute the diffusive transport. The integration of the horizontal diffusion term is explicit with time step limitation:

$$\Delta t \leq \frac{1}{D_H}\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right) \tag{7.18}$$

The derivatives are used in the integral for the baroclinic pressure force in the momentum equation:

$$P_x\left(x,z\right) = \frac{1}{\rho_0}\int_z^\zeta g\frac{\partial \rho\left(x,s\right)}{\partial x}ds \tag{7.19}$$

Originally, this approach was implemented in Delft3D-FLOW. Slørdal (1997) stated that the above approximation may sometimes produce errors of the same sign which leads to a systematic underestimation of the baroclinic pressure term. This underestimation can be ascribed to the non-linear filter, which selects the minimum of the two gradients under consideration. This limiter is fully analogous to the min-mod limiter used for the construction of monotone advection schemes (Hirsch, 1990). Since the same approximation of the horizontal gradient is used for the horizontal diffusion flux, it is important to ensure that the difference operator is positive definite in order to get physically realistic solutions. The maximum and minimum of a variable being transported by diffusion do not increase or decrease (min-max principle). By taking the minimum of the gradients, Stelling and Van Kester (1994) show that, the min-max principle is fulfilled. Beckers *et al.* (1998) show that any nine-point consistent linear discretization of the horizontal diffusion on the σ-grid does not fulfil the min-max principle. From numerical tests Slørdal (1997) concluded that the underestimation is reduced by increasing the vertical resolution, but is sometimes enhanced by increasing the horizontal resolution.

Let s_4 be a consistent approximation of the horizontal gradient $s_4 = (s_1 + s_2)/2$. Slørdal (1997) suggested to take s_4 as approximation of the horizontal gradient. He calls his approach the "modified Stelling and Van Kester scheme". It is equivalent to linear interpolation at a certain z-level before taking the gradient. It is more accurate than taking the minimum of the absolute value of the two slopes s_1 and s_2 but it does not fulfil the min-max principle for the diffusion operator. It may introduce wiggles and a small persistent artificial vertical diffusion (except for linear vertical density distributions). Due to the related artificial mixing, stratification may disappear entirely for long term simulations, unless the flow is dominated by the open boundary conditions.

By introducing an additional approximation of the horizontal gradient in the filter algorithm defined by $s_3 = (c_2 - c_1)/\Delta x$, the stringent conditions of the minimum operator can be relaxed somewhat. The drawback of underestimation of the baroclinic pressure force reported by Slørdal (1997) can be minimised without loosing that the method fulfils the min-max principle. This third gradient s_3, which is consistent for $\min(|s_1|, |s_2|) < s_3 < \max(|s_1|, |s_2|)$, has point-to-point transfer properties and therefore leads to a positive scheme for sufficiently small time steps. The following non-linear approach presently available in D-Flow FM is both

consistent and assures the min-max principle:

$$
\begin{array}{l}
\texttt{If } s_1 \times s_2 < 0 \texttt{ Then} \\
\quad \frac{\Delta c}{\Delta x} = 0 \\
\texttt{Elseif } |s_4| < |s_3| \texttt{ Then} \\
\quad \frac{\Delta c}{\Delta x} = s_4 \\
\texttt{Elseif } \min\left(|s_1|, |s_2|\right) < |s_3| < \max\left(|s_1|, |s_2|\right) \texttt{ Then} \\
\quad \frac{\Delta c}{\Delta x} = s_3 \\
\texttt{Else} \\
\quad \frac{\Delta c}{\Delta x} = \text{sign}\left(s_1\right) \min\left(|s_1|, |s_2|\right) \\
\texttt{Endif}
\end{array}
\tag{7.20}
$$

The method requires a binary search to find the indices of neighbouring grid boxes, which is time consuming. The increase in computation time is about 30 %.

If the streamlines are strictly horizontal, transport of matter discretised on a σ co-ordinate grid may still generate some numerical vertical diffusion by the discretisation of the advection terms.

7.6 Secondary flow

The flow in a river bend is basically three-dimensional. The velocity has a component in the plane perpendicular to the river axis. This component is directed to the inner bend near the riverbed and directed to the outer bend near the water surface, see Figure 7.15.

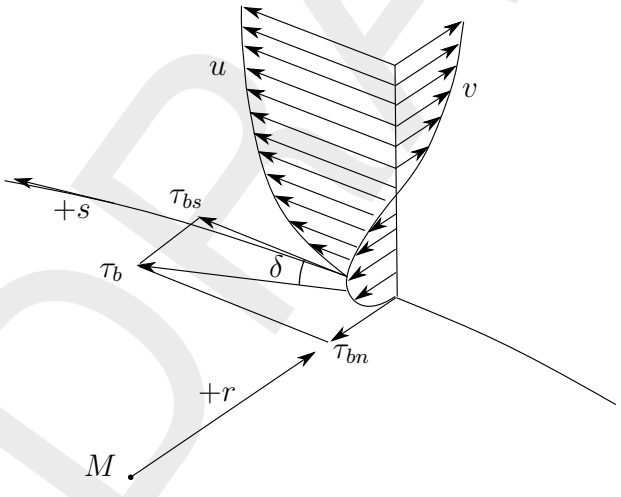


Figure 7.15: *Vertical profile secondary flow (v) in river bend and direction bed stress*

This so-called "secondary flow" (spiral motion) is of importance for the calculation of changes of the riverbed in morphological models and the dispersion of matter. In a 3D model the secondary flow is resolved on the vertical grid, but in 2D depth-averaged simulations the secondary flow has to be determined indirectly using a secondary flow model. It strongly varies over the vertical but its magnitude is small compared to the characteristic horizontal flow velocity.

7.6.1 Definition

The secondary flow will be defined here as the velocity component $v\,(\sigma)$ normal to the depth-averaged main flow. The spiral motion intensity of the secondary flow I is a measure for the magnitude of this velocity component along the vertical:

$$I = \int_0^1 |v\,(\sigma)|\, d\sigma \tag{7.21}$$

A vertical distribution for a river bend is given in Figure 7.15. The spiral motion intensity I leads to a deviation of the direction of the bed shear stress from the direction of the depth-averaged flow and thus affects the bedload transport direction. This effect can be taken into account in morphological simulations.

The component of the bed shear stress normal to the depth-averaged flow direction τ_{br} reads:

$$\tau_{br} = -2\rho\alpha^2 \left(1 - \frac{\alpha}{2}\right) |\boldsymbol{u}|\, I \tag{7.22}$$

where α is defined in Equation (7.33) and $|\boldsymbol{u}|$ is the magnitude of the depth-averaged velocity. To take into account the effect of the secondary flow on the depth-averaged flow, the depth-averaged shallow water equations have to be extended with:

- ◇ An additional advection-diffusion equation to account for the generation and adaptation of the spiral motion intensity.
- ◇ Additional terms in the momentum equations to account for the horizontal effective shear stresses originating from the secondary flow.

7.6.2 Depth-averaged continuity equation

The depth-averaged continuity equation is given by:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = Q \tag{7.23}$$

where u and v indicate the depth-averaged velocities along Cartesian axis.

7.6.3 Momentum equations in horizontal direction

The momentum equations in x- and y-direction are given by:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fu = -\frac{1}{\rho_0}P_x - \frac{gu\sqrt{u^2+v^2}}{C_{2D}^2 h} + F_x + F_{sx} + M_x \tag{7.24}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fv = -\frac{1}{\rho_0}P_v - \frac{gv\sqrt{u^2+v^2}}{C_{2D}^2 h} + F_y + F_{sy} + M_y \tag{7.25}$$

The fourth term in the right-hand side represents the effect of the secondary flow on the depth-averaged velocities (shear stresses by depth-averaging the non-linear acceleration terms).

7.6.4 Effect of secondary flow on depth-averaged momentum equations

To account for the effect of the secondary flow on the depth-averaged flow, the momentum equations have to be extended with additional shear stresses. To close the equations these stresses are coupled to parameters of the depth-averaged flow field. The main flow is assumed to have a logarithmic velocity profile and the secondary flow originates from a multiplication of a universal function with the spiral motion intensity, see Kalkwijk and Booij (1986). Depth averaging of the 3D equations leads to correction terms in the depth-averaged momentum equations for the effect of spiral motion:

$$F_{sx} = \frac{1}{h}\left(\frac{\partial hT_{xx}}{\partial x} + \frac{\partial hT_{xy}}{\partial y}\right) \tag{7.26}$$

$$F_{sy} = \frac{1}{h}\left(\frac{\partial hT_{xy}}{\partial x} + \frac{\partial hT_{yy}}{\partial y}\right) \tag{7.27}$$

with the shear-stresses, resulting from the secondary flow, modelled as:

$$T_{xx} = -2\beta uv \tag{7.28}$$

$$T_{xy} = T_{yx} = \beta(u^2 - v^2) \tag{7.29}$$

$$T_{yy} = 2\beta uv \tag{7.30}$$

and:

$$\beta = \beta^* \frac{h}{R_s^*} \tag{7.31}$$

$$\beta^* = \beta_c \left(5\alpha - 15.6\alpha^2 + 37.5\alpha^3\right) \tag{7.32}$$

$\beta_c \in [0, 1]$, correction coefficient specified by you,

$$\alpha = \frac{\sqrt{g}}{\kappa C_{2D}} < \frac{1}{2} \tag{7.33}$$

with R_s^* the effective radius of curvature of a 2D streamline to be derived from the intensity of the spiral motion and κ the Von Kármán constant. The spiral motion intensity is computed by Equation (7.34). The limitation on α, Equation (7.33), is set to ensure that the length scale L_a in Equation (7.41) is always positive. For $\beta_c = 0$, the depth-averaged flow is not influenced by the secondary flow.

Remark:

- ◇ Equation (7.33) effectively means a lower limit on C_{2D}.

7.6.5 The depth averaged transport equation for the spiral motion intensity

The variation of the spiral motion intensity I in space and time, is described by a depth-averaged advection-diffusion equation:

$$\frac{\partial hI}{\partial t} + \frac{\partial uhI}{\partial x} + \frac{\partial vhI}{\partial y} = h\frac{\partial}{\partial x}\left(D_H \frac{\partial I}{\partial x}\right) + h\frac{\partial}{\partial x}\left(D_H \frac{\partial I}{\partial y}\right) + hS \tag{7.34}$$

with:

$$S = -\frac{I - I_e}{T_a} \tag{7.35}$$

$$I_e = I_{be} - I_{ce} \tag{7.36}$$

$$I_{be} = \frac{h}{R_s}\left|\boldsymbol{u}\right| \tag{7.37}$$

$$I_{ce} = f\frac{h}{2} \tag{7.38}$$

$$\left|\boldsymbol{u}\right| = \sqrt{u^2 + v^2} \tag{7.39}$$

$$T_a = \frac{L_a}{\left|\boldsymbol{u}\right|} \tag{7.40}$$

$$L_a = \frac{(1 - 2\alpha)\, h}{2\kappa^2 \alpha} \tag{7.41}$$

and R_s the radius of curvature of the stream-line defined by:

$$\frac{u_s}{R_s} = -\frac{\partial u_r}{\partial s} \tag{7.42}$$

with u_s and u_r the components along and perpendicular to the streamline. The effective radius of curvature to be used for the evaluation of the coefficient β, Equation (7.32), reads:

$$R_s^* = \frac{h\left|\boldsymbol{u}\right|}{I} \tag{7.43}$$

To guarantee stability the effective radius of curvature is bounded by the following empirical relation:

$$R_s^* \geq 10h \tag{7.44}$$

The above formulas account for two sources of secondary flow:

- ◇ The centrifugal force in case of curved streamlines, I_{be}.
- ◇ The effect of the Coriolis force, I_{ce}.

7.7 Drying and flooding

Estuaries and coastal embayments contain large, shallow, and relatively flat areas separated and interleaved by deeper channels and creeks. When water levels are high, the entire area is covered by water. But as tide falls, the shallow areas are exposed, and ultimately the flow is confined only to the deeper channels. The dry tidal flats may occupy a substantial fraction of the total surface area. The accurate reproduction of covering or uncovering of the tidal flats is an important feature of numerical flow models based on the shallow water equations.

Many rivers have compound channels, consisting of a main channel that always carries flow (the summer bed) and one or two flood plains which only convey flow during extreme river

discharges (the winter bed). The summer bed is surrounded by low dykes, which could be overtopped if the river discharge increases. The winter-bed is surrounded by much higher dykes, which are designed to protect the polders against water levels due extreme river discharges. The flooding of the flood plains increases the drainage capacity of the river and reduces the local water level gradients.

In a numerical model, the process of drying and flooding is represented by removing grid points from the flow domain that become *dry* when the tide falls and by adding grid points that become *wet* when the tide rises. Drying and flooding is constrained to follow the sides of grid cells. In this section, we specify the algorithms which have been used to determine the moment when a grid cell (water level point) or cell boundary (velocity point) becomes dry or wet. Drying and flooding gives a discontinuous movement of the closed boundaries and may generate small oscillations in water levels and velocities. The oscillations introduced by the drying and flooding algorithm are small if the grid sizes are small and the bottom has smooth gradients.

Essential elements of the wetting and drying algorithm are the definition of the water level, the definition of the bed level and the criteria for setting a velocity and/or water level point wet or dry. In the following subsections, these three items will be discussed.

7.7.1 Definitions

In section 7.3.1, the locations of the primary flow variables (water level and flow velocity) have been described. Through Figure 7.3 it has been clarified that the water level is computed at the location of the circumcenter (cell center), whereas the face normal flow velocity is computed at the midpoint of each cell face (face center).

For the computation of these two primary variables, the level of the bed must be known both at the cell center and at the face center. The user can specify the way these values are interpreted from the available bathymetry by means of the MDU-file keywords `bedlevtyp` and `conveyance2D`. For a proper understanding of the possibilities of D-Flow FM, Figure 7.16 is provided with a three-dimensional representation of two adjacent triangular cells.

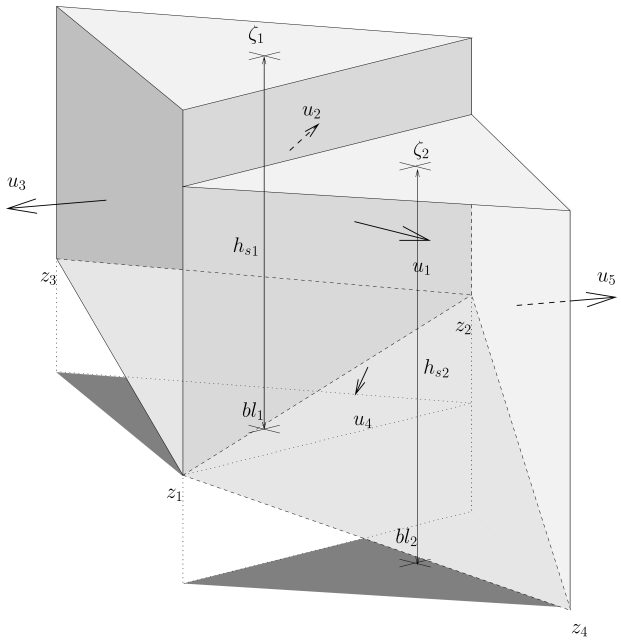


Figure 7.16: *Definition of the water levels, the bed levels and the velocities in case of two adjacent triangular cells.*

To the keyword `bedlevtyp`, the values `1`, `2`, `3`, `4`, `5` and `6` can be assigned. For the keyword `conveyance2D`, the values `-1`, `0`, `1`, `2` and `3` are available.

The most common case is the definition of the bed levels at the corner nodes of the cell and a choice for the keyword `bedlevtyp = 3`. Depending on the choice for `conveyance2D`, the face center bed levels and cell center bed levels are computed.

7.7.1.1 Piecewise constant approach for the bed level

In principle, the bed levels are considered as piecewise constant in space. This approach is followed if `conveyance2D` < 1. The keyword `bedlevtyp` can be used in combination with the piecewise constant approach as highlighted in the table below. Note that the bed level is defined with respect to the reference level (not to be confused with a water depth given as a positive value downwards). With `conveyance2D` < 1, we have:

Keyword	Value	Cell center bed level	Face center bed level
bedlevtyp	1	user specified	the highest cell center bed level considering the two cells next to the face
bedlevtyp	2	the lowest face center bed level considering all the faces of the cell	user specified
bedlevtyp	3	the lowest face center bed level considering all the faces of the cell	the mean corner bed level considering the two corner nodes the face is connecting
bedlevtyp	4	the lowest face center bed level considering all the faces of the cell	the minimum corner bed level considering the two corner nodes the face is connecting
bedlevtyp	5	the lowest face center bed level considering all the faces of the cell	the maximum corner bed level considering the two corner nodes the face is connecting
bedlevtyp	6	the mean corner bed level considering all the corners of the cell	the highest cell center bed level considering the two cells next to the face

The former Delft3D-FLOW version, running on curvilinear meshes, has utilized the piecewise constant approach for bed levels as well. The treatment of the bed level itself is, however, different from D-Flow FM. In Delft3D, the user can distinctly specify the treatment type for the cell center bed level and the face center bed level. In D-Flow FM, the choice for the one implies the choice for the other. A strict, *exact* match of settings for which Delft3D-FLOW and D-Flow FM treat the bed similarly, is not facilitated. Hence, the user himself should take care in comparing the Delft3D-FLOW results and D-Flow FM results when it comes to the bed level treatment settings.

7.7.1.2 Piecewise linear approach for the bed levels

A piecewise linear bed level approach can be chosen for through setting conveyance2D ≥ 1. In this case, only the approach for bedlevtyp equal to 3, 4 and 5 is affected. With conveyance2D ≥ 1, we have:

Keyword	Value	Cell center bed level	Face center bed level
bedlevtyp	3, 4, 5	the lowest corner node bed level considering all the nodes of the cell	linearly varying from the bed level at the one corner node to the bed level at the other corner node

Notice that the choice for either bedlevtyp equal to 3, 4 or 5 does not imply different bed level treatment approaches. For the case conveyance2D ≥ 1, the bed is assumed linearly varying within a face only to compute the wet cross-sectional area of the vertical fase;

it should, however, be remarked that for the computation of the water column volume in a cell, this linear variation of the bed is *not* taken into account.

7.7.1.3 Hybrid bed level approach

In addition to the previously described bed level treatment approaches, D-Flow FM facilitates a hybrid approach for the computation of the cell center bed level by means of the keywords `blminabove` and `blmeanbelow`. In this approach, the cell center bed level is computed as the mean of the associated face center bed levels, be it only below the user specified level `blmeanbelow`. For levels above the user specified level `blminabove`, the minimum value of the associated face center bed levels is used. In between these two user specified levels, the bed levels are constructed by means of a linear interpolation between the two approaches' results.

7.7.2 Specification in Delta Shell

The specification of the treatment of the bed level locations can be achieved through the tab fields 'Numerical Parameters' and 'Physical Parameters'.

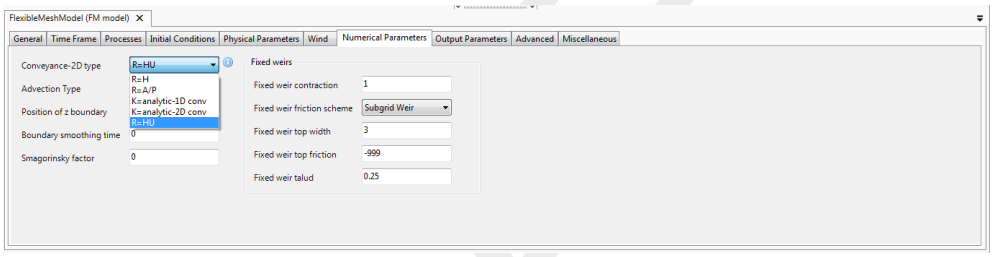


Figure 7.17: *Specification of the conveyance option in Delta Shell.*

The tab field 'Numerical Parameters' contains the choice for the conveyance options: see Figure 7.17).

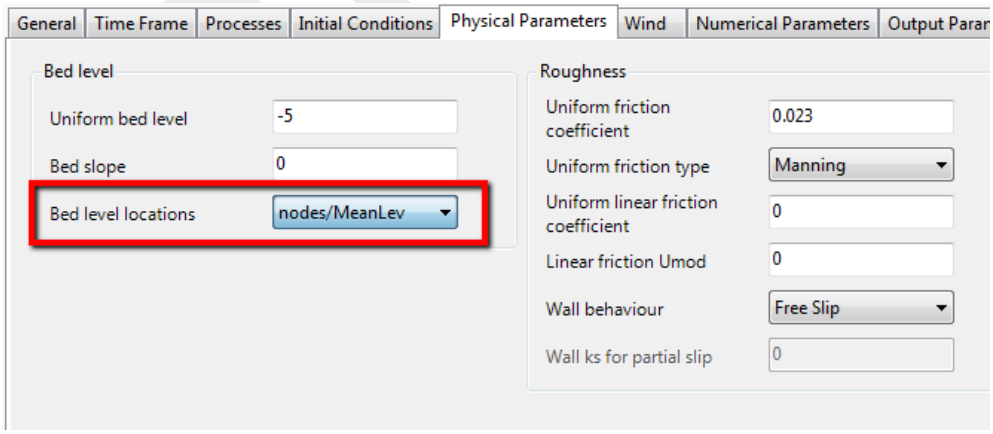


Figure 7.18: *Specification of the bed level treatment type in Delta Shell.*

The tab field 'Physical Parameters' contains the choice for the Bed level locations. Five options are facilitated: `bedlevtyp` numbers 1 up to 5; the option 6 is not facilitated in the user interface.

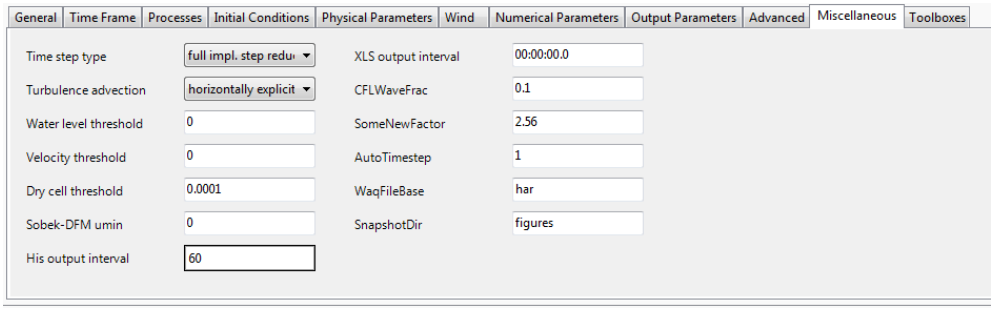


Figure 7.19: *Specification of the hybrid bed options (with keywords* `blminabove` *and* `blmeanbelow`*).*

By means of the tab field 'Miscellaneous', the hybrid options with the keywords `blminabove` and `blmeanbelow` can be enabled.

7.8 Intakes, outfalls and coupled intake-outfalls

Many engineering studies concern the design of intakes and outfalls. For instance, studies about positioning of waste water diffusers or coupled intake-outfall design for cooling water at power plants. Intakes and outfalls can be modeled using sinks and sources. A source is a point in the model where a discharge Q in [m^3/s] is prescribed by a time series ASCII file (section D.2.1) with at least two and maximum four columns.

1 When salinity and temperature are not used in the computation:
Model expects two columns, where the first column is the time in minutes, the second is the discharge in [m^3/s].
2 When either salinity or temperature is used in the computation:
Model expects three columns, where the first column is the time in minutes, the second is the discharge in [m^3/s], the third column contains either the salinity in [ppt] or the temperature in [°C]. Note that third column can be either salinity or temperature depending which constituent is used in the model and which is not.
3 When salinity and temperature are present in the model:
Model expects four columns, where the first column is the time in minutes, the second is the discharge in [m^3/s], the third column contains the salinity in [ppt] and the fourth contains the temperature in [°C].

The location of the source or sink is specified in a polyline file (section B.2), containing a polyline with either multiple points or just one point. If two or more points are specified, a coupled source sink pair is made, the first point is the FROM (or sink) point, the last point is the TO (or source) point. Three variants may occur:

1 Sink point side lies inside a grid cell A, source point also lies inside a grid cell B (A may equal B, but that is rarely useful): water is extracted from cell A and transported to B.
2 Sink point lies outside of the grid, source point lies in a grid cell B: water is discharged into B, a bit like an inflow discharge boundary condition.
3 Sink side lies inside a grid cell A, source side lies outside of the grid: water is extracted from A, a bit like an outflow discharge boundary condition.

Specifying a negative discharge value effectively interchanges the role of the source and sink points. If only one point is in the $<*$.pli$>$ file, it is assumed to be a source point. Specifying a negative discharge turns the source into a sink.

For 3D computations, the polyline file should have a third column with z-values. It is good practice to change the $<*.\text{pli}>$ file into a $<*.\text{pliz}>$ file. The z-values are used to determine in which vertical grid cell the source and/or sink lie. The layer number can vary in time in sigma models.

In the case of a coupled pair of sink source points (variant 1), the third and fourth column with the salinity and temperature specification are interpreted as delta salinity and delta temperature. So the values at the source point become the values at the sink point plus the specified delta values.

The sources and sinks are specified in the $<*.\text{ext}>$ file in a way similar to the boundary conditions:

```
QUANTITY=discharge_salinity_temperature_sorsin
FILENAME=chan1_westeast.pli  # A file 'chan1_westeast.tim', with same basename
                             # as the polyline should be present
FILETYPE=9
METHOD  =1
OPERAND =O
AREA    =1.5
```

The specified area in the last line of this file determines (together with the specified discharge) the amount of momentum uQ that is released at the source point. This is currently only implemented in advection scheme 33 (cf. D-Flow FM TRM (2015) on Momentum advection). Omitting this line or specifying a zero area switches off the release of momentum at the source point. The direction of the discharged momentum is in direction of the last two points of the polyline. So a one point polyline is momentumless. Both in 2D and 3D, the momentum can only be directed in horizontal direction.

Sources and sinks are treated explicity in the numerical scheme. This implies that the actual discharged or extracted amounts of water are limited by the velocity Courant condition $Q\Delta t/V < 1$. Not doing so could lead to severe timestep restrictions. Consider for instance a specified extraction in case the extraction point has fallen dry. In that case, a real pump would not be able to extract water and the specified extraction is more likely an input error than an actual description of a physically feasible situation. So, we limit the specified discharges to the local velocity Courant restriction. By specifying observation cross-sections (section 4.4.2.3), one can compare prescribed discharges to the discharges that were actually realised in the model. In case of large differences, the discharge should probably be distributed over a larger number of gridcells, or the extraction channel that feeds the extraction point should be dredged.

When outfalls are adjacent to a closed model boundary, one might consider specifying a discharge boundary instead of a point source. These are treated more implicitly in the numerical scheme and are preferable for that reason.

When modelling freshwater inflow from a river into a sea, the vertical distribution of the discharge that one should specify depends on the amount of detail available for modelling the saline water - fresh water interface. If the river is modeled with sufficient detail, and the river is well mixed at the upstream model boundary, the mixing process can be part of the modelling and the river can be discharged over the whole vertical. If the mixing process cannot be resolved in the model, for instance if the river is modeled as a point discharge adjacent to a closed boundary, make sure that the whole river is discharged into the top layer or in the top

layers, depending on the estimated thickness of the fresh water plume at the discharge cell. If one would have distributed the river discharge over the whole vertical, the size of the fresh water plume would be underestimated because of too much mixing at the river discharge cell.

For example input files see example directories:

➢ `f17_sources_sinks/c010_sourcesink_2D/`
➢ `f17_sources_sinks/c020_sourcesink_3D/`

7.9 Equations of state for the density

The density of water ρ is a function of salinity (s) and temperature (t).

In D-Flow FM we copied the implementation from Delft3D of the formulation derived by Eckart (1958) that is based on a limited number of measurements dating from 1910 (only two salinities at 5 temperatures). In the original equation the pressure is present, but at low pressures the effect on density can be neglected.

Eckart formulation

The Eckart formulation is given by (Eckart, 1958):

Range: $0 < T < 40$ °C, $0 < s < 40$ ppt

$$\rho = \frac{1\,000 P_0}{\lambda + \alpha_0 P_0}, \tag{7.45}$$

where:

$$\lambda = 1\,779.5 + 11.25T - 0.074\,5T^2 - (3.80 + 0.01T)\,s, \tag{7.46}$$
$$\alpha_0 = 0.698\,0, \tag{7.47}$$
$$P_0 = 5\,890 + 38T - 0.375T^2 + 3s. \tag{7.48}$$

with the salinity s in [ppt] and the water temperature T in [°C].

The keyword that selects the equation of state in the mdu file is called Idensform. The influence of salinity and or temperature on water motion through the baroclinic pressure can be switched off by setting Idensform=0

UNESCO formulation

The UNESCO formulation is given by (UNESCO, 1981a):

Range: $0 < T < 40$ °C, $0.5 < s < 43$ ppt

$$\rho = \rho_0 + As + Bs^{3/2} + Cs^2 \tag{7.49}$$

where

$$\rho_0 = 999.842\,594 + 6.793\,952 \times 10^{-2}T - 9.095\,290 \times 10^{-3}T^2 + \\ + 1.001\,685 \times 10^{-4}T^3 - 1.120\,083 \times 10^{-6}T^4 + 6.536\,332 \times 10^{-9}T^5 \tag{7.50}$$

$$A = 8.244\,93 \times 10^{-1} - 4.089\,9 \times 10^{-3}T + 7.643\,8 \times 10^{-5}T^2 + \\ - 8.246\,7 \times 10^{-7}T^3 + 5.387\,5 \times 10^{-9}T^4 \tag{7.51}$$

$$B = -5.724\,66 \times 10^{-3} + 1.022\,7 \times 10^{-4}T - 1.654\,6 \times 10^{-6}T^2 \tag{7.52}$$

$$C = 4.831\,4 \times 10^{-4} \tag{7.53}$$

with the salinity s in [ppt] and the water temperature T in [°C].

Note: The UNESCO formulation is set as default.

Remarks:

- ◇ Equation (7.51) is known as the International Equation of State for Seawater (EOS80) and is based on 467 data points. The standard error of the equation is 3.6×10^{-3} kg/m^3 (Millero and Poisson, 1981).
- ◇ The Practical Salinity Scale (UNESCO, 1981b, Par. 3.2) and the International Equation of State are meant for use in all oceanic waters. However, these equations should be used with caution in waters that have a chemical composition different from standard seawater. In such waters, densities derived with the methods based on practical salinity measurements and the International Equation of State may deviate measurably from the true densities. However, in water masses different in composition from standard seawater the *differences* in densities derived by the new equations involve only very small errors.

Recommendation

The UNESCO formulae serve as an international standard. Further, the UNESCO formulae show the correct temperature of 4 degrees Celsius where fresh water has its maximum density. The latter is of importance for thermal stratification in deep lakes in moderate climate zones. Therefore we recommend the application of the UNESCO formulae and to select the Eckart formulation only for consistence with previous projects in which it has been used. At this moment the default is UNESCO.

Nevertheless, the UNESCO formulae have their limitations as they are based on the general properties of seawater mixed with fresh water. Particularly in cases where marginal density differences play a role, typically lakes, a variable mineral content of the water may create density differences not detected by just temperature and salinity. For such dedicated cases, you are warranted to check the accuracy of the UNESCO formulae against experimental density-relations derived from the (lake) water. In case of deviations or other constituents determining the water density, we then recommend to contact the Helpdesk for further assistance such as the implementation of a more dedicated density formulation.

7.10 Tide generating forces

Numerical models of tidal motion in coastal seas generally do not account for the direct local influence of the tide generating forces. The amount of water mass in these models is relatively small and the effect of these forces on the flow can be neglected. In that case, tidal motion can often be reproduced with sufficient accuracy just by prescribing the tidal forcing along open model boundaries.

In models covering larger seas or oceans, the contribution of the gravitational forces on the water motion increases considerably and can no longer be neglected. In a global model, open boundaries are absent and the tidal motion can only be induced by including tide generating forces. Because tidal forces only play a significant role in the larger models, and because the exact position of each computational point on earth must be known, we have implemented these forces only in combination with spherical coordinates. By default, tide generating forces is switched on in spherical models. You can switch it off by setting in the mdu file: Tidalforcing=0

The tide generating forces originate from the Newtonian gravitational forces of the terrestrial system (Sun, Moon and Earth) on the water mass. The equilibrium tide is the tide that would result from the gravitational forces if a solid earth would be completely covered by an ocean of about 21.5 km deep, such that the wave propagation speed would match the speed of the celestial forces over the ocean surface. The interacting frequencies that result can be grouped as diurnal, semi diurnal and long periodic. The total number of tide generating frequencies that is evaluated in the computation is a tradeoff between required accuracy and computational cost. Per default, we use a set of 60 frequencies, similar to TRIWAQ.

A smaller set of 11 main frequencies as used in Delft3D can also be selected by setting in the MDU file :

```
Doodsonstart =  57.555
Doodsonstop  = 275.555
Doodsoneps   =   0.030
```

The full set of 484 components can be selected by specifying:

```
Doodsonstart =  55.565
Doodsonstop  = 375.575
Doodsoneps   =   0.000
```

For the set of 60 components these numbers are:

```
Doodsonstart =  55.565
Doodsonstop  = 375.575
Doodsoneps   =   0.030
```

The earth itself is deformed by the celestial forces, this is called the solid earth tide. An estimate of this influence is based on the work of Love (1927), is included in the total tide generating potential.

We have gratefully applied the Fortran subroutines written by E.J.O. Schrama. Details on the implementation of tide generating forces can be found in his lecture notes Schrama (2007).

In order to save computation cost, the tidal potential is not computed for each computational point, but on a grid with a resolution of 1 degree in both the South-North and West-East direction.

The tidal and surge motions of the seas and ocean also deform the earth , which is called tidal loading. Next to that, the water at some point is attracted by all moving water elsewhere on the globe. This is called self attraction. The combined influence of these two processes is implemented in a beta version.

8 Transport of matter

8.1 Introduction

In D-Flow FM, transport is formulated as

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_{V(t)} c\,\mathrm{d}V + \int_{\partial V(t)} c(\boldsymbol{u}-\boldsymbol{v})\bullet\boldsymbol{n}\,\mathrm{d}S = \int_{\partial V(t)} (K\nabla c)\bullet\boldsymbol{n}\,\mathrm{d}S + \int_{V(t)} s\,\mathrm{d}V, \tag{8.1}$$

where $V(t)$ is a three-dimensional control volume, c is a concentration, $\boldsymbol{u}$ the flow velocity field, $\boldsymbol{v}$ the velocity of the (vertically) moving control volume, K is a diagonal matrix $K = diag(\kappa,\kappa,\kappa_z)$ with diffusion coefficients and s a source term. For two-dimensional (depth-averaged) flow, we obtain

$$\frac{\partial hc}{\partial t} + \nabla\bullet(h\boldsymbol{u}c) = \nabla\bullet(h\kappa\nabla c) + hs, \tag{8.2}$$

where h is the water depth. In case of three-dimensional (layer-averaged) flow, with Δz a layer thickness from $z_0(x,y,t)$ to $z_1(x,y,t)$, we obtain

$$\begin{aligned}\frac{\partial \Delta z\, c}{\partial t} + \nabla\bullet(\Delta z\,\boldsymbol{u}c) + [\omega_{z_1}c]_{z=z_1} - [\omega_{z_0}c]_{z=z_0} = \nabla\bullet(\Delta z\,\kappa\nabla c) + \\ \left[\kappa_z\frac{\partial c}{\partial z} - \kappa\nabla z_1\bullet\nabla c\right]_{z=z_1} - \left[\kappa_z\frac{\partial c}{\partial z} - \kappa\nabla z_0\bullet\nabla c\right]_{z=z_0} + \Delta z\, s,\end{aligned} \tag{8.3}$$

where by $\boldsymbol{u}$ and ∇ still the horizontal components are meant, i.e. $\boldsymbol{u} = (u,v)^{\mathrm{T}}$ and $\nabla = \left(\frac{\partial}{\partial x},\frac{\partial}{\partial y}\right)^{\mathrm{T}}$ and κ_z is the vertical diffusion coefficient. Furthermore ω_{z_0} and ω_{z_1} are the velocity component normal and relative to the moving $z=z_0$ and $z=z_1$ layer interfaces respectively. Note that taking $c=1$ yields

$$\omega_{z_1} + \frac{\partial z_1}{\partial t} = \omega_{z_0} - \nabla\bullet(\Delta z\boldsymbol{u}) + \frac{\partial z_0}{\partial t}, \tag{8.4}$$

which, combined with a zero-flux condition at the bed, recursively defines ω_{z_0} and ω_{z_1} for all layers.

We apply Equation (8.2) and Equation (8.3) to transport of

- ◇ salinity,
- ◇ temperature,
- ◇ suspended sediment,
- ◇ tracers,
- ◇ other, intentionally not mentioned,

and ultimately to the water itself (the continuity equation) to obtain the relative layer interface velocities as expressed by Equation (8.4).

In the following we will highlight various physical and numerical settings in D-Flow FM. First and foremost, it is important to understand that there are *two* numerical implementations available, that differ slightly. These are selected with the keyword `transportmethod` in the mdu-file:

```
transportmethod = 0
```

or

```
transportmethod = 1                # default.
```

The difference mainly concerns the treatment of vertical advection as explained in the next section. Note that tracers are only available with `transportmethod` '1'.

8.2 Some words about suspended sediment transport

In D-Flow FM *two* sediment models are available.

The first is a genuine D-Flow FM implementation, while the second is adopted from Delft3D-SED and is only available in combination with `transportmethod` '1'.

For a description of the latter, see chapter 18 in this manual.

We will not discuss the specifics of either of the two sediment models further and confine ourselves to mentioning the relevant settings that concern suspended sediment transport of the one of chapter 18.

8.3 Transport processes

Looking at the equations that govern transport of matter, we can identify three processes, namely advection, diffusion and sources/sinks. The next sections will describe the relevant user settings.

8.3.1 Advection

Advection of matter is expressed by the term $\nabla \bullet (h\boldsymbol{u}c)$ in Equation (8.2) in the case of two-dimensional modelling.

In three dimensions, we make a distinction between horizontal advection $\nabla \bullet (\Delta z\, \boldsymbol{u}c)$ and vertical advection $[\omega_{z_1} c]_{z=z_1} - [\omega_{z_0} c]_{z=z_0}$ in Equation (8.3). A higher-order numerical approximation of these terms can be obtained by setting their "limiter type" to an appropriate value. Setting the limiter type to "0" reduces the numerical approximation to a low-order upwind method (i.e. severe limiting).

Although not restricted to the advection of salinity only, the choices for *all* matter are set with keyword `limtypsa` in the mdu-file, for example

```
[numerics]
  limtypsa = 0         # first-order upwind, or
```

or

```
[numerics]
  limtypsa = 4         # MC limiter
```

For `transportmethod`=1, only the monotonized central (MC) limiter is available and used when `limtypsa`>0, for example 1 or 2 or 6, but not -1. For `transportmethod`=0 other limiters are available as well and the MC limiter is selected by setting `limtypsa` to '4', which is its default value. We will not discuss the non-default limiters.

In three-dimensional modelling horizontal advection is similarly as in two dimension, but now vertical advection can be selected with the keyword `Vertadvtypsal` in the mdu-file, i.e.

```
[numerics]
  Vertadvtypsal = 0        # no vertical advection
```

or

```
[numerics]
  Vertadvtypsal = 5        # default
```

The various combinations of `transportmethod` and `Vertadvtypsal` have the following meaning:

Vertadv-typsal	transport method 0 space	0 time	1 space	1 time
0	none	none	none	none
1	1^{st} order upwind	forward Euler	salt and temperature: central, other: higher-order limited upwind	salt and temperature: θ-method, other: forward Euler
2	central	forward Euler		
3	1^{st} order upwind	θ-method		
4	central	θ-method		
5	neg. stratification or water depth < `chkadvd`: 1^{st} order upwind, otherwise: central	θ-method		
6	as 5	as 5	temperature: central, other: higher-order limited upwind	temperature: θ-method, other: forward Euler

For the limited higher-order upwind discretization the MC limiter is used if `transportmethod`=1 if `limtypsa`>0, regardless of its specific value, and 1^{st}-order upwind if `limtypsa`=0.

8.3.2 Diffusion

Diffusion of matter is expressed by the term $\nabla \bullet (h\kappa\nabla c)$ for two-dimensional modelling and a similar and additional terms in three dimensions, see Equation (8.3).

Clearly, we have horizontal diffusivity κ and vertical diffusivity κ_z. The horizontal diffusivity κ is a summation of

- ◇ the molecular diffusivity κ_l, only for `transportmethod`=1. We use the following values:

$$\kappa_l = \begin{cases} \frac{1}{700}\nu_l, & \text{salt,} \\ \frac{1}{6.7}\nu_l, & \text{temperature,} \\ 0\nu_l, & \text{sediment,} \\ 0\nu_l, & \text{tracers,} \end{cases} \tag{8.5}$$

  where $\nu_l = 10^{-6}\ m^2/s$ is the kinematic viscosity,
- ◇ a background diffusivity, user-specified as
  - □ spatially varying values by `horizontaleddydiffusivitycoefficient` in the ext-file, or

- a uniform value `Dicouv` in the mdu-file,

in that order of precedence, and

- a contribution from turbulent transport expressed as ν_t/σ_t, where ν_t is the eddy viscosity coefficient and σ_t is the turbulent Prandtl-Schmidt number for which the following values are used:

$$\sigma_t = \begin{cases} 0.7, & \text{salt,} \\ 0.7, & \text{temperature,} \\ 1.0, & \text{sediment,} \\ 1.0, & \text{tracers.} \end{cases} \tag{8.6}$$

Horizontal diffusion is turned off when `Dicouv`=0.

The user has to be aware of the following. The explicit nature of the horizontal diffusion terms in the time-integration method imposes a condition on the time step for numerical stability. Recall that we have a similar condition due to explicit horizontal advection. Although we always decrease the time step to satisfy the advection-related time step criterion, we do not do so for diffusion. Instead, diffusion is limited such that our time step is restricted by advection only, or by a user-specified maximum time step if it is smaller. For further details, consult D-Flow FM TRM (2015).

Be aware that the modelled *diffusion may be be smaller than anticipated. However, the actual* effective *diffusion encountered may be (much) larger than anticipated due to numerical diffusion of the advection scheme.*

Not considering suspended sediment, and similar to the horizontal diffusivity, the vertical diffusivity κ_z is a summation of

- the molecular diffusivity κ_l (for both transport methods), see Equation (8.5), not added for transport method '1' if `Dicoww`=0,
- a background vertical diffusivity, user-specified as a uniform value `Dicoww` in the mdu-file, and
- a contribution from turbulent transport, similar to its horizontal counterpart, but with the horizontal viscosity coefficient now replaced by the vertical (eddy) viscosity coefficient.

Time integration is performed with a method that does not impose an additional constraint on the time step. Unlike horizontal diffusion which is limited to ensure numerical stability while maintaining the time-step size, vertical diffusion is *not* limited.

Vertical diffusion is turned off when, again not considering suspended sediment:

- for transport method '0': `Dicoww`=0 or `Vertadvtypsal`=1 or `Vertadvtypsal`=2,
- for both transport methods: the water depth is smaller than a threshold $10^{-2}\,m$.

For the vertical diffusivity of suspended sediment, see chapter 18.

8.3.3 Sources and sinks

Sources and sinks may be provided by an entry in the ext-file as follows:

```
quantity=discharge_salinity_temperature_sorsin
```

This simultaneously prescribes sources and sinks of

- ◇ water volume itself (i.e. discharge),
- ◇ salinity, and
- ◇ temperature.

See section 7.8 for more details.

8.3.4 Forester filter

The central vertical advection schemes of transport method '0' may cause nonphysical oscillations, or wiggles, especially near regions of large gradients. The user has the option to suppress salt and temperature wiggles with a filter inspired by the so-called Forester filter. This filter also penalizes physically unstable stratification. The maximum number of iterations in the filter is controlled with keywords `Maxitverticalforestersal` for salt (default 100) and `Maxitverticalforestertem` for temperature (default 0, i.e. no filtering). Note that the filter is unavailable when using transport method '1'.

8.4 Transport boundary and initial conditions

The equations that govern transport of matter are complemented with boundary and initial conditions. We make the distinction between "horizontal" boundaries, that are either "open" or "closed", and vertical boundaries, only relevant for three-dimensional modelling.

8.4.1 Open boundary conditions

At "horizontal" open boundaries the following boundary conditions are applied:

- ◇ salt, temperature and tracers:
  - ▫ inflow: user-specified Dirichlet condition,
  - ▫ outflow: homogeneous Neumann condition,
- ◇ suspended sediment: see chapter 18.

The user-specified Dirichlet conditions are supplied in the usual manner through the ext-file, i.e.

```
quantity=salinitybnd
```

for salt and

```
quantity=temperaturebnd
```

for temperature. Boundaries conditions for multiple tracers may be defined by appending their name to the `tracerbnd` keyword, for example

```
quantity=tracerbndMY_FIRST_TRACER
```

and

```
quantity=tracerbndMY_SECOND_TRACER
```

8.4.2 Closed boundary conditions

At "horizontal" closed boundaries zero-flux conditions are applied.

8.4.3 Vertical boundary conditions

At the "vertical" boundaries, i.e. at the bed and at the water surface, zero-flux conditions are applied, except for temperature that is, see chapter 10 for further details on that matter.

8.4.4 Thatcher-Harleman boundary conditions

Consider (a part of) an open boundary where the flow reverts from outflowing to inflowing. According to section 8.4.1, at that very moment a Dirichlet condition becomes effective and a user-specified boundary value is prescribed. This value does in general not reflect the true condition at the boundary and causes a discontinuous temporal behaviour. The so-called Thatcher-Harleman boundary condition is intended to regularize this behaviour. The actual value applied at the boundary is smoothly transformed from the last value under outflow conditions to the user-specified value under inflow conditions within a user-specified *return time*. This return time is prescribed with the keyword `return_time` in the “new style” external forcings file for boundary condition, for example

```
[boundary]
quantity     = salinitybnd
locationfile = tfl_01.pli
forcingfile  = tfl.bc
return_time  = 250
```

See section B.5 for more details on this format. Note that the Thatcher-Harleman boundary conditions are only available currently for two-dimensional modelling.

8.4.5 Initial conditions

We will only consider intitial conditions for salinity, temperature and tracers. For initial sediment concentrations, see chapter 18.

Initial conditions are specified in three possible ways, namely

- ◇ a horizontally spatially varying field in the usual way through the ext-file,
- ◇ a vertical profile in three dimensions, horizontally uniformly distributed, for salinity and temperature only in the ext-file, and
- ◇ uniform values for salinity and temperature in the mdu-file.

In the ext-file we have

```
quantity     = initialsalinity
```

for the intial salinity, and

```
quantity     = initialsalinitytop
```

for the initial salinity in the top layer in case of three-dimensional modelling. When specified, the initial salinity field is linearly distributed from the "initialsalinity" in the lowest layer to the

"initialsalinitytop" in the top layer. When *not* specified, the initial salinity field is vertically uniformly distributed.

The initial temperature field is prescribed with

```
quantity     = initialtemperature
```

which in three dimensions is vertically uniformly distributed.

A horizontally uniformly distributed vertical profile of salinity and temperature can be prescribed with `initialverticalsalinityprofile` and `initialverticaltemperatureprofile` respectively, for example for salinity

```
QUANTITY=initialverticalsalinityprofile
FILENAME=inisal.pol
FILETYPE=10
METHOD=4
OPERAND=O
```

The polygon file contains (z, salinity) value pairs, where z is the vertical coordinate in meters. For example for linearly varying salinity from 30 to 20 ppt from -10 to 0 m:

```
L1
2 2
-10 30
 0 20
```

The initial field of an arbitrary number of tracers are prescribed in the same way, except for the user-specified tracername that is added to the keyword `initialtracer`, similar to the tracer boundary conditions, for example

```
quantity=initialtracerMY_FIRST_TRACER
```

and

```
quantity=initialtracerMY_SECOND_TRACER
```

Default values for salinity and temperature are defined in the mdu-file with `Initialsalinity` and `Initialtemperature` respectively.

9 Turbulence

Note: The 3D-implementation is a β-functionality.

D-Flow FM solves the Navier-Stokes equations for an incompressible fluid. Usually the grid (horizontal and/or vertical) is too coarse and the time step too large to resolve the turbulent scales of motion. The turbulent processes are "sub-grid". The primitive variables are space- and time-averaged quantities. Filtering the equations leads to the need for appropriate closure assumptions.

For 3D shallow water flow the stress and diffusion tensor are an-isotropic. The horizontal eddy viscosity coefficient ν_H and eddy diffusivity coefficient D_H are much larger than the vertical coefficients ν_V and D_V, i.e. $\nu_H \gg \nu_V$ and $D_H \gg D_V$. The horizontal coefficients are assumed to be a superposition of three parts:

1 a part due to molecular viscosity.
2 a part due to "2D-turbulence",
3 a part due to "3D-turbulence" see Uittenbogaard *et al.* (1992) and

The 2D part is associated with the contribution of horizontal motions and forcings that cannot be resolved ("sub-grid scale turbulence") by the horizontal grid (Reynolds averaged or eddy resolving computations). The 3D part is referred to as the three-dimensional turbulence and is computed following one of the turbulence closure models, described in this section. For 2D depth-averaged simulations, the horizontal eddy viscosity and eddy diffusivity coefficient should also contain a contribution due to the vertical variation of the horizontal flow (Taylor shear dispersion).

The background horizontal viscosity coefficient ν_H^{back} and eddy diffusivity coefficient D_H^{back} (constant or space-varying) can be specified in the Delta Shell GUI and D-Flow FM's MDU file. In Delft3D-FLOW a sub-grid scale model, HLES for 2D-turbulence is implemented. (see Delft3D-FLOW User Manual). In D-Flow FM we have not yet achieved this, but we implemented a simple horizontal model, the so called Smagorinsky model, so that we can at least cope with possibly very large grid size variations.

The horizontal eddy coefficients are typically an order of magnitude larger than the vertical coefficients determined by the turbulence closure model.

In D-Flow FM, two two-equation turbulence closure models have been implemented to determine the vertical eddy viscosity (ν_V) and vertical eddy diffusivity (D_V):

1 k-ε turbulence closure model.
2 k-τ turbulence closure model(in β-version).

The k-τ model is a mathematical variant of the k-ε model. Both models solve equations for production, dissipation and transport of turbulent kinetic energy k. In the k-ε model the dissipation rate of turbulent kinetic energy ε, is modeled, whereas in the k-τ model the dissipation timescale τ is modeled.

Both models are based on the so-called eddy viscosity concept of Kolmogorov (1942) and Prandtl (1945).

A brief description of each of these turbulence closure model will be given further on in this section, for more details we refer to Uittenbogaard *et al.* (1992). The k-ε model has been used in tidal simulations by Baumert and Radach (1992) and Davies and Gerritsen (1994), for

stratified flow of a river plume by Postma *et al.* (1999) and for the evolution of a thermocline by Burchard and Baumert (1995).

For strongly stratified flows it is important to introduce suitably chosen constant ambient (background) mixing coefficients, because the mixing coefficients computed by turbulence models with shear production only, reduce to zero. In the latter situation the vertical layers are completely de-coupled (frictionless). Disturbances are hardly damped and also the erosion of the vertical stratification is reduced to molecular diffusion.

Based on our experience with highly stratified flows we suggest applying an ambient or background vertical eddy viscosity in the order of 10^{-4} m^2/s for the vertical exchange of momentum. This value corresponds with field measurements in the Rotterdam Waterway, The Netherlands.

Eddy diffusivity

The vertical eddy diffusivity is a scaled form of the eddy viscosity according to:

$$D_{3D} = \frac{\nu_{3D}}{\sigma_c}. \tag{9.1}$$

Parameter σ_c is the Prandtl-Schmidt number. Its numerical value depends on the substance c.

In Delft3D-FLOW the following settings of σ_c are used:

- ◇ In all cases, regardless the turbulence closure model, $\sigma_c = 0.7$ for the transport of heat, salinity, and tracer concentrations. For suspended sediment concentrations in online sediment transport computations, $\sigma_c = 1.0$.
- ◇ For the transport of turbulent kinetic energy k in the k-L model and k-ε model $\sigma_c = 1.0$, and for the transport of turbulent kinetic energy dissipation ε in the k-ε model $\sigma_c = 1.3$.

In the mathematical formulation, the fluxes are instantaneously influenced by changes in the vertical gradients of velocity and density. A physical adjustment time of the turbulence to the variations of the vertical gradients, is not taken into account. The fluxes are not a monotone function of the gradients. For the transport equation of heat, for small temperature gradients the heat flux increases when the temperature gradient increases but for large temperature gradients the heat flux decreases because the vertical eddy diffusivity is damped. For large values of the density gradients and small values of the velocity gradients, the vertical diffusion equation becomes mathematically ill-posed Barenblatt *et al.* (1993), and the computed vertical profiles may become discontinuous (stepwise). The number of “steps” is dependent on the vertical grid.

The numerical scheme for the vertical advection of heat and salt (central differences) may introduce small vertical oscillations. This computational noise may enhance the turbulent mixing. D-Flow FM has a vertical filtering technique to remove this noise and to reduce the undesirable mixing. For more details, see section 8.3.4.

In strongly-stratified flows, the turbulent eddy viscosity at the interface reduces to zero and the vertical mixing reduces to molecular diffusion. To account for the vertical mixing induced by shearing and breaking of short and random internal gravity waves, we suggest to apply an ambient eddy diffusivity in the order of 10^{-4} to 10^{-5} m^2/s dependent on the Prandtl-Schmidt number. In Delft3D-FLOW for stable stratified flows, the minimal eddy diffusivity may be based on the Ozmidov length scale L_{oz}, specified by you and the Brunt-Väisälä frequency of internal

waves:

$$D_V = \max\left(D_{3D}, 0.2L_{oz}^2\sqrt{-\frac{g}{\rho}\frac{\partial\rho}{\partial z}}\right). \tag{9.2}$$

This feature is still to be implemented in D-Flow FM

For a detailed description of the turbulence closure models of Delft3D-FLOW we refer to Rodi (1984) and Uittenbogaard *et al.* (1992).

9.1 k-ε turbulence model

In the k-ε turbulence model, transport equations must be solved for both the turbulent kinetic energy k and for the energy dissipation ε. The mixing length L is then determined from ε and k according to:

$$L = c_D\frac{k\sqrt{k}}{\varepsilon}. \tag{9.3}$$

In the transport equations, the following two assumptions are made:

- ◇ The production, buoyancy, and dissipation terms are the dominating terms.
- ◇ The horizontal length scales are larger than the vertical ones (shallow water, boundary layer type of flows).

Because of the first assumption, the conservation of the turbulent quantities is less important and the transport equation is implemented in a non-conservation form.

The transport equations for k and ε are non-linearly coupled by means of their eddy diffusivity D_k, D_ε and the dissipation terms. The transport equations for k and ε are given by:

$$\frac{\partial k}{\partial t} + u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} + \frac{\omega}{\zeta - z_b}\frac{\partial k}{\partial \sigma} = \\ + \frac{1}{(\zeta - z_b)^2}\frac{\partial}{\partial\sigma}\left(D_k\frac{\partial k}{\partial\sigma}\right) + P_k + P_{kw} + B_k - \varepsilon, \tag{9.4}$$

$$\frac{\partial \varepsilon}{\partial t} + u\frac{\partial \varepsilon}{\partial x} + v\frac{\partial \varepsilon}{\partial y} + \frac{\omega}{\zeta - z_b}\frac{\partial \varepsilon}{\partial \sigma} = \\ \frac{1}{(\zeta - z_b)^2}\frac{\partial}{\partial\sigma}\left(D_\varepsilon\frac{\partial \varepsilon}{\partial\sigma}\right) + P_\varepsilon + P_{\varepsilon w} + B_\varepsilon - c_{2\varepsilon}\frac{\varepsilon^2}{k}. \tag{9.5}$$

with

$$D_k = \frac{\nu_{mol}}{\sigma_{mol}} + \frac{\nu_{3D}}{\sigma_k} \quad \text{and} \quad D_\varepsilon = \frac{\nu_{3D}}{\sigma_\varepsilon} \tag{9.6}$$

In the production term P_k of turbulent kinetic energy, the horizontal gradients of the horizontal velocity and all the gradients of the vertical velocities are neglected. The production term is given by:

$$P_k = \nu_{3D}\frac{1}{(\zeta - z_b)^2}\left[\left(\frac{\partial u}{\partial\sigma}\right)^2 + \left(\frac{\partial v}{\partial\sigma}\right)^2\right]. \tag{9.7}$$

For small-scale applications (e.g. simulation of laboratory flume), you can switch on a more extended production term P_k of turbulent kinetic energy (option “partial slip”, rough side wall) given by:

$$P_k = 2\nu_{3D}\left[\frac{1}{2\left(\zeta - z_b\right)^2}\left\{\left(\frac{\partial u}{\partial \sigma}\right)^2 + \left(\frac{\partial v}{\partial \sigma}\right)^2\right\}\right] + \\ + 2\nu_{3D}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]. \quad (9.8)$$

In this expression, ν_{3D} is the vertical eddy viscosity, prescribed by Equation (9.16). In Equation (9.7) and Equation (9.8) it has been assumed that the gradients of the vertical velocity w can be neglected with respect to the gradients of the horizontal velocity components u and v. The horizontal and vertical (σ-grid) curvature of the grid has also been neglected.

The turbulent energy production due to wave action is given by P_{kw}, but has not been implemented yet in D-Flow FM: Wave forcing in 3D models is being prepared for an upcoming release.

Near the closed walls the normal derivative of the tangential velocity is determined with the law of the wall:

$$\frac{\partial u}{\partial y} = \frac{u_*}{\kappa y}. \quad (9.9)$$

In stratified flows, turbulent kinetic energy is converted into potential energy. This is represented by a buoyancy flux B_k defined by:

$$B_k = \frac{\nu_{3D}}{\rho\sigma_\rho}\frac{g}{h}\frac{\partial \rho}{\partial \sigma} \quad (9.10)$$

with the Prandtl-Schmidt number $\sigma_\rho = 0.7$ for salinity and temperature and $\sigma_\rho = 1.0$ for suspended sediments.

The production term P_ε and the buoyancy flux B_ε are defined by:

$$P_\varepsilon = c_{1\varepsilon}\frac{\varepsilon}{k}P_k, \quad (9.11)$$

$$B_\varepsilon = c_{1\varepsilon}\frac{\varepsilon}{k}\left(1 - c_{3\varepsilon}\right)B_k, \quad (9.12)$$

with L prescribed by Equation (9.3) and the calibration constants by (Rodi, 1984):

$$c_{1\varepsilon} = 1.44, \quad (9.13)$$

$$c_{2\varepsilon} = 1.92, \quad (9.14)$$

$$c_{3\varepsilon} = \begin{cases} 0.0 & \text{unstable stratification} \\ 1.0 & \text{stable stratification} \end{cases} \quad (9.15)$$

In D-Flow FM in the ε-equation for stable stratification the buoyancy flux is switched off, so $c_{3\varepsilon} = 1.0$ and for unstable stratification the buoyancy flux is switched on $c_{3\varepsilon} = 0.0$.

The energy production and energy dissipation due to waves, the terms P_{kw} and $P_{\varepsilon w}$ in Equation (9.4) and Equation (9.5), have not been implemented yet in D-Flow FM: Wave forcing in 3D models is being prepared for an upcoming release.

The coefficients of the 3D k-ε turbulence closure model as implemented in D-Flow FM are not the same as in the depth-averaged k-ε turbulence closure model (Rodi, 1984), therefore for depth-averaged simulations, the k-ε turbulence closure model is not available for you.

The vertical eddy viscosity ν_{3D} is determined by:

$$\nu_{3D} = c'_\mu L\sqrt{k} = c_\mu \frac{k^2}{\varepsilon}, \tag{9.16}$$

with:

$$c_\mu = c_D c'_\mu. \tag{9.17}$$

To solve the transport equation, boundary conditions must be specified. A local equilibrium of production and dissipation of kinetic energy is assumed at the bed which leads to the following Dirichlet boundary condition:

$$k|_{\sigma=-1} = \frac{u_{*b}^2}{\sqrt{c_\mu}}. \tag{9.18}$$

The friction velocity u_{*b} at the bed is determined from the magnitude of the velocity in the grid point nearest to the bed, under the assumption of a logarithmic velocity profile. The bed roughness (roughness length) may be enhanced by the presence of wind generated short crested waves.

In case of wind forcing, a similar Dirichlet boundary condition is prescribed for the turbulent kinetic energy k at the free surface:

$$k|_{\sigma=0} = \frac{u_{*s}^2}{\sqrt{c_\mu}}. \tag{9.19}$$

In the absence of wind, the turbulent kinetic energy k at the surface is set to zero.

At open boundaries, the turbulent energy k is computed using the equation for k without horizontal advection. For a logarithmic velocity profile this will approximately lead to the following linear distribution based on the shear-stress at the bed and at the free surface:

$$k\left(z\right) = \frac{1}{\sqrt{c_\mu}}\left[u_{*b}^2\left(1 - \frac{z - z_b}{\zeta - z_b}\right) + u_{*s}^2\frac{z - z_b}{\zeta - z_b}\right]. \tag{9.20}$$

For ε the bed boundary condition reads:

$$\frac{\partial \varepsilon}{\partial z} = \frac{\left(\varepsilon_{b+1} - \varepsilon_b\right)}{\Delta z_b} = \frac{u_*^3}{\kappa\left(\frac{\Delta z_b}{2} + 9z_0\right)^2} \tag{9.21}$$

The k-ε turbulence model was successfully applied for the simulation of stratified flow in the Hong Kong waters (Postma *et al.*, 1999) and verified for the seasonal evolution of the thermocline (Burchard and Baumert, 1995).

9.2 k-τ turbulence model

The k-τ turbulence model is derived by Speziale *et al.* (1992) as a transformation of the ε-equation of the k-ε turbulence model where the variable τ models a typical time-scale of turbulent eddies.

The k-τ turbulence model used in D-Flow FM deviates from the equation of Speziale *et al.* (1992) at a few points, to derive their k-τ model they used a different version of the k-ε model and the most important difference is that they do not include buoyancy in their model.

The transport equations for k and τ used in D-Flow FM read (see for a derivation Dijkstra (2014)):

$$\frac{\partial k}{\partial t} + u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} + \frac{\omega}{\zeta - z_b}\frac{\partial k}{\partial \sigma} = \frac{1}{(\zeta - z_b)^2}\frac{\partial}{\partial \sigma}\left(D_k \frac{\partial k}{\partial \sigma}\right) + P_k + P_{kw} + B_k - k\tau, \quad (9.22)$$

$$\frac{\partial \tau}{\partial t} + u\frac{\partial \tau}{\partial x} + v\frac{\partial \tau}{\partial y} + \frac{\omega}{\zeta - z_b}\frac{\partial \tau}{\partial \sigma} = \frac{1}{(\zeta - z_b)^2}\left\{\frac{\partial}{\partial \sigma}\left(D_\tau \frac{\partial \tau}{\partial \sigma}\right) + \frac{2}{k}D_\tau \frac{\partial \tau}{\partial \sigma}\frac{\partial k}{\partial \sigma} - \frac{2}{\tau}D_\tau \frac{\partial \tau}{\partial \sigma}\frac{\partial \tau}{\partial \sigma} - \frac{\tau}{k}\frac{\partial}{\partial \sigma}\left(\left(\frac{1}{\sigma_\varepsilon} - \frac{1}{\sigma_k}\right)\right)\frac{\partial k}{\partial \sigma}\right\} - \frac{\tau}{k}(c_{\varepsilon 1} - 1)P_k - \frac{\tau}{k}(c_{\varepsilon 3} - 1)B_k + c_{\varepsilon 2} - 1 \quad (9.23)$$

with

$$D_k = \frac{\nu_{mol}}{\sigma_{mol}} + \frac{\nu_{3D}}{\sigma_k} \quad \text{and} \quad D_\tau = \frac{\nu_{3D}}{\sigma_\tau}. \quad (9.24)$$

10 Heat transport

This chapter is an almost integral copy of the Delft3D-FLOW manual. The difference is that in Delft3D-FLOW five heat flux models are implemented, whereas in D-Flow FM only two models are implemented. These are the most complete heat flux model, the so called Composite heat flux model (i.e. the Ocean heat flux model nr 5 in Delft3D-FLOW) and the most simple model, the Excess temperature model (model nr 3 in Delft3D-FLOW). In D-Flow FM, the parameter that sets the temperature model is called `Temperaturemodel` in the mdu-file. We kept the numbering of Delft3D. When specifying `Temperaturemodel=1`, the temperature is taken into account in the transport solver and in the equation of state, but heat fluxes though the water surface are not taken into account. This may be useful when mixing is the primary factor that determines the temperature distribution.

The heat radiation emitted by the sun reaches the earth in the form of electromagnetic waves with wavelengths in the range of 0.15 to 4 μm. In the atmosphere the radiation undergoes scattering, reflection and absorption by air, cloud, dust and particles. On average neither the atmosphere nor the earth accumulates heat, which implies that the absorbed heat is emitted back again. The wavelengths of these emitted radiations are longer (between 4 and 50 μm) due to the lower prevailing temperature in the atmosphere and on Earth. Schematically the radiation process, along with the heat flux mechanisms at the water surface, is shown in Figure 10.1.

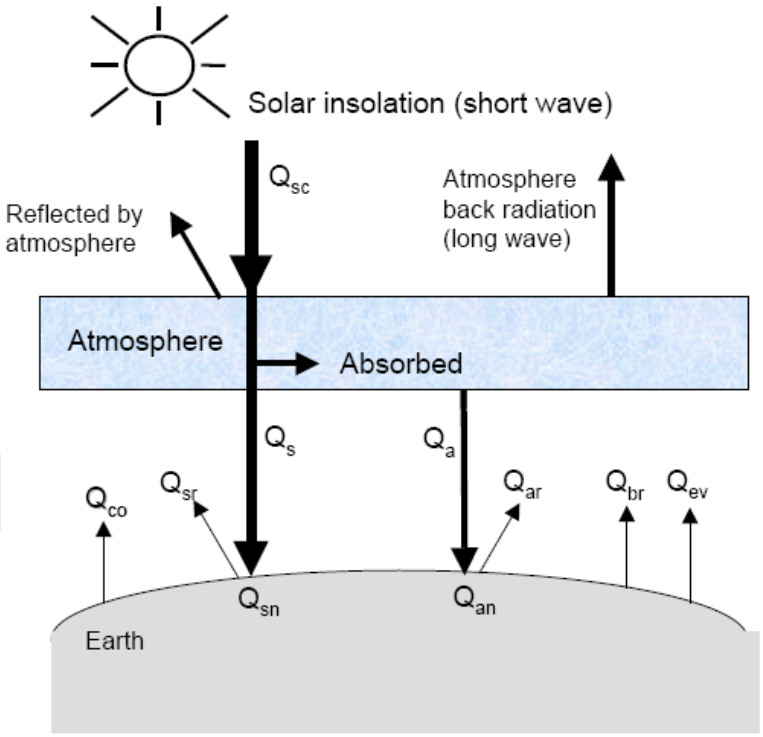


Figure 10.1: *Overview of the heat exchange mechanisms at the surface*

Legend for Figure 10.1:

Q_{sc}	radiation (flux) for clear sky condition in [J/m^{2}s]
Q_{co}	heat loss due to convection (sensible) in [J/m^{2}s]
Q_{sr}	reflected solar radiation in [J/m^{2}s]
Q_s	solar radiation (short wave radiation) in [J/m^{2}s]
Q_{sn}	net incident solar radiation (short wave), $= Q_s - Q_{sr}$

Q_a	atmospheric radiation (long wave radiation) in [J/m^{2}s]
Q_{an}	net incident atmospheric radiation (long wave)
Q_{ar}	reflected atmospheric radiation in [J/m^{2}s]
Q_{br}	back radiation (long wave radiation) in [J/m^{2}s]
Q_{ev}	heat loss due to evaporation (latent) in [J/m^{2}s]

In D-Flow FM the heat exchange at the free surface is modeled by taking into account the separate effects of solar (short wave) and atmospheric (long wave) radiation, and heat loss due to back radiation, evaporation and convection. The heat losses due to evaporation and convection are functions of the wind speed. In absence of wind, these terms become zero. However, since water vapor is lighter than air, water may be cooled by evaporation and convection even in a no wind situation. The terms are called Q_{evfree} and Q_{cofree} respectively.

Excess temperature model - heat flux model 3

In the Excess temperature model the heat exchange flux at the air-water interface is computed based upon the prescribed background air temperature, the computed water temperature of the top layer and the prescribed wind speed. This relatively simple model is sometimes used in intake–outfall design studies. It can be applied when the temperature mixing process itself is more relevant than the actual heat loss through the air water interface. The applied heat exchange coefficient is mainly a function of the windspeed and water surface temperature.

The excess temperature model 3 is based on Sweers (1976), the heat exchange flux is represented by a bulk exchange formula:

$$Q_{tot} = -\lambda \left(T_s - T_{back}\right), \tag{10.1}$$

with T_s the water temperature at the free surface and T_{back} the natural background temperature, both in °C.

The heat exchange coefficient λ is a function of the surface temperature T_s and the wind speed U_{10}. It is derived by linearization of the exchange fluxes for back radiation, evaporation and convection. The following relation was derived by Sweers (1976):

$$\lambda = 4.48 + 0.049T_s + f\left(U_{10}\right)\left(1.12 + 0.018T_s + 0.00158T_s^2\right). \tag{10.2}$$

Composite - heat flux model 5

The heat flux model 5 following Gill (1982) and Lane (1989) was calibrated for the North Sea and successfully applied for great lakes.

In the Composite heat flux model, the relative humidity in [%], air temperature in [°C] and cloudiness in [%] are prescribed.

These quantities may be either uniform or specially varying. In the external forcingsfile one may have:

```
QUANTITY =humidity_airtemperature_cloudiness
FILENAME =meteo.hac
FILETYPE =6
METHOD   =3
OPERAND  =O
```

For example input files see example directories:

➢ `f20_heat_flux/**/`

The effective back radiation and the heat losses due to evaporation and convection are computed by the model. Additionally, when air and water densities and/or temperatures are such that free convection occurs, free convection of latent and sensible heat is computed by the model.

Normally, solar radiation is computed based upon time of day, position on earth and cloudiness. However, if solar radiation was measured, it can also be prescribed (in [W/m^2]), e.g.:

```
QUANTITY =humidity_airtemperature_cloudiness_solarradiation
FILENAME =meteo.hacs
FILETYPE =6
METHOD   =3
OPERAND  =O
```

In both heat flux models, the wind forcing may be uniform or spatially varying.

If wind is uniform, the wind speed and direction are prescribed, wind speed is in m/s, and direction follows nautical convention: 0 means wind coming from North, 90 means wind is coming from East. In the external forcings file specify, e.g.:

```
QUANTITY=windxy
FILENAME=zeg99-10.wnd
FILETYPE=2
METHOD=1
OPERAND=O
```

If wind is spatially varying, the air pressure is also prescribed:

```
QUANTITY =airpressure_windx_windy
FILENAME =CSM_2015.apwxwy
FILETYPE =6
METHOD   =3
OPERAND  =O
```

Air pressure is in [Pa], wind x- and y-components are given [m/s].

For the physical background of the heat exchange at the air-water interface and the definitions, we refer to Sweers (1976) for the Excess temperature model (Temperaturemodel=3), and to Gill (1982) and Lane (1989) for the Ocean heat flux model (Temperaturemodel=5).

10.1 Heat balance

The total heat flux through the free surface reads:

$$Q_{tot} = Q_{sn} + Q_{an} - Q_{br} - Q_{ev} - Q_{co} - Q_{evfree} - Q_{cofree}, \tag{10.3}$$

with:

Q_{sn}	net incident solar radiation (short wave)
Q_{an}	net incident atmospheric radiation (long wave)
Q_{br}	back radiation (long wave)
Q_{ev}	evaporative heat flux (latent heat)
Q_{co}	convective heat flux (sensible heat)
Q_{evfree}	evaporative heat flux (free convection latent heat)
Q_{cofree}	convective heat flux (free convection sensible heat).

The subscript n refers to a net contribution. Each of the heat fluxes in Equation (10.3) will be discussed in detail.

The change in temperature in the top layer T_s [°C] is given by:

$$\frac{\partial T_s}{\partial t} = \frac{Q_{tot}}{\rho_w c_p \Delta z_s}, \tag{10.4}$$

where Q_{tot} [J/m^{2}s] is the total heat flux through the air-water surface, c_p (= 3930 J kg^{-1} K) is the specific heat capacity of sea water, ρ_w is the specific density of water [kg/m^3] and Δz_s [m] is the thickness of the top layer. As in Delft3D-FLOW, the heat exchange at the bed is assumed to be zero. This may lead to over-prediction of the water temperature in shallow areas. Also the effect of precipitation on the water temperature is not taken into account.

Remarks:

- The temperature T is by default expressed in °C. However, in some formulas the absolute temperature $\bar{T}$ in K is used. They are related by:

$$\bar{T} = T + 273.15. \tag{10.5}$$

- In Equation (10.4) the total incoming heat flux is absorbed with exponential decay as a function of depth. See the parameter Secchi-depth in the mdu-file.

10.2 Solar radiation

The short-wave radiation emitted by the sun that reaches the earth surface under a clear sky condition can be evaluated by means of:

- Applying Stefan-Boltzmann's law for radiation from a black-body:

$$Q = \sigma \bar{T}^4 \tag{10.6}$$

  with σ = Stefan-Boltzmann's constant = 5.67×10^{-8} J/(m^{2}s K^4) and $\bar{T}$ the (absolute) temperature in K.

- Direct measurements.

Not all of the radiation is absorbed at the water surface. A part is transmitted to deeper water. Short waves can penetrate over a distance of 3 to 30 meters, depending on the clarity of the water, while the relatively longer waves are absorbed at the surface. Therefore, it is convenient to separate the incoming solar insolation into two portions:

1 βQ_{sn}, the longer wave portion, which is absorbed at the surface and
2 $(1-\beta)\,Q_{sn}$, the remainder part, which is absorbed in deeper water.

The absorption of heat in the water column is an exponential function of the distance H from the water surface:

$$(1-\beta)\,Q_{sn} = \int_0^H e^{-\gamma z}\,dz \Rightarrow \tag{10.7}$$

$$Q_{sn}\,(h) = \frac{\gamma e^{-\gamma h}}{1-e^{-\gamma H}}(1-\beta)Q_{sn}, \tag{10.8}$$

with:

β	part of Q_{sn} absorbed at the water surface which is a function of the wavelength. The default value of β in D-Flow FM is 0.06.
γ	extinction coefficient (measured) in m^{-1}, also related to the so-called Secchi-depth $\gamma = \frac{1.7}{H_{Secchi}}$
h	distance to the water surface in meters.
H	total water depth.

The incoming energy flux at the water surface depends on the angle (declination) between the incoming radiation and the Earth's surface. This declination depends on the geographical position on the Earth and the local time. The Earth axis is not perpendicular to the line connecting the Sun with Earth. This tilting (angle δ) varies with the time of the year and it leads to a seasonal variation of the radiation flux. At June 21, the declination is maximal, 23.5 degrees. Of course, by the rotation of the Earth the solar radiation also varies during the day. Near twelve o'clock local time, the sun elevation above the horizon is maximal. For an overview of the angles used to determine the solar elevation angle γ, see Figure 10.2.

The temporal and latitude-dependent solar elevation angle γ is estimated by:

$$\sin(\gamma) = \sin(\delta)\sin\left(\frac{\pi\phi}{180}\right) - \cos(\delta)\cos\left(\frac{\pi\phi}{180}\right)\cos(\omega_1 t) \tag{10.9}$$

with:

$$\delta = \frac{23.5\pi}{180}\cos(\omega_0 t - 2.95), \tag{10.10}$$

where ω_0 is the frequency of the annual variation and ω_1 the frequency of the diurnal variation; ϕ is the latitude.

The incoming short-wave solar radiation through a clear sky at ground level Q_{sc} is about 0.76 of the flux incident at the top of the atmosphere (Gill, 1982):

$$Q_{sc} = \begin{cases} 0.76S\sin(\gamma), & \sin(\gamma) \geq 0, \\ 0.0, & \sin(\gamma) < 0. \end{cases} \tag{10.11}$$

The solar constant $S = 1\,368$ J/(m^{2}s) or W/m^2. This is the average energy flux at the mean radius of the Earth.

A part of the radiation that reaches the water surface is reflected. The fraction reflected or scattered (surface albedo) is dependent on latitude and season. Cloud cover will reduce the magnitude of the radiation flux that reaches the sea surface. The cloudiness is expressed by

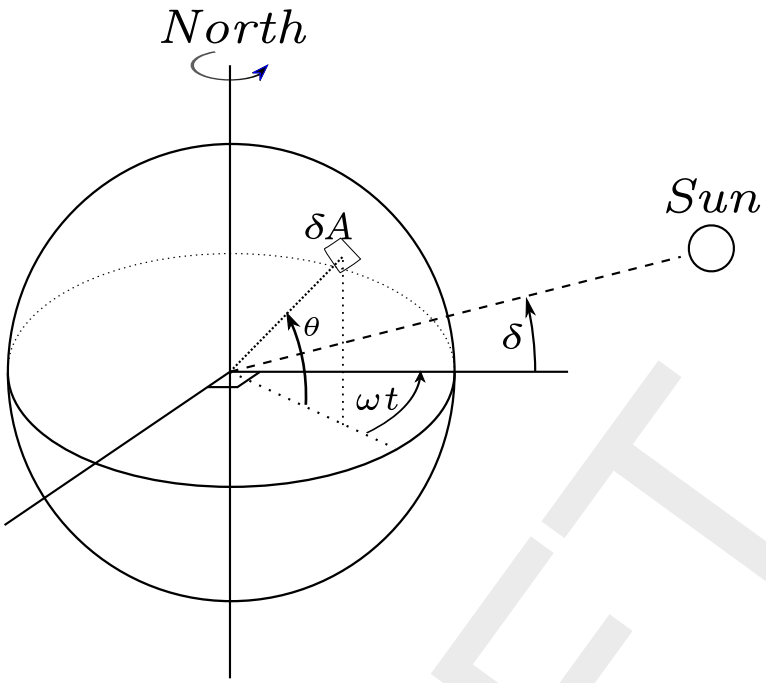


Figure 10.2: *Co-ordinate system position Sun*
δ: declination; θ: latitude; ωt: angular speed

a cloud cover fraction F_c, the fraction of the sky covered by clouds. The correction factor for cloud cover is an empirical formula. The absorption of solar radiation is calculated (Gill, 1982) as the product of the net downward flux of short wave-radiation in cloudless conditions and factors correcting for reflection and cloud cover:

$$Q_{sn} = Q_s - Q_{sr} = (1 - \alpha)\, Q_{sc}(1.0 - 0.4F_c - 0.38F_c^2), \tag{10.12}$$

with:

Q_{sn}	net heat radiation (flux) from the Sun
Q_s	solar radiation (short wave radiation) in [J/m^{2}s]
Q_{sr}	reflected solar radiation in [J/m^{2}s]
Q_{sc}	radiation (flux) for clear sky condition
α	albedo (reflection) coefficient (=0.06)
F_c	fraction of sky covered by clouds (user-defined input)

10.3 Atmospheric radiation (long wave radiation)

Atmospheric radiation is primarily due to emission of absorbed solar radiation by water vapour, carbon dioxide and ozone in the atmosphere. The emission spectrum of the atmosphere is highly irregular. The amount of atmospheric radiation that reaches the earth is determined by applying the Stefan-Boltzmann's law that includes the emissivity coefficient of the atmosphere ε. Taking into account the effect of reflection by the surface and reflection and absorption by clouds, the relation for the net atmospheric radiation Q_{an} reads (Octavio *et al.*, 1977):

$$Q_{an} = (1 - r)\, \varepsilon \sigma \bar{T}_a^4 g\,(F_c)\,, \tag{10.13}$$

where $\bar{T}_a$ is the air temperature (in K) and the reflection coefficient $r = 0.03$. The emissivity factor of the atmosphere ε may depend both on vapour pressure and air temperature. The emissivity of the atmosphere varies between 0.7 for clear sky and low temperature and 1.0. The presence of clouds increases the atmospheric radiation. This is expressed in the cloud function $g\,(F_c)$.

with T_a the air temperature (in °C). The cloud function $g\left(F_c\right)$ in Equation (10.13) is given by:

$$g\left(F_c\right) = 1.0 + 0.17F_c^2.2 - 9 \tag{10.14}$$

The linearisation of Equation (10.13) is carried out around $T_a = 15$ °C.

Remark:

- ◇ The atmospheric radiation is part of the total long-wave radiation flux, the so-called effective back radiation, see section 10.5.

10.4 Back radiation (long wave radiation)

Water radiates as a near black body, so the heat radiated back by the water can be described by Stefan-Boltzmann's law of radiation, corrected by an emissivity factor $\varepsilon = 0.985$ of water (Sweers, 1976; Octavio *et al.*, 1977) and the reflection coefficient for the air-water interface $r = 0.03$:

$$Q_{br} = \left(1 - r\right)\varepsilon\sigma\bar{T}_s^4, \tag{10.15}$$

with $\bar{T}_s$ the (absolute) water surface temperature in K.

10.5 Effective back radiation

The total net long wave radiation flux is computed. This is called the effective back radiation:

$$Q_{eb} = Q_{br} - Q_{an}. \tag{10.16}$$

The atmospheric radiation depends on the vapour pressure e_a, see section 10.6, the air temperature T_a and the cloud cover F_c. The back radiation depends on the surface temperature T_s.

The effective back radiation Q_{eb} is computed following:

$$Q_{eb} = \varepsilon\sigma\bar{T}_s^4\left(0.39 - 0.05\sqrt{e_a}\right)\left(1.0 - 0.6F_c^2\right), \tag{10.17}$$

with the actual vapour pressure e_a given by Equation (10.22).

10.6 Evaporative heat flux

Evaporation is an exchange process that takes place at the interface between water and air and depends on the conditions both in the water near the surface and the air above it. The evaporation depends on meteorological factors (wind-driven convection) and vapour pressures.

Forced convection of latent heat

The latent heat flux due to forced convection for the ocean heat flux model reads:

$$Q_{ev,\text{forced}} = L_V\rho_a f\left(U_{10}\right)\left\{q_s\left(T_s\right) - q_a\left(T_a\right)\right\}, \tag{10.18}$$

with q_s and q_a the specific humidity of respectively saturated air and remote air (10 m above water level):

$$q_s\left(T_s\right) = \frac{0.62e_s}{P_{atm} - 0.38e_s}, \tag{10.19}$$

$$q_a\left(T_a\right) = \frac{0.62e_a}{P_{atm} - 0.38e_a}. \tag{10.20}$$

The saturated and remote vapour pressures e_s and e_a are given by:

$$e_s = 10^{\frac{0.7859+0.03477T_s}{1.0+0.00412T_s}}, \tag{10.21}$$

$$e_a = r_{hum}10^{\frac{0.7859+0.03477T_a}{1.0+0.00412T_a}}. \tag{10.22}$$

With L_v the latent heat of vaporisation in J/kg water:

$$L_v = 2.5\,10^6 - 2.3\,10^3 T_s. \tag{10.23}$$

The wind function in Equation (10.18) is defined as:

$$f\left(U_{10}\right) = c_e U_{10}, \tag{10.24}$$

Without the influence of free convection, the Dalton number c_e in the Composite heat flux model was calibrated for the North Sea to be $c_e = 0.0015$. This value should be close to the C_d coefficient that is used in the computation of wind stresses. The exchange coefficients of latent heat and momentum transfer are closely related. Specifying a negative Dalton number in the mdu file forces the use of the specified C_d coefficient, thus taking into account the specified dependency between windspeed and the C_d coefficient.

Here r_{hum} is the relative humidity in [-].

Remarks:

- The relative humidity r_{hum} is specified in the input files in percentages.
- When the computed E is negative, it is replaced by zero, assuming that it is caused by modelling misfit and not by the actual physical process of water condensation out of the air into the water. The same applies to the part associated with free convection.

For the excess temperature model, the wind speed function $f\left(U_{10}\right)$ following Sweers (1976) is used:

$$f\left(U_{10}\right) = (3.5 + 2.0U_{10})\left(\frac{5.0\times10^6}{S_{area}}\right)^{0.05}, \tag{10.25}$$

where S_{area} is the exposed water surface in m^2, defined in the input and fixed for the whole simulation. The coefficients calibrated by Sweers were based on the wind speed at 3 meter above the free surface; the coefficients in Equation (10.25) are based on the wind speed 10 meter above the water level.

Free convection of latent heat

Loss of heat due to evaporation occurs not only by forced convection, wind driven, but also by free convection. Free convection is driven by buoyant forces due to density differences (by temperature and/or water vapour content) creating unstable conditions in the atmospheric boundary layer. Evaporation due to free convection is important in circumstances where inverse temperature/density gradients are present and wind speeds are almost negligible so that the amount of forced convection is small. Neglecting free convection in this situation will lead to underestimating the heat loss. (Ryan *et al.*, 1974) developed a correction to the wind function, accounting for free convection. The derivation of evaporation by just free convection is based on the analogy of heat and mass transfer.

The latent heat flux due to free convection reads:

$$Q_{ev,\text{free}} = k_s L_V \overline{\rho}_a \left(q_s - q_a\right), \tag{10.26}$$

with the average air density:

$$\overline{\rho}_a = \frac{\rho_{a0} + \rho_{a10}}{2}, \tag{10.27}$$

and with the heat transfer coefficient defined as:

$$k_s = \begin{cases} 0 & \text{if} \quad \rho_{a10} - \rho_{a0} \leq 0 \\ c_{fr.\text{conv}} \left\{ \frac{g\alpha^2}{\nu_{air}\overline{\rho}_a} \left(\rho_{a10} - \rho_{a0}\right) \right\}^{1/3} & \text{if} \quad \rho_{a10} - \rho_{a0} > 0 \end{cases} \tag{10.28}$$

where the coefficient of free convection $c_{fr.\text{conv}}$ was calibrated to be 0.14, see (Ryan *et al.*, 1974). The viscosity of air ν_{air} is assumed to have the constant value 16.0×10^{-6} m^2/s. The molecular diffusivity of air α m^2/s is defined as

$$\alpha = \frac{\nu_{air}}{\sigma}, \tag{10.29}$$

with $\sigma = 0.7$ (for air) the Prandtl number. In Equation (10.26), the saturated air density is given by:

$$\rho_{a0} = \frac{\frac{100P_{atm} - 100e_s}{R_{dry}} + \frac{100e_s}{R_{vap}}}{T_s + 273.15}, \tag{10.30}$$

the remote air density (10 m above the water level):

$$\rho_{a10} = \frac{\frac{100P_{atm} - 100e_a}{R_{dry}} + \frac{100e_a}{R_{vap}}}{T_{air} + 273.15}, \tag{10.31}$$

where R_{dry} is the gas constant for dry air: 287.05 J/(kg K) and R_{vap} is the gas constant for water vapour: 461.495 J/(kg K). The specific humidity of respectively saturated air and remote air (10 m above the water level), q_s and q_a are given by Equation (10.19) and Equation (10.20). The saturated and remote vapour pressure e_s and e_a are defined in Equation (10.21) and Equation (10.22).

The total heat flux due to evaporation then results from adding the forced convection of latent heat in Equation (10.18) and the free convection of latent heat in Equation (10.26):

$$Q_{ev} = Q_{ev,\text{forced}} + Q_{ev,\text{free}}. \tag{10.32}$$

10.7 Convective heat flux

In the Ocean heat flux model, the convective heat flux is split into two parts, just as the evaporative heat flux. The convective heat flux is divided into a contribution by forced convection and a contribution by free convection.

Forced convection of sensible heat

The sensible heat flux due to forced convection is computed by:

$$Q_{co,\text{forced}} = \rho_a c_p g\left(U_{10}\right)\left(T_s - T_a\right), \tag{10.33}$$

with c_p the specific heat of air. It is considered constant and taken to be $1\,004.0$ J/(kg K). The wind-speed function $g\left(U_{10}\right)$ is defined following Gill (1982):

$$g\left(U_{10}\right) = c_H U_{10}, \tag{10.34}$$

with c_H the so-called Stanton number. Without the influence of free convection, the Stanton number was calibrated for the North Sea to be $c_H = 0.00145$.

Free convection of sensible heat

$$Q_{co,\text{free}} = k_s \overline{\rho}_a c_p \left(T_s - T_a\right), \tag{10.35}$$

with the heat transfer coefficient k_s given by Equation (10.28).

The total heat flux due to convection then results from adding the forced convection of sensible heat in Equation (10.33) and the free convection of sensible heat in Equation (10.35):

$$Q_{co} = Q_{co,\text{forced}} + Q_{co,\text{free}}. \tag{10.36}$$

11 Wind

Various external influences can exert a force on the flow field. One of these influences is the wind. The force exerted by the wind is coupled to the flow equations as a shear stress. The magnitude is determined by the following widely used quadratic expression:

$$|\boldsymbol{\tau}_s| = \rho_a C_d U_{10}^2 \tag{11.1}$$

where:

ρ_a	the density of air.
U_{10}	the wind speed 10 meter above the free surface (time and space dependent).
C_d	the wind drag coefficient, dependent on U_{10}.

In order to specify the wind shear stress, a drag coefficient is required as well as the wind field in terms of velocity magnitude and wind direction. In this chapter, the backgrounds are provided of how wind fields should be imposed, in addition to section 4.4.9.4. Relevant definitions are addressed in section 11.1, whereas supported file formats are addressed in section 11.2.

11.1 Definitions

When imposing wind conditions, two definitions are respected: a definition for the wind direction (see section 11.1.1) and a definition regarding the drag coefficient (see section 11.1.2).

11.1.1 Nautical convention

The wind direction is defined according to the nautical definition, i.e. relative to true North and positive measured clockwise. In Figure 11.1 the wind direction is about +60 degrees, i.e. an East-North-East wind.

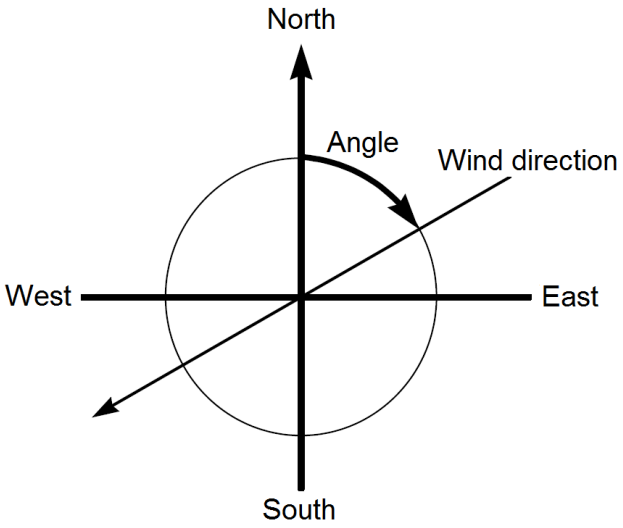


Figure 11.1: *Nautical conventions for the wind.*

11.1.2 Drag coefficient

The dependency of the drag coefficient on the wind speed should be specified by the user. The user can choose between the following concepts:

- ◇ a constant drag coefficient,
- ◇ a dependency according to Smith and Banke (1975),
- ◇ a dependency according to Charnock (1955),
- ◇ a dependency according to Hwang (2005a) and Hwang (2005b).

The specification of the type of wind drag formulation should be accomplished in the MDU-file. For this purpose, the keyword `ICdtyp` can be utilized. For this keyword `ICdtyp`, five options could be demanded for:

- ◇ `ICdtyp = 1` – constant drag coefficient,
- ◇ `ICdtyp = 2` – linearly varying drag coefficient (cf. Smith and Banke (1975)),
- ◇ `ICdtyp = 3` – piecewise linearly varying drag coefficient (cf. Smith and Banke (1975)),
- ◇ `ICdtyp = 4` – Charnock (1955) formulation (no breakpoints),
- ◇ `ICdtyp = 5` – Hwang (2005a) and Hwang (2005b) formulation (no breakpoints).

If a Smith & Banke type dependency is chosen for, the additional entries `Cdbreakpoints` and `Windspeedbreakpoints` come into play. In the following sections, the specification of either of these options are depicted.

Smith & Banke type formulation

When specifying a Smith & Banke type dependency, the definition as sketched in Figure 11.2 should be kept in mind.

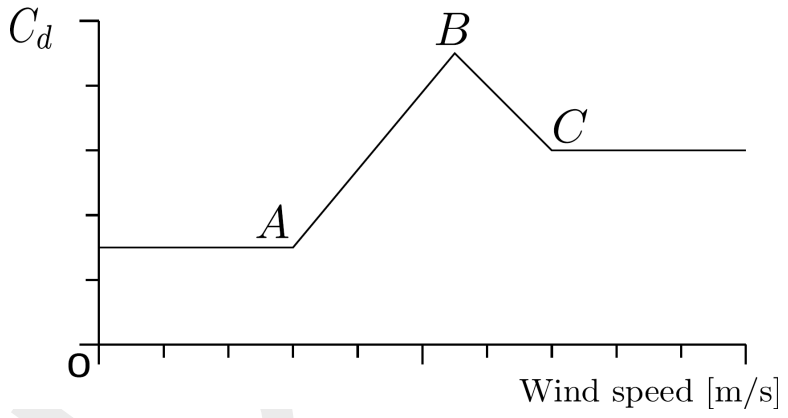


Figure 11.2: *Prescription of the dependency of the wind drag coefficient C_d on the wind speed is achieved by means of at least 1 point, with a maximum of 3 points.*

From this sketch, it can be seen that the wind drag is considered as dependent on the wind speed in a piecewise linear way. The options, that are facilitated in this respect, are:

- ◇ define *one* set of coordinates (breakpoint A), specifying a constant drag coefficient, valid for all wind speeds,
- ◇ define *two* sets of coordinates (breakpoints A and B), specifying a linearly varying dependency for one range of wind speeds,
- ◇ define *three* sets of coordinates (breakpoints A, B and C), specifying a piecewise linear dependency for two ranges of wind speeds.

Remark that for the latter two options, the drag coefficient is taken constant for wind speeds

lower/higher than the lowest/highest specified wind speed, with a drag coefficient equal to the drag coefficient associated with the lowest/highest specified lowest/highest wind speed. In case of three breakpoints, the expression reads:

$$C_d\left(U_{10}\right) = \begin{cases} C_d^A, & U_{10} \leq U_{10}^A, \\ C_d^A + \left(C_d^B - C_d^A\right) \dfrac{U_{10} - U_{10}^A}{U_{10}^B - U_{10}^A}, & U_{10}^A \leq U_{10} \leq U_{10}^B, \\ C_d^B + \left(C_d^C - C_d^B\right) \dfrac{U_{10} - U_{10}^B}{U_{10}^C - U_{10}^B}, & U_{10}^B \leq U_{10} \leq U_{10}^C, \\ C_d^C, & U_{10}^C \leq U_{10}, \end{cases} \tag{11.2}$$

By means of the entries `Cdbreakpoints` and `Windspeedbreakpoints`, the coordinates of the breakpoints (see Figure 11.2) can be specified. Typical values associated with the Smith and Banke (1975) formulation are $C_d = 6.3 \times 10^{-4}$ for $U = 0$ m/s and $C_d = 7.23 \times 10^{-3}$ for $U = 100$ m/s. In this case, the entries in the MDU-file should be specified as follows:

```
[wind]
ICdtyp                          =  2
Cdbreakpoints                   =  0.00063   0.00723
Windspeedbreakpoints            =  0.00000 100.00000
```

Charnock formulation

The Charnock formulation (see Charnock (1955)) is based on the assumption of a fully developed turbulent boundary layer of the wind flow over the water surface. The associated wind speed profile follows a logithmic shape. In the Charnock formulation, the wind speed is considered at 10 meters above the free water surface, hence yielding the following expression:

$$\frac{U_{10}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z_{10}}{z_0}\right) \tag{11.3}$$

with κ the Von Kármán constant, z_{10} the distance to the water surface (equal to 10 m), u_* the friction velocity and U_{10} the wind speed at 10 m above the water surface. The drag coefficient C_d is defined as:

$$C_d = \frac{u_*^2}{U_{10}^2}. \tag{11.4}$$

Charnock (1955) has proposed to represent the friction of the water surface as z_0 according to:

$$z_0 = \frac{b\, u_*^2}{g}, \tag{11.5}$$

with g the gravitation acceleration and b a specific constant. Charnock (1955) has proposed $b = 0.012$. The value of the constant b can be specified in the MDU-file by the user by means of one single value for `Cdbreakpoints`. Since the above relation yields an implicit relation for u_*, the system is solved for iteratively. The user should be aware of interpretation of the specified wind field as the wind field at 10 m above the water surface. See paragraph 11.2.4 for a space and time varying Charnock coefficient b.

Hwang formulation

The dynamic roughness could also be related to the steady state wave conditions of the flow field under consideration. The connection of the wave parameters with the drag coefficient as elaborated by Hwang (2005a) is available within D-Flow FM through `ICdtyp = 5`, given a wave field. The Hwang-formulation interpretes the user defined wind speed as the wind speed at 10 m above the water surface.

The drag coefficient is computed as:

$$C_d = \left[\frac{1}{\kappa}\ln\left(\frac{k_p z_{10}}{k_p z_0}\right)\right]^{-2} \tag{11.6}$$

with $z_{10} = 10$ m, κ the Von Kármán constant. With wavelength scaling, $k_p z_0$ is the natural expression of the dimensionless roughness, where k_p is the wave number of the spectral peak, computed on the basis of the actual water depth and the provided peak period T_p as wave field. Further following Hwang (2005a),

$$k_p z_0 = \pi \exp\left(-\kappa C_{\lambda/2}^{-0.5}\right) \tag{11.7}$$

in which $C_{\lambda/2}$ is the drag coefficient at half the wavelength above surface. This parameter $C_{\lambda/2}$ is computed as:

$$C_{\lambda/2} = A_{10}\left(\frac{\omega_p U_{10}}{g}\right)^{a_{10}} \tag{11.8}$$

in which $A_{10} = 1.289 \times 10^{-3}$, $a_{10} = 0.815$, U_{10} the wind speed at 10 m above the water surface and ω_p the wave peak frequency ($\omega_p = 2\pi/T_p$). Thus, the drag coefficient C_d is defined.

11.2 File formats

The wind field should be provided by means of an ascii-type file. This file should contain the grid on which the wind field is defined as well as the wind velocity vector(s).

D-Flow FM currently supports four types of wind field prescriptions, i.e. four grid types on which the wind field can be given. This wind grid does not need to be the same as the computational grid. The grid options to provide the wind data on are:

1. the computational grid — in this case, no specific wind grid is provided. The provided wind field is considered to be uniform over the entire model area. The wind field can be time dependent.
2. an equidistant grid — in this case, a wind field can be prescribed that varies both in space and in time. A Cartesian arcinfo-type grid should be provided on which the wind field is defined.
3. a curvilinear grid — this case is conceptually similar to the previous type (the equidistant grid) in the sense that a wind field can be imposed that both varies in space and time. However, a separate file should be provided in which a curvilinear grid is defined (a classic $<*$.grd$>$-type file as known from Delft3D) on which the wind field is defined.
4. a spiderweb grid — this type of wind specification is specially devoted to cyclone winds and is only available in combination with computational grids that are of spherical type. In this case, a cyclone wind field is given on a polar grid with the center ('eye') of the cyclone being the origin of the polar coordinate system. The location of this eye and the associated wind field usually varies in time.

Each of these filetypes can be assigned through the entry in the external forcings file (the $<*$.ext$>$-file) named FILETYPE. In this chapter, the various types of wind field specifications are highlighted subsequently. Each of the options is illustrated by means of an example.

11.2.1 Defined on the computational grid

In D-Flow FM, the specification of the wind on the computational grid is equivalent to the specification of a uniform wind, since no separate wind grid is provided to the model. The specification of a uniform wind field can be done in two ways:

1 componentwise: as velocity in the longitudinal x-direction [m/s] and in the latitudal y-direction [m/s] — the associated FILETYPE in the external forcings file is depicted as uniform, which has FILETYPE=1.
2 by magnitude [m/s] and direction [degN] (see Figure 11.1) — the associated FILETYPE in the external forcings file is depicted as unimagdir, which has FILETYPE=2.

These two types are treated below separately.

11.2.1.1 Specification of uniform wind through velocity components

Since no particular wind grid is used, only timeseries for the x-component and the y-component of the wind need to be specified. The specification of these timeseries can be done separately (one single file for the x-component and one single file for the y-component) or jointly (one single file containing the x-component and the y-component of the wind).

Uniform wind should be provided as an $<*$.wnd$>$-file containing either 2 colums (in case of separate specification of the x-component and y-component of the wind) or 3 columns (in case of joint specification of the velocity components). In either case, the first column contains the time in minutes with respect to the overall reference time.

Example

As an example, a uniform wind field is applied to a certain model. The uniform wind is provided in a file named windxdirydir.wnd. The contents of this wind file are:

```
  0.00000   10.00000   10.00000
 60.00000  -10.00000  -10.00000
```

The first column denotes the time in minutes with respect to the reference date (specified in the mdu-file). The second column denotes the wind velocity in x-direction, whereas the third column denotes the wind velocity in y-direction; both wind components are provided in one single file.

The connection with the flow model itself is laid through the external forcings file. The actual specification of the wind is in this case:

```
QUANTITY =windxy
FILENAME =windxdirydir.wnd
FILETYPE =1
```

```
METHOD   =1
OPERAND  =O
```

Since the two components are given in one single file, the `QUANTITY` is set to `windxy`. If two separate files would have been provided, the `QUANTITY` would have been set to `windx` and `windy` over two separate datablocks in the external forcings file.

11.2.1.2 Specification of uniform wind through magnitude and direction

Instead of specifying the separate components of the wind field, the uniform wind vector can also be prescribed through its magnitude and direction (see Figure 11.1).

This kind of specification should be done by means of one single file, containing three columns, representing the time (in minutes with respect to the reference date), the velocity magnitude [m/s], not necessarily positive, and the direction (nautical convention).

Example

As an example, the previous uniform wind case is reformulated as a case with magnitude and direction of the wind field prescribed. The unimagdir wind is provided in a file named <windinput.wnd>. The contents of this file are:

```
  0.00000   14.14213562373095  225.00000
 60.00000  -14.14213562373095  225.00000
```

The first column denotes the time in minutes with respect to the reference date (specified in the mdu-file). The second column denotes the wind velocity magnitude, whereas the third column denotes the wind direction. Note that there is a clear difference between the above case and a case in which the magnitude is kept positive (14.1421 m/s) and the direction varies (and hence *rotates*!) from 225 degN to 45 degN.

The connection with the flow model itself is laid through the external forcings file. The actual specification of the wind is in this case:

```
QUANTITY =windxy
FILENAME =windinput.wnd
FILETYPE =2
METHOD   =1
OPERAND  =O
```

11.2.2 Defined on an equidistant grid

The vector components of the velocity vectors can also be specified on a distinct grid, either of equidistant type or of curvilinear type. In both cases, the characteristics of the grid should be provided. In case of an equidistant grid, the grid is specified in arcinfo-style. That means, the constant grid sizes Δx and Δy should be specified such that a grid is spanned with respect to the location of the lower left corner of the grid (either the center of the lower left cel or the lower left corner of the lower left cell).

Example

As an example, a grid with $\Delta x = \Delta y = 100$ m is spanned, based on the center of the lower left cell, located at $x = y = 60$ m with respect to the origin. The input data for the x-component and the y-component should be specified separately, in two distinct files. The input of the x-component data should be given in an $<*$.amu$>$-type file, such as $<$windxdir.amu$>$ as an example:

```
### START OF HEADER
### This file is created by Deltares
### Additional commments
FileVersion      =    1.03
filetype         =    meteo_on_equidistant_grid
NODATA_value     =    -9999.0
n_cols           =    5
n_rows           =    4
grid_unit        =    m
x_llcenter       =     60
y_llcenter       =     60
dx               =    110
dy               =    110
n_quantity       =    1
quantity1        =    x_wind
unit1            =    m s-1
### END OF HEADER
TIME = 0 hours since 2006-01-01 00:00:00 +00:00
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
TIME = 1 hours since 2006-01-01 00:00:00 +00:00
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
```

For the y-component data, a similar file (e.g. $<$windydir.amv$>$) should be provided. In addition, the pressure could be specified in a similar file (e.g. $<$pressure.amp$>$). Note that `x_llcorner` and `y_llcorner`, instead of `x_llcenter` and `y_llcenter`, are also supported.

Wind on an equidistant grid has been provided a filetype specification as `FILETYPE=4`. The connection with the flow model itself is laid through the external forcings file. The actual specification of the wind is in this case:

```
QUANTITY =windx
FILENAME =windxdir.amu
FILETYPE =4
METHOD   =2
OPERAND  =O

QUANTITY =windy
FILENAME =windydir.amv
FILETYPE =4
METHOD   =2
OPERAND  =O
```

```
QUANTITY =atmosphericpressure
FILENAME =pressure.amp
FILETYPE =4
METHOD   =2
OPERAND  =O
```

11.2.3 Defined on a curvilinear grid

In analogy with the wind specification on an equidistant grid, the wind can be specified on a curvilinear grid. This curvilinear grid should be provided as a classic $<*$.grd$>$-file as known from Delft3D. A difference with the equidistant grid wind is the necessity to compile all data blocks (i.e. pressure, x-component and y-component) in one single file. This file should have the extension $<*$.apwxwy$>$. The sequence of this datablock is: 1) pressure, 2) x-velocity component, 3) y-velocity component.

Example

As an example, a curvilinear grid named <meteo.grd> is present, providing the underlying coordinates of the wind data field. The input data, comprising the atmospheric pressure, the x-velocity component *and* the y-velocity component, are given in one single file (as is compulsory). The contents of the example <meteo.apwxwy>-file is:

```
### START OF HEADER
### This file is created by Deltares
### Additional commments
FileVersion      =    1.03
filetype         =    meteo_on_curvilinear_grid
NODATA_value     =    -9999.0
grid_file        =    meteo.grd
first_data_value =    grid_llcorner
data_row         =    grid_row
n_quantity       =    3
quantity1        =    apwxwy
unit1            =    Pa
### END OF HEADER
TIME = 0.0 hours since 2006-01-01 00:00:00 +00:00
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
10 10 10 10 10
TIME = 1.0 hours since 2006-01-01 00:00:00 +00:00
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
101325 101325 101325 101325 101325
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
```

```
-10 -10 -10 -10 -10
-10 -10 -10 -10 -10
```

Note that `grid_llcenter`, instead of `grid_llcorner`, is also supported. On the contrary, `grid_column` is *not* supported instead of `grid_row`.

Wind on a curvilinear grid has been provided a filetype specification as `FILETYPE=6`. The connection with the flow model itself is laid through the external forcings file. The actual specification of the wind is in this case:

```
QUANTITY =airpressure_windx_windy
FILENAME =meteo.apwxwy
FILETYPE =6
METHOD   =3
OPERAND  =O
```

Notice that `METHOD=3` is chosen for wind on a curvilinear grid, instead of `METHOD=2` in case of wind on an equidistant grid.

11.2.4 Space and time varying Charnock coefficients

The value for the Charnock coefficient b in Eq. ((11.5)) can be a constant given in the MDU-file, but also be given as a space and time varying field.

For a space and time varying Charnock coefficient, the user should provide a NetCDF-file with meteorological forcing, including Charnock coefficients, and use the file specification `FILETYPE=11`.

The specification is in this case:

```
QUANTITY =airpressure_windx_windy_charnock
FILENAME =meteo.nc
FILETYPE =11
METHOD   =3
OPERAND  =O
```

11.2.5 Defined on a spiderweb grid

Cyclone winds can be imposed by means of a 'spiderweb'-like polar grid. The origin typically coincides with the cyclone eye and can move in time. Spiderwebs can only be used in combination with a spherical computational grid. The origin of the spiderweb should be given as longitude (for x_{eye}) and latitude (for y_{eye}). The number of rows (discretisation in radial direction) and the number of columns (discretisation in angular direction) should be given, as well as the radius of the grid (in meters). The definition of the spiderweb grid is illustrated in Figure 11.3.

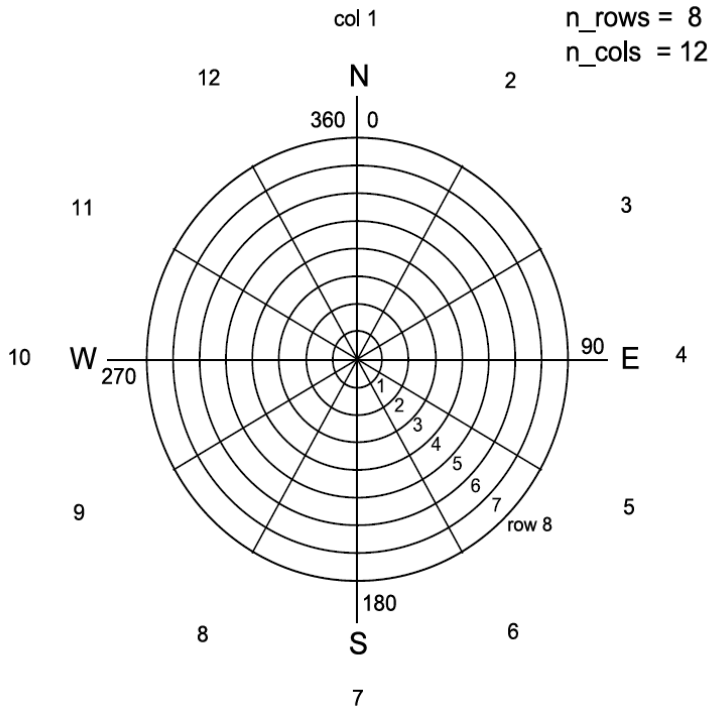


Figure 11.3: *Grid definition of the spiderweb grid for cyclone winds.*

The files containing the spiderweb data and metadata have the extension $<*$.spw$>$. They consist of a global header containing properties that are not varying in time, followed by blocks of data for subsequent time levels. Each of these data blocks is headed by a set of properties for the corresponding time level. A detailed description of the spiderweb file format can be found in section B.12.3.

Through the specified unit for atmospheric pressure in the file, it can be specified whether the values should be interpreted as mbar (=hPa), instead of Pa, which is the default. Specifying the spiderweb merge fraction β in `spw_merge_frac` allows for linear fading of wind speed and pressure drop towards the outer rim. For a spiderweb with radius R, the weigth assigned to the spiderweb wind and pressure at a radius r is given by $(R - r)/\beta R$ for r between $(1 - \beta)R$ and R. The weight equals unity within the inner circle and zero beyond the outer rim.

Example

As an example, a spiderweb grid named <spwsimple.spw> is present, providing the underlying coordinates of the wind data field. The input data, comprising the atmospheric pressure drops, the wind velocity magnitudes (in [m/s]) *and* the wind directions (in [degN]), are given in one single file (as is compulsory). The contents of the example <spwsimple.spw>-file is:

```
### Spiders web derived from TRACK file: gonu.trk
### This file is created by Deltares
### All text on a line behind the first # is parsed as commentary
### Additional commments
FileVersion      = 1.03
filetype         = meteo_on_spiderweb_grid
### Spiders web derived from TRACK file: gonu.trk
### This file is created by Deltares
### All text on a line behind the first # is parsed as commentary
### Additional commments
NODATA_value     = -1001
n_cols           = 4
n_rows           = 4
spw_radius       = 600000.0
spw_merge_frac   = 0.75
spw_rad_unit     = m
### END OF HEADER
TIME             = 340000.00   minutes since 2005-01-01 00:00:00 +00:00
x_spw_eye        =  265.00
y_spw_eye        =   33.00
p_drop_spw_eye    = 7000.000
 5.000000  5.000000  5.000000  5.000000
10.000000 10.000000 10.000000 10.000000
15.000000 15.000000 15.000000 15.000000
20.000000 20.000000 20.000000 20.000000
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
  4000.00   4000.00   4000.00   4000.00
  3000.00   3000.00   3000.00   3000.00
  2000.00   2000.00   2000.00   2000.00
  1000.00   1000.00   1000.00   1000.00
TIME             = 380000.00   minutes since 2005-01-01 00:00:00 +00:00
x_spw_eye        =  275.00
y_spw_eye        =   18.00
p_drop_spw_eye    = 8000.000
 5.000000  5.000000  5.000000  5.000000
10.000000 10.000000 10.000000 10.000000
15.000000 15.000000 15.000000 15.000000
20.000000 20.000000 20.000000 20.000000
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
   270.00      0.00     90.00    180.00
  4000.00   4000.00   4000.00   4000.00
  3000.00   3000.00   3000.00   3000.00
  2000.00   2000.00   2000.00   2000.00
  1000.00   1000.00   1000.00   1000.00
```

Wind on a spiderweb grid has been provided a filetype specification as `FILETYPE=5`. The connection with the flow model itself is laid through the external forcings file. The actual specification of the wind is in this case:

```
QUANTITY =airpressure_windx_windy
FILENAME =spwsimple.spw
FILETYPE =5
METHOD   =1
OPERAND  =O
```

Notice that METHOD=1 is chosen for wind on a spiderweb grid, instead of METHOD=2 in case of wind on an equidistant grid and METHOD=3 in case of wind on a curvilinear grid.

Alternatively, the spiderweb wind and pressure can be specified in the external forcings file as separate quantities referring to the same file (or specify one and omit the other):

```
QUANTITY =windxy
FILENAME =spwsimple.spw
FILETYPE =5
METHOD   =1
OPERAND  =O

QUANTITY =airpressure
FILENAME =spwsimple.spw
FILETYPE =5
METHOD   =1
OPERAND  =O
```

(NB. There is a slight difference between both specifications regarding their effect on the flow. The first approach requires an additional interpolation of wind on the velocity points, which in some cases of coarse computational grids and small scale wind could introduce smoothing.)

11.2.6 Combination of several wind specifications

The combination of the various wind specification types can *only* be achieved if the QUANTITY of the winds to be combined is the same, for instance QUANTITY=windx. The option OPERAND=+ can be used to add a wind field to an existing wind field.

Example

If the uniform wind is to be combined with a wind specified on an equidistant grid, then the wind field could be assigned in the external forcings file as follows:

```
QUANTITY =windx
FILENAME =windxdir.wnd
FILETYPE =1
METHOD   =1
OPERAND  =O

QUANTITY =windy
FILENAME =windydir.wnd
FILETYPE =1
METHOD   =1
OPERAND  =O
```

```
QUANTITY =windx
FILENAME =windxdir.amu
FILETYPE =4
METHOD   =2
OPERAND  =+

QUANTITY =windy
FILENAME =windydir.amv
FILETYPE =4
METHOD   =2
OPERAND  =+
```

The same is possible for e.g. a uniform wind and two spiderweb cyclones:

```
QUANTITY=windxy
FILENAME=uni.tim
FILETYPE=2
METHOD=1
OPERAND=O

QUANTITY =windxy
FILENAME =spwsimple.spw
FILETYPE =5
METHOD   =1
OPERAND  =+

QUANTITY =windxy
FILENAME =spwsimple2.spw
FILETYPE =5
METHOD   =1
OPERAND  =+

QUANTITY =atmosphericpressure
FILENAME =spwsimple.spw
FILETYPE =5
METHOD   =1
OPERAND  =+

QUANTITY =atmosphericpressure
FILENAME =spwsimple2.spw
FILETYPE =5
METHOD   =1
OPERAND  =+
```

In the above example, the wind is first prescribed as a spatially uniform time-varying field, onto which the spiderweb winds are added Note that the uniform wind has the `'O'` operand, which means that it overrides rather than adds. However, since the default wind is zero, one might just as well have used the `'+'` operand. If the spiderweb merge fraction is specified in the spiderweb file, a gradual transition between the spiderweb wind and the background wind is applied using the linearly varying weight as described above. The same is done for atmospheric pressure, if specified except that pressure is added to, whereas wind is averaged with the background values. Without any input, the background atmospheric pressure is set to `PavBnd` in the section `[wind]` in the MDU-file, if present and zero otherwise.

11.3 Masking of points in the wind grid from interpolation ('land-sea mask')

A mask can be supplied by the user to prevent selected points in the wind grid from contributing to the wind interpolation on velocity points, e.g. to exclude land points. This feature was included to conform to SIMONA and therefore implemented in the same way.

For each individual grid point for which to interpolate from the wind grid:

- ◇ Masked wind points are excluded from the interpolation.
- ◇ The total of the weight factors for the remaining wind points is determined.
- ◇ If this total falls below `1E-03`, the mask is ignored and the original bilinear weights are used.
- ◇ Otherwise, the weights for the remaining wind points are normalised again.

The effect of the mask, when applied as a land-sea mask, is that for velocity points close to shore the interpolated wind is no longer influenced by the wind over land (which would otherwise yield a zone of points with reduced wind near the shore).

Specification and format of the mask file

The name of the mask file, if any, is specified in the <.ext> file, labelled `SOURCEMASK`, directly following the `FILENAME` specification, e.g.:

```
QUANTITY   =windxy
FILENAME   =meteo.wxwy
SOURCEMASK =meteo_mask.asc
FILETYPE   =6
METHOD     =3
OPERAND    =O
```

The mask file itself has the same layout as the wind file, though the number of required header fields is reduced, e.g.:

```
FileVersion      =    1.03
.
.

unit1            =    Pa
### END OF HEADER
1       1       1       1       1
1       1       1       0       0
1       1       1       0       0
1       1       0       0       0
```

The lines in the header are ignored. The number of columns and rows in the matrix of ones and zeros should match those of a block (for a single variable and a single timestep) in the meteo files. Zeros signify the position of rejected points (and ones those of the accepted points) in the wind grid.

12 Hydraulic structures

12.1 Introduction

Obstacles in the flow may generate sudden transitions from flow contraction to flow expansion. The grid resolution is often low compared to the gradients of the water level, the velocity and the bathymetry. The hydrostatic pressure assumption may locally be invalid. Examples of these obstacles in civil engineering are: gates, barriers, dams, groynes and weirs. The obstacles generate energy losses and may change the direction of the flow.

The forces due to obstacles in the flow which are not resolved (sub-grid) on the horizontal grid, should be parameterised. The obstacles are denoted in D-Flow FM as hydraulic structures. In the numerical model the hydraulic structures should be located at velocity points of the grid. The direction of the forces should be specified at input. To model the force on the flow generated by a hydraulic structure, a quadratic energy or linear loss term is added to the momentum equation.

Note: Structure definitions can be made in Delta Shell, and will then be saved into a structures <∗.ini>-file (section B.11).

12.2 Structures

The user can insert the hydraulic structures by the means of polygons on the grid. By selecting the required structure and drawing a polygon on the computational grid, the location of structure can be defined (see Figure 12.1). The supported structures in D-Flow FM are

- Fixed Weirs
- (Adjustable) weirs
- Gates
- Pumps
- Thin dams

In practice, the word 'barrier' is often used for structures. However, in D-Flow FM such structures are modelled as a gate or a weir in combination with a so-called Control Group (D-Real Time Control model).

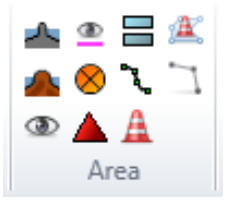


Figure 12.1: *Selection of structures (and other items) in the toolbar.*

12.2.1 Fixed weirs

In D-Flow FM, a fixed weir is a fixed non-movable construction generating energy losses due to constriction of the flow. They are commonly used to model sudden changes in depth (roads, summer dikes) and groynes in numerical simulations of rivers. Such structures are applied to keep the river in its bed for navigation purposes. Others are built, for instance, to protect an area behind a tidal weir from salt intrusion. Upstream of a weir the flow is accelerated due to contraction and downstream the flow is decelerated due to expansion. The expansion introduces an important energy loss due to turbulence. The energy loss is dependent on the shape of the weir and its crest level.

Weirs are located in D-Flow FM on the velocity points of the computational grids. For a description of the input of weirs, we refer you to section 4.4.2.9.

In D-Flow FM, two different approaches are applied to simulate the energy losses by fixed weirs. First of all, a numerical approach has been implemented. Then, a special discretization of the advective terms around the fixed weir is applied. For a detailed description we refer to D-Flow FM TRM (2015, section 6.7.1–6.7.4). Next to the numerical approach, there is an emperical approach. Based on measurements in flume laboratories empirical formulae can be derived in order to match the measurements as accurately as possible. In this empirical approach, the energy loss due to a weir is described by the loss of energy height ($[m]$). The energy loss in the direction perpendicular to the weir is denoted as ΔE. This energy loss is added as an opposing force in the momentum equation by adding a term $-g\Delta E/\Delta x$ to the right hand side of the momentum equation, resulting in a jump in the water levels by ΔE at the location of the weir. For the computation fo the energy loss ΔE two options are availabe in D-Flow FM, namely the so-called 'Tabellenboek' and 'Villemonte' approaches. The two corresponding empirical formulas have been taken from the Simona software suite. For a detailed description of both formulas we refer to D-Flow FM TRM (2015, section 6.7.5–6.7.6). In this empirical approach the discretization of the advective terms does not change, unlike the numerical approach in D-Flow FM for modelling fixed weirs.

12.2.2 (adjustable) Weirs

Unlike the fixed weir (with fixed crest level), an adjustable weir has geometric parameters that can be adjusted in time. The controllable weirs, which are called weirs or gates in D-Flow FM, are weirs which can be controlled with a predefined time series or get controlled based on the water level or other conditions. Two type of weirs are possible in D-Flow FM, namely a so-called simple weir and a general structure. In case of a simple weir only a crest level and a contraction coefficient can be specified, which is shown in Figure 12.2.

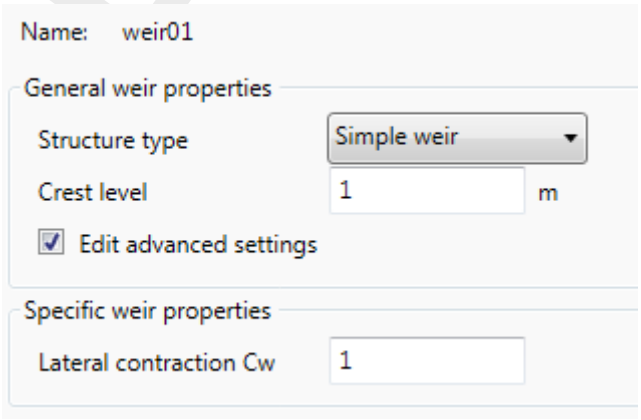


Figure 12.2: *Input for simple weir*

The general structure gives more freedom in defining the dimensions and the geometry of the hydraulic structure. The geometrical shape is given in Figure 12.3 and Figure 12.4. The discharge through a general structure is computed on basis of upstream and downstream energy levels.

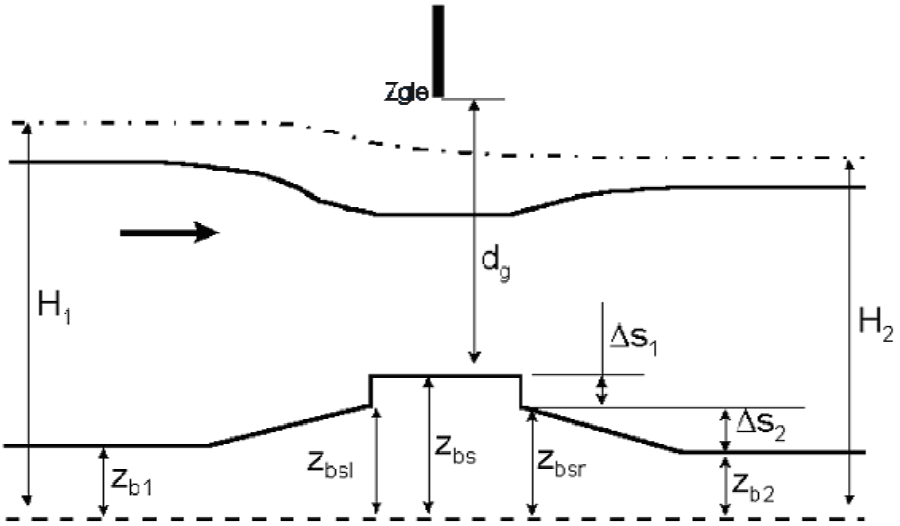


Figure 12.3: *General structure, side view*

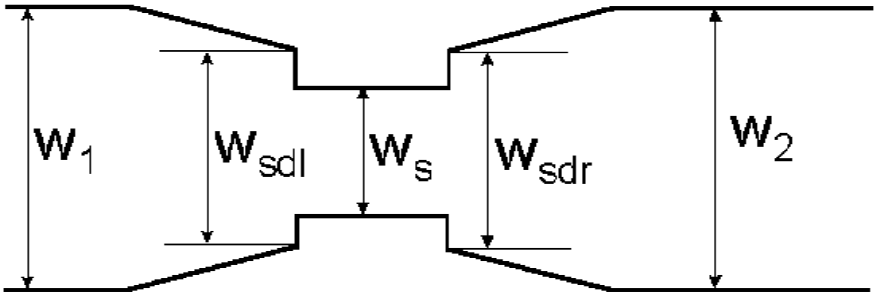


Figure 12.4: *General structure, top view*

In the GUI of D-Flow FM the coefficients of a general structure can be set as shown in Figure 12.5. Flow across the general structure can be of the following types: drowned weir flow, free weir flow, drowned gate flow, and free gate flow, depending on the dimensions of the structure and the flow conditions. Whether or not the gate is in the flow or above the flow yields either submerged or free flow. Furthermore, the flow can be either subcritical or critical. Both for incoming flow ("Flow") which represents flood and for outgoing flow ("Reverse") which represents ebb, contraction coefficients can be specified. This can be seen as tuning parameters for the user.

In Figure 12.5 the geometric parameters of a weir can be specified. The five values for the width (Upstream 1, Upstream 2, Crest, Downstream 1 and Downstream 2) coincide with the five width parameters in Figure 12.4, which are W_1, W_{sdl}, W_s, W_{sdr} and W_2, respectively. Similarly, the five values for the level correspond with Z_{b1}, Z_{bsl}, Z_{bs}, Z_{bsr} and Z_{b2} in Figure 12.3.

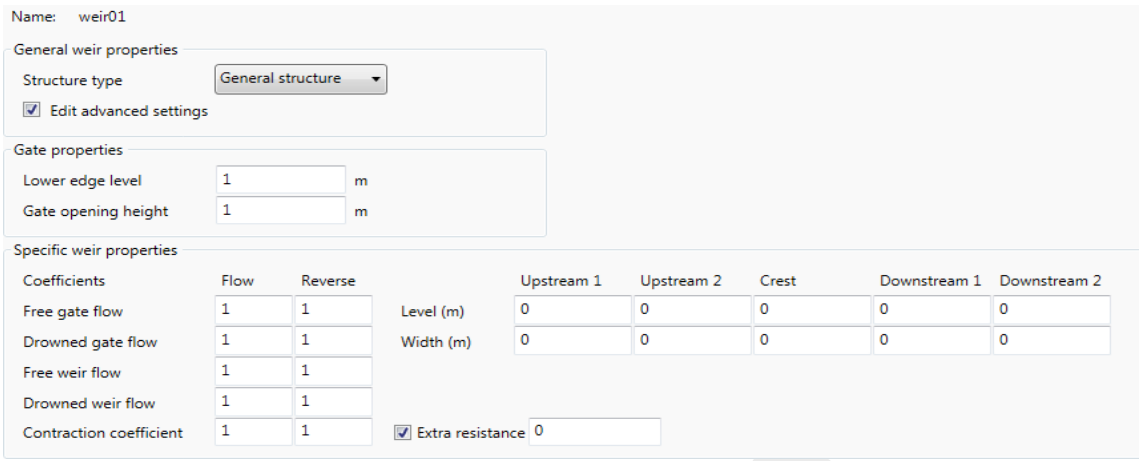


Figure 12.5: *Input for a general structure*

The structure parameters for a (adjustable) weir can be defined via the <structures.ini> file:

```
type            = weir
id              = weir02
polylinefile    = weir02.pli
crest_level     = weir02_crest_level.tim
lat_cont_coeff = 1
```

12.2.3 Gates

Constructions which partially block the horizontal flow can be modelled as so-called "gates". Its horizontal and vertical position can be specified. Upstream of the gate the flow is accelerated due to contraction and downstream the flow is decelerated due to expansion. A gate may include two type of openings, namely, in horizontal and in vertical directions. In two-dimensional simulations, the vertical effect is parameterized by a quadratic energy loss term.

The horizontal effect are mimicked by setting the velocities of the computational faces (at position of the gate) to zero. This generates structure of the horizontal flow around the gate which is more realistic. There is no transport of salt or sediment through the blocked computational faces of a gate. The width of a gate is assumed to be zero, so it has no influence on the water volume.

In D-Flow FM the gates can be imposed by polygons, and can be edited in a similar way as the other structures. For more details on gates in Delta Shell, we refer you to section 4.4.2.10. In Figure 12.6 the geometric parameters of a gate are shown.

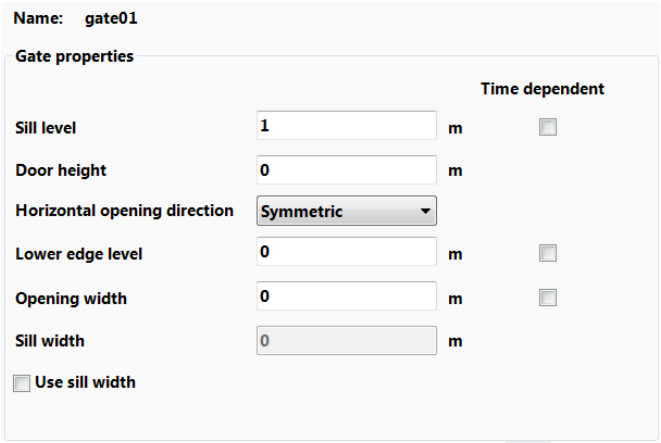


Figure 12.6: *Input for a gate*

The structure of the input file for the gates is as follows:

```
type                          = gate
id                            = gate01
polylinefile                  = gate01.pli
lower_edge_level              = 15
opening_width                 = gate01_opening_width.tim
sill_level                    = 7
door_height                   = 5
horizontal_opening_direction  = symmetric
```

12.2.4 Pumps

Pumps are another type of structures in D-Flow FM. Unlike the other structures, a pump can force the flow only on one direction. However, pumps can be defined by polygons, like all other structures in D-Flow FM.

The pump includes specific capacity, and pumps the water by its capacity, as long as the water level is sufficient. In the case, the water level is lower than a required value, pump will not pump any flow, despite of their capacity. The structure of the input file for the pumps is as follows:

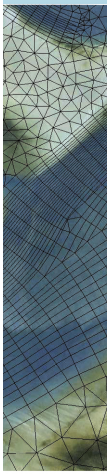
```
type                        = pump
id                          = pump01
polylinefile                = pump01.pli
capacity                    = pump01_capacity.tim
start_level_delivery_side   = 0
stop_level_delivery_side    = 0
start_level_suction_side    = 3
stop_level_suction_side     = 2
reduction_factor_no_levels  = 0
```

12.2.5 Thin dams

Thin dams are similar to fixed weirs. The only difference between the thin dams and fixed weirs are in their crest levels. Thin dams, in principle, include infinitely high crest levels and hence, they do not allow water flux. Similar to the other structures, the thin dams can be selected from the toolbar and drawn by a polygon. D-Flow FM adjusts the polygon to the nearest velocity points. The input data for a thin dam is identical to those for fixed-weir, except for the crest level.

13 Bedforms and vegetation

The terrain and vegetation exert shear stresses on the passing flow. The magnitude of the shear stress of the bed is often characterised by means of roughness coefficient of type Chézy, Manning or White-Colebrook. Within the main stream flow the shear stresses are largely determined by the local conditions of the alluvial bed (bed composition and bedform characteristics). In other areas, such the floodplains of rivers and in the intertidal areas of estuaries, the flow resistance is determined by a combination of vegetation and an alluvial bedforms or even a non-alluvial bed. To accurately represent such conditions in the numerical model, D-Flow FM has been extended with a vegetation model. Another related feature known from Delft3D-FLOW is the bedform roughness predictors; these are not available in D-Flow FM yet. These types of flow resistance may be resolved in a 2D numerical model using the trachytope approach (see section 13.2).



13.1 Bedform heights

The dune height and Van Rijn (2007) bedform roughness predictors, known from Delft3D-FLOW, are not available yet in D-Flow FM. They will be in an upcoming release.

13.2 Trachytopes

This functionality allows you to specify the bed roughness and flow resistance on a sub-grid level by defining and using various land use or roughness/resistance classes, further referred to as trachytopes after the Greek word $\tau\rho\alpha\chi\acute{\upsilon}\tau\eta\varsigma$ for roughness. The input parameters and files to use the trachytopes functionality are described in section B.6.

At every time step (or less frequent as requested by the user) the trachytopes are converted into a representative bed roughness C, k or n and optional linear flow resistance coefficient λ per velocity point with index j.

$$M = -\frac{1}{2}\lambda_j u_j \left|\boldsymbol{u}_j\right| \tag{13.1}$$

To save computational time the user may choose to update the computed bed roughness and resistance coefficients less frequently than every time step. See section B.6 for a description of the keywords and input files associated with this feature.

The following two sections describe the various classes of trachytopes distinguished and the way in which they are combined, respectively.

13.2.1 Trachytope classes

Three base classes of trachytopes are distinguished: area classes, line classes and point classes. The area classes (type range 51–200) basically cover the whole area, therefore, they are generally the dominant roughness factor. The line classes (type range 201–250) may be used to represent hedges and similar flow resistance elements; it will add anisotropy to the roughness field. The point class (type range 251–300) represents a set of point flow resistance elements. The next six sections provide an overview of the various trachytope formulae implemented.

Special classes (1–50)

In addition to the three base classes two special trachytope classes have been defined: a flood protected area and a composite trachytope class. The first class represents a sub-grid area

that is protected from flooding and thus does not contribute to the bed roughness; however, the effect on the flow resistance should be taken into account. The second class can be used to make derived trachytope classes that are a combination of two other trachytopes: an area fraction α of trachytope type T_1 and an area fraction β (often equal to $1-\alpha$) of trachytope type T_2.

FormNr	Name	Formula
Special classes (1–50)		
1	flood protected area	area fraction shows up as f_b in Eqs. (13.53) and (13.56)
2	composite trachytope	fraction α of type T_1 and fraction β (generally $\beta = 1-\alpha$) of type T_2

Area trachytope classes (51–200)

The class of area trachytopes is subdivided into three types: simple (51–100), alluvial (101–150) and vegetation (151–200). Four simple area trachytopes have been implemented representing the four standard roughness types of flow module.

FormNr	Name	Formula
51	White-Colebrook value	k
52	Chézy value	C
53	Manning value	$C = \sqrt[6]{h}/n$
54	z_0 value	$k = 30 z_0$

Six alluvial trachytopes have been implemented.

FormNr	Name	Formula
101	simplified Van Rijn	Equation (13.2)
102	power relation	Equation (13.3)
103	Van Rijn (1984c)	Equations (13.4) to (13.12)
104	Struiksma	Equations (13.13) to (13.16)
105	bedforms quadratic	Equation (13.17)
106	bedforms linear	Equation (13.18)

The first alluvial roughness formula is a simplified version of the Van Rijn (1984c) alluvial roughness predictor

$$k = A h^{0.7} \left[1 - e^{-B h^{-0.3}}\right] \tag{13.2}$$

it is obtained from Equation (13.4) by noting that $h_b \propto h^{0.7}$ and $L_b \propto h$ and ignoring the grain related roughness. The parameters A and B can be calibrated by the user. The second formula implemented is a straightforward general power law

$$C = A h^B \tag{13.3}$$

where A and B are calibration coefficients. The Van Rijn (1984c) alluvial roughness predictor reads

$$k = k_{90} + 1.1 h_b \left(1 - e^{-25 h_b / L_b}\right) \tag{13.4}$$

where the bedform height h_b and length L_b are given by

$$h_b = 0.11 h \left(\frac{D_{50}}{h}\right)^{0.3} \left(1 - e^{-T/2}\right) (25 - T) \tag{13.5}$$

$$L_b = 7.3 h \tag{13.6}$$

where h is the local water depth and the transport stage parameter T is given by

$$T = \frac{u'^2_* - u^2_{*,cr}}{u^2_{*,cr}} \tag{13.7}$$

where u'_* is the bed shear velocity given by

$$u'^2_* = g u^2 / C^2_{g,90} \tag{13.8}$$

where

$$C_{g,90} = 18\ ^{10}\log(12h/k_{90}) \text{ and } k_{90} = 3D_{90} \tag{13.9}$$

and $u_{*,cr}$ is the critical bed shear velocity according Shields given by

$$u^2_{*,cr} = g \Delta D_{50} \theta_c \tag{13.10}$$

given

$$\theta_c = \begin{cases} 0.24/D_* & \text{if } D_* \leq 4 \\ 0.14 D_*^{-0.64} & \text{if } 4 < D_* \leq 10 \\ 0.04 D_*^{-0.10} & \text{if } 10 < D_* \leq 20 \\ 0.013 D_*^{0.29} & \text{if } 20 < D_* \leq 150 \\ 0.055 & \text{if } 150 < D_* \end{cases} \tag{13.11}$$

where

$$D_* = D_{50} \left(\frac{g\Delta}{\nu^2}\right)^{1/3} \tag{13.12}$$

This predictor does not contain any calibration coefficients but requires D_{50} and D_{90} data from the morphology module. It does not include the advective and relaxation behaviour that is available by explicitly simulating the dune height as described in section 13.1 combined with trachytope number 106.

The second alluvial roughness predictor proposed by (Struiksma, pers. comm.) allows for a lot of adjustments, it reads

$$\frac{1}{C^2} = (1 - \xi)\frac{1}{C^2_{90}} + \xi \frac{1}{C^2_{min}} \tag{13.13}$$

where

$$C_{90} = A_1\ ^{10}\log(A_2 h / D_{90}) \tag{13.14}$$

and

$$\xi = \frac{\max(0, \theta_g - \theta_c)}{\theta_m - \theta_c} \frac{\theta_m^2 - \theta_c \theta_g}{(\theta_m - \theta_c)\theta_g} \tag{13.15}$$

which varies from 0 at $\theta_g \leq \theta_c$ to 1 at $\theta_g = \theta_m$ where

$$\theta_g = \frac{u^2}{C_{90}^2 \Delta D_{50}} \tag{13.16}$$

and $A_1, A_2, \theta_c, \theta_m, C_{\min}$ are coefficients that the user needs to specify. This formula requires also D_{50} and D_{90} data from the morphology module. The fifth formula is based on Van Rijn (2007) and reads

$$k = \min(\sqrt{k_{s,r}^2 + k_{s,mr}^2 + k_{s,d}^2}, \frac{h}{2}) \tag{13.17}$$

It uses the roughness heights of ripples k_r, mega-ripples k_{mr} and dunes k_d. These formulae depend on sediment properties D_{50} and D_{90} data which may be either specified as part of the roughness type or obtained from the morphology module. The sixth formula is similar, but uses a linear addition

$$k = \min(k_{s,r} + k_{s,mr} + k_{s,d}, \frac{h}{2}) \tag{13.18}$$

Four vegetation based area trachytopes have been implemented. Two formulae (referred to as 'Barneveld') are based on the work by Klopstra *et al.* (1996, 1997) and two on the work by Baptist (2005).

FormNr	**Name**	**Formula**
151	Barneveld 1	Eqs. (13.19) – (13.28), $C_D = 1.65$
152	Barneveld 2	Eqs. (13.19) – (13.25), (13.29) – (13.31)
153	Baptist 1	Eqs. (13.32) and (13.33)
154	Baptist 2	Eqs. (13.34), (13.36) and (13.37)

The formula by Klopstra *et al.* (1997) reads

$$C = \frac{1}{h^{3/2}} \left\{ \begin{array}{l} \frac{2}{\sqrt{2A}} \left(\sqrt{C_3 e^{h_v \sqrt{2A}} + u_{v0}^2} - \sqrt{C_3 + u_{v0}^2} \right) + \\ \quad \frac{u_{v0}}{\sqrt{2A}} \ln \left(\frac{(\sqrt{C_3 e^{h_v \sqrt{2A}} + u_{v0}^2} - u_{v0})(\sqrt{C_3 + u_{v0}^2} + u_{v0})}{(\sqrt{C_3 e^{h_v \sqrt{2A}} + u_{v0}^2} + u_{v0})(\sqrt{C_3 + u_{v0}^2} - u_{v0})} \right) + \\ \quad \frac{\sqrt{g(h-(h_v-a))}}{\kappa} \left((h - (h_v - a)) \ln \left(\frac{h-(h_v-a)}{z_0} \right) - a \ln \left(\frac{a}{z_0} \right) - (h - h_v) \right) \end{array} \right\} \tag{13.19}$$

where

$$A = \frac{n C_D}{2\alpha} \tag{13.20}$$

$$C_3 = \frac{2g(h - h_v)}{\alpha \sqrt{2A}(e^{h_v \sqrt{2A}} + e^{-h_v \sqrt{2A}})} \tag{13.21}$$

$$a = \frac{1 + \sqrt{1 + \frac{4E_1^2\kappa^2(h-h_v)}{g}}}{\frac{2E_1^2\kappa^2}{g}} \tag{13.22}$$

and

$$z_0 = ae^{-F} \tag{13.23}$$

where

$$E_1 = \frac{\sqrt{2A}C_3e^{h_v\sqrt{2A}}}{2\sqrt{C_3e^{h_v\sqrt{2A}} + u_{v0}^2}} \tag{13.24}$$

and

$$F = \frac{\kappa\sqrt{C_3e^{h_v\sqrt{2A}} + u_{v0}^2}}{\sqrt{g(h-(h_v-a))}} \tag{13.25}$$

Here, h is the water depth, h_v is the vegetation height, and $n = mD$ where m is the number of stems per square metre and D is the stem diameter. For the first implementation the parameter α in Equation (13.21) is given by

$$\alpha = \max(0.001, 0.01\sqrt{hh_v}) \tag{13.26}$$

and the velocity within the vegetation is approximated by $u_{v0}\sqrt{i}$ where

$$u_{v0}^2 = \frac{2g}{C_Dn} \tag{13.27}$$

and i is the water level gradient. For emerged vegetation the first implementation reads

$$\frac{1}{C^2} = \frac{C_Dnh}{2g} \tag{13.28}$$

The second implementation of Klopstra *et al.* (1996) is based on a modification by Van Velzen *et al.* (2003); it is identical except for the following modifications to Eqs. (13.26) – (13.28). The main difference between the two implementations is the inclusion of the roughness C_b of the bed itself (without vegetation). The parameter α in Equation (13.21) is now given by

$$\alpha = 0.0227h_v^{0.7} \tag{13.29}$$

and the velocity within the vegetation is approximated by $u_{v0}\sqrt{i}$ where

$$u_{v0}^2 = \frac{h_v}{\frac{C_Dh_vn}{2g} + \frac{1}{C_b^2}} \tag{13.30}$$

and i is the water level gradient. For emerged vegetation the second implementation reads

$$\frac{1}{C^2} = \frac{C_Dnh}{2g} + \frac{1}{C_b^2} \tag{13.31}$$

For large values of C_b the latter two equations simplify to the corresponding equations of the first implementation. The first implementation requires vegetation height h_v and density n as input parameters (the drag coefficient C_D is equal to 1.65); for second implementation you'll also need to specify the drag coefficient C_D and the alluvial bed roughness k_b (C_b in Equation (13.31) is computed as $18\ ^{10}\log(12h/k_b)$).

The first implementation of the roughness predictor by Baptist (Baptist, 2005) reads for the case of submerged vegetation

$$C = \frac{1}{\sqrt{\frac{1}{C_b^2} + \frac{C_D n h_v}{2g}}} + \frac{\sqrt{g}}{\kappa} \ln(\frac{h}{h_v}) \tag{13.32}$$

where n is the vegetation density ($n = mD$ where m is the number of stems per square metre and D is the stem diameter). The second term goes to zero at the transition from submerged to emerged vegetation. At that transition the formula changes into the formula for non-submerged vegetation which reads

$$C = \frac{1}{\sqrt{\frac{1}{C_b^2} + \frac{C_D n h}{2g}}} \tag{13.33}$$

which is identical to the non-submerged case of the second implementation of the work by Klopstra *et al.* (1996) (see Equation (13.31)).

The drawback of the three vegetation based formulations above is that they parameterize the flow resistance by means of the bed roughness. Consequently, the presence of vegetation will lead to a higher bed roughness and thus to a higher bed shear stress and larger sediment transport rates in case of morphological computations. Therefore, we have included a $-\frac{\lambda}{2}u^2$ term in the momentum equation where λ represents the flow resistance of the vegetation. For the case of non-submerged vegetation $h < h_v$ the flow resistance and bed roughness are strictly separated

$$C = C_b \quad \text{and} \quad \lambda = C_D n \tag{13.34}$$

In the case of submerged vegetation $h > h_v$ the two terms can't be split in an equally clean manner. However, we can split the terms such that the bed shear stress computed using the depth averaged velocity u and the net bed roughness C equals the bed shear stress computed using the velocity u_v within the vegetation layer and the real bed roughness C_b.

$$\frac{u^2}{C^2} = \frac{u_v^2}{C_b^2} \tag{13.35}$$

With this additional requirement we can rewrite Equation (13.32) as

$$C = C_b + \frac{\sqrt{g}}{\kappa} \ln(\frac{h}{h_v}) \sqrt{1 + \frac{C_D n h_v C_b^2}{2g}} \tag{13.36}$$

and

$$\lambda = C_D n \frac{h_v}{h} \frac{C_b^2}{C^2} \tag{13.37}$$

which simplify to Equation (13.34) for $h = h_v$. Both formulae by Baptist require vegetation height h_v, density n, drag coefficient C_D and alluvial bed roughness C_b as input parameters.

Linear trachytope classes (201–250)

Two formulae have been implemented for linear trachytopes such as hedges or bridge piers.

FormNr	Name	Formula
201	hedges 1	Eqs. (13.38) to (13.40)
202	hedges 2	Eqs. (13.41) to (13.43)

The first implementation reads

$$\frac{1}{C^2} = \frac{h}{2g}\frac{L_{hedge}}{W_{cell}L_{cell}}\frac{1-\mu^2}{\mu^2} \tag{13.38}$$

where L_{hedge} is the projected length of the hedge, W_{cell} and L_{cell} are the width and length of the grid cell. The ratio L_{hedge}/W_{cell} may be interpreted as the number of hedges that the flow encounters per unit width. The second ratio is thus the inverse of the average distance between these hedges within the grid cell. The last term may be loosely referred to as the drag of the hedge, which is determined by the hedge pass factor μ given by

$$\mu = 1 + 0.175n\left(\frac{h}{h_v} - 2\right) \tag{13.39}$$

if the hedge extends above the water level ($h_v > h$) and is given by

$$\mu = 1 - 0.175n\left(\frac{h}{h_v}\right) \tag{13.40}$$

if the hedge is fully submerged ($h > h_v$) where n is a dimensionless hedge density. The second implementation reads

$$\frac{1}{C^2} = \frac{C_D n L_{hedge} h}{2gL_{cell}W_{cell}} \tag{13.41}$$

or equivalently

$$C = \sqrt{\frac{2gL_{cell}W_{cell}}{hL_{hedge}}}\left(\sqrt{\frac{1}{C_D n}}\right) \tag{13.42}$$

for non-submerged conditions and

$$C = \sqrt{\frac{2gL_{cell}W_{cell}}{hL_{hedge}}}\left(\frac{h_v}{h}\sqrt{\frac{1}{C_D n}} + m_0\sqrt{\frac{\left(\frac{h-h_v}{h}\right)^2}{1-\left(\frac{h-h_v}{h}\right)^2}}\right) \tag{13.43}$$

for submerged conditions. We recognize the same ratio $L_{cell}W_{cell}/L_{hedge}$ that represents the average distance between hedges. Equation (13.41) can be directly compared to similar equations for area trachytopes (Equation (13.28)), point trachytopes (Equation (13.44)). Note that the formula for computing the loss coefficient for a bridge explicitly includes the reduction in the flow area and the resulting increase in the effective flow velocity, whereas the above mentioned trachytope formulae don't.

Point trachytope classes: various (251–300)

One formula for point trachytopes has been implemented. It may be used to represent groups of individual trees or on a smaller scale plants.

FormNr	Name	Formula
251	trees	Eqn. (13.44)

The implemented formula reads

$$C = \sqrt{\frac{2g}{C_D n \min(h_v, h)}} \tag{13.44}$$

where $n = mD$ with m the number of trees per unit area and D the characteristic tree diameter, h_v is the vegetation height and h is the local water depth. The formula is identical to Equation (13.33) except for the fact that the point trachytope formula has no bed roughness and area associated with it. The generalization of Equation (13.44) to the submerged case ($h > h_v$) lacks the extra term in Equation (13.32).

13.2.2 Averaging and accumulation of trachytopes

Point and linear roughnesses are accumulated by summing the inverse of the squared Chézy values C_i.

$$\frac{1}{C_{pnt}^2} = \sum_i \frac{1}{C_{pnt,i}^2} \tag{13.45}$$

$$\frac{1}{C_{lin}^2} = \sum_i \frac{1}{C_{lin,i}^2} \tag{13.46}$$

The area roughnesses are accumulated weighted by the surface area fraction f_i. These roughnesses are accumulated as White-Colebrook roughness values and as Chézy values; for the latter values both the linear sum (“parallel”) and the sum of inverse of squared values (“serial”) are computed. Roughness values are converted into each other as needed based on the local water depth.

$$k_{area} = \sum_i f_i k_i \tag{13.47}$$

$$\frac{1}{C_{area,s}^2} = \sum_i f_i \frac{1}{C_i^2} \tag{13.48}$$

$$C_{area,p} = \sum_i f_i C_i \tag{13.49}$$

For the fraction of the grid cell area for which no roughness class is specified the default roughness is used.

The flow resistance coefficients are also accumulated proportionally to the surface area fraction f_i associated with the trachytope considered. For the fraction of the grid cell area for which no flow resistance is specified, obviously none is used.

$$\lambda = \sum_i f_i \lambda_i \tag{13.50}$$

The final effective bed roughness of the grid cell may be computed by either one of the following two methods.

Method 1

The total mean roughness is computed by summing the White-Colebrook values for the areas and line and point resistance features.

$$k_m = k_{area} + k_{lin} + k_{pnt} \tag{13.51}$$

where $k_{lin} = 12h10^{-C_{lin}/18}$ and $k_{pnt} = 12h10^{-C_{pnt}/18}$. The effect of the water free area fraction f_b is taken into account by means of the following empirical relation in which $C_m = 18\ ^{10}\log(12h/k_m)$ is the mean Chézy value corresponding to the total mean White-Colebrook roughness value obtained from Equation (13.51).

$$f_b = \max(\min(0.843, f_b), 0.014) \tag{13.52}$$

$$C_{\text{total}} = C_m \left(1.12 - 0.25 f_b - 0.99\sqrt{f_b}\right) \tag{13.53}$$

The resulting C_{total} value is used in the computation. This method together with trachytope classes 1, 51, 101, 151 and 201 corresponds to the NIKURADSE option of the WAQUA/TRIWAQ flow solver.

Method 2

The total roughness is computed by first averaging over the serial and parallel averages of the Chézy values according

$$C_{area} = \alpha_s C_{area,s} + (1 - \alpha_s) C_{area,p} \tag{13.54}$$

where $\alpha_s = 0.6$ by default. Subsequenty the effect of the water free area fraction f_b is taken into account by means of the following empirical relation (identical to Equation (13.53) of method 1).

$$f_b = \max(\min(0.843, f_b), 0.014) \tag{13.55}$$

$$C_{area,corr} = C_{area} \left(1.12 - 0.25 f_b - 0.99\sqrt{f_b}\right) \tag{13.56}$$

Finally the Chézy value representing the total bed roughness is computed by accumulating the inverses of the squared Chézy values.

$$\frac{1}{C_{total}^2} = \frac{1}{C_{area,corr}^2} + \frac{1}{C_{lin}^2} + \frac{1}{C_{pnt}^2} \tag{13.57}$$

The resulting C_{total} value is used in the computation. This method together with trachytope classes 1, 51, 52, 53, 101, 152, 202 and 251 corresponds to the ROUGHCOMBINATION option of the WAQUA/TRIWAQ flow solver.

13.3 (Rigid) three-dimensional vegetation model

The (rigid) 3D Vegetation model (Winterwerp and Uittenbogaard (1997)), as known from Delft3D-FLOW, is not available yet in D-Flow FM.

14 Calibration factor

The current chapter explains the effect of the calibration factor. The calibration factor is multiplier of the roughness. The calibration factor may be constant, discharge- or water-level-dependent. By assigning different areas to different calibration classes, each region can be independently calibrated. Calibration roughness definitions can also be combined by assigning multiple field definitions and a weighting for each gridcell edge (net link). This approach allows thus both abrupt and gradual transitions and the modeller can control how the calibration factor is going to be used. The approach is similar to the roughness and link definitions used in the trachytopes module for alluivial- and bedform-roughness (see chapter 13).

The calibration factor is defined by means of two files (see section B.8):

- ◇ Calibration factor definition file (CLD-file). This file defines the calibration factor (e.g. constant, water-level- or discharge dependent).
- ◇ Calibration factor area file (CLL-file). This file associates calibration factor defintions with the edges of the model grid and include a relative weighting.

The resulting weighted calibration factor is multiplied by the roughness type as expressed by the `UnifFrictCoef` keyword in the [physics] section in the .mdu file (see Appendix A). This implies that the effect of the calibration will be different depending on the definition of `UnifFrictCoef`. For example, if the `UnifFrictCoef`=0 (i.e. Chézy) a local calibration factor of 0.5 will imply an increase of the bed shear stress, whereas if `UnifFrictCoef`=2 (i.e. White-Colebrook) a reduction of the bed shear stress may be expected. A background calibration factor equal to one is applied if the sum of the weights at a single link is lower than one.

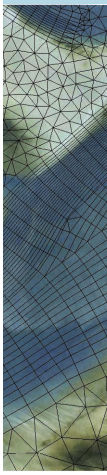
The calibration factor approach cannot be combined with multiple roughness types as specified through the external forcing file. This will lead to an error. Such a spatial variation in the roughness can be achieved by defining these areas through the trachytopes module.

It is good to be aware of the following known differences with the trachytopes module:

- ◇ The weighting of the calibration factors is done for all entries in the calibration area defintion file. Averaging for the trachytopes area file is only done for the last sequence of trachytope area defintions at one and the same location.
- ◇ When a calibration factor definition is imposed at a location outside of the grid, and this calibration factor definition depends on a water level station or cross-section which is also outside of the domain, the model crashes, however the trachytopes module allows this.

15 Coupling with D-Waves (SWAN)

This chapter is on the *coupling* of hydrodynamics and waves. Full documentation on D-Waves is available in its own User Manual; this chapter is limited to the details of running coupled flow-wave models, and the physical interaction processes between the two of them.



15.1 Getting started

The Delta Shell framework implements the concept of an *Integrated model* in order to couple different models, such as: hydrodynamics coupled with the controlling of structures, waves, morphology and/or water quality.

Two types of coupling are distinguished: *offline* and *online* coupling. In case of an *Integrated model* with *offline* coupling, the entire hydrodynamic simulation is done first, i.e., *separately* from the second simulation. The file-based hydrodynamic output serves as input for the second simulation. As such, the hydrodynamic flow drives the controlling of structures or the simulation of waves or water quality. In this case there is no feedback on the hydrodynamic simulation. For many applications, this is good practice.

An *online* coupling, on the other hand, exchanges data *every time* after computing a specified time interval. This tight coupling allows for direct feedback of the various processes on one another. This is crucial for controlling structures.

Note: *Offline* is also referred to as *sequential* coupling and *online* as *parallel* coupling.

With respect to waves, *offline* and *online* results into:

1. *offline*: First, a separate D-Waves computation is executed, resulting in a communication file (com-file) containing wave data. Then a D-Flow FM computation is executed, using the wave data from the com-file.
2. *online*: D-Flow FM computations are alternated with D-Waves calculations. D-Flow FM writes flow data to the com-file, D-Waves uses this flow data for the wave calculation and writes wave data to the com-file. D-Flow FM uses the updated wave data.

Both modes are started by executing DIMR with a <dimr_config.xml> file as argument. This file prescribes the mode and when the D-Flow FM computation should be paused to perform a D-Waves calculation. From within the working directory, the following run-scripts in the installation directory can be called:

- ◇ On Windows:
  <win64\scripts\run_dimr.bat>
- ◇ On Linux:
  <lnx64/scripts/run_dimr.sh>
- ◇ On Windows, a computation with D-Flow FM in parallel using MPI:
  <win64\scripts\run_dimr_parallel.bat>
- ◇ On Linux, submitting a job on the Deltares cluster (sequential and parallel):
  <lnx64/scripts/submit_dimr.sh>
  This script can be used for clusters outside Deltares too, but system specific modifications will be needed.

See the DIMR documentation for more information.

15.1.1 Input D-Flow FM

Optionally add the following lines to the .mdu file:

```
[numerics]
Epshu           = 0.05 # Input for threshold water depth for wet and dry cells

[waves]
Wavemodelnr     = 3    # Wave model nr, 0=no, 1=fetch/depth limited hurdlestive,
                        2=youngverhagen, 3 = D-Waves, 4=wave group forcing
Rouwav          = FR84
Gammax          = 0.5  # Maximum wave height/water depth ratio

[output]
EulerVelocities = 1    # 0 (default): GLM, 1: Euler.
Only relevant when using waves
```

Description:

Wavemodelnr	Key switch to enable wave modelling. Use “3” for wave data from D-Waves (online or offline) and passing hydrodynamic data to D-Waves (online only). A file will be generated automatically named <”runid”_com.nc> to exchange data.
Rouwav	Necessary to include bed shear-stress enhancement by waves. See also Delft3D-FLOW manual.
EulerVelocities	Optional flag to write Eulerian velocities to the D-Flow FM map file. Currently, only Eulerian values will be written for the cell centre velocity x-component and y-component (parameters ucx and ucy). Check that the ”long_name” contains the word ”Eulerian”.
Epshu	Optionally overwrite the default value of “1.0e-4”. Depending on your model, the default value of Epshu in combination with modelling waves may lead to huge local velocities near (almost) dry points. This will result in very small time steps. Increasing Epshu might be a reasonable workaround.
Gammax	Optionally overwrite the default value of “1.0”. Depending on your model, the default value of Gammax may lead to huge local velocities in shallow water. Decreasing Gammax might be a reasonable workaround.

15.1.2 Input D-Waves

Optionally add the following lines to the .mdw file:

```
[Output]
  MapWriteNetCDF        = true
  COMFile               = ../fm/dflowfmoutput/fff_com.nc
  NetCDFSinglePrecision = false
  locationFile          = ../fm/loo_obs.xyn
  writeTable            = true
```

Description:

MapWriteNetCDF	Default value “false”, resulting in no output written in NetCDF format. The coupling with D-Flow FM is only implemented for NetCDF format, so this flag must be set to “true” when being coupled with D-Flow FM.
COMFile	Necessary reference to the file being used to communicate data to and from D-Flow FM. The name must exactly match with the name of the com-file being generated by D-Flow FM.
NetCDFSinglePrecision	Optional flag to write data in single precision instead of double precision. Default value is “false”. Might be useful to decrease the size of the com-file or to compare with a Delft3D-FLOW computation.
locationFile	Optional reference to observation points in D-Flow FM. When in combination with the “writeTable” flag, D-Waves will produce a history file in NetCDF format for these observation points.
writeTable	Optional flag to force SWAN to produce an output file in table format for each set of locations specified in a locationFile. Default value is “false”.

15.1.3 Input dimr

Both D-Flow FM and D-Waves are used as dynamic libraries (DLL’s on Windows, so’s on Linux). DIMR is a small executable steering both dynamic libraries. Its input file, usually called “dimr_config.xml”, looks like this:

```
<?xml version="1.0" encoding="iso-8859-1"?>
<dimrConfig xmlns="http://schemas.deltares.nl/dimrConfig"
            xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
            xsi:schemaLocation="http://schemas.deltares.nl/dimrConfig
            http://content.oss.deltares.nl/schemas/d_hydro-1.00.xsd">
   <documentation>
      <fileVersion>1.00</fileVersion>
      <createdBy>Deltares, Coupling team</createdBy>
      <creationDate>2015-05-20T07:56:32+01</creationDate>
   </documentation>

   <control>
      <parallel>
         <startGroup>
            <time>0.0 60.0 99999999.0</time>
            <coupler name="flow2rtc"/>
            <start name="myNameRTC"/>
            <coupler name="rtc2flow"/>
         </startGroup>
         <startGroup>
            <time>0.0 3600.0 99999999.0</time>
            <start name="myNameWave"/>
         </startGroup>
         <start name="myNameDFlowFM"/>
      </parallel>
   </control>

   <component name="myNameDFlowFM">
      <library>dflowfm</library>
      <process>0 1 2</process>
      <mpiCommunicator>DFM_COMM_DFMWORLD</mpiCommunicator>
      <workingDir>fm</workingDir>
      <inputFile>weirtimeseries.mdu</inputFile>
   </component>
   <component name="myNameWave">
      <library>wave</library>
      <process>0</process>
      <workingDir>wave</workingDir>
      <!-- component specific -->
```

```
      <inputFile>weir.mdw</inputFile>
   </component>
   <component name="myNameRTC">
      <library>RTCTools_BMI</library>
      <process>0</process>
      <workingDir>rtc</workingDir>
      <!-- component specific -->
      <inputFile>.</inputFile>
   </component>

   <coupler name="flow2rtc">
      <sourceComponent>myNameDFlowFM</sourceComponent>
      <targetComponent>myNameRTC</targetComponent>
      <item>
         <sourceName>observations/Upstream/water_level</sourceName>
         <targetName>input_ObservationPoint01_water_level</targetName>
      </item>
   </coupler>
   <coupler name="rtc2flow">
      <sourceComponent>myNameRTC</sourceComponent>
      <targetComponent>myNameDFlowFM</targetComponent>
      <item>
         <sourceName>output_weir_crest_level</sourceName>
         <targetName>weirs/weir01/crest_level</targetName>
      </item>
   </coupler>
</dimrConfig>
```

Description:

<control> Specifies the workflow of the deltaresHydro executable. It indicates which components are started in which order. If the data transfer is to be arranged by the main program dimr, then a coupler should be included. The main <control> block is a sequential block; this means that each component is initialized, time stepped, and finalized before the next component starts. For each component/coupler listed inside the <control> block there will be a corresponding component/ coupler specification block defined below.

<parallel> Within a <parallel> tag the components are started concurrently (if the mpi process ids listed per component don't overlap) or executed synchronously in sequence (first all initialize, then time stepping, and to conclude all finalization calls). The order of the components is retained.

<start/> A <parallel> block contains exactly one <start/> component, defining the start and end time of the simulation. This is the component inside the <parallel> block with the smallest time step and can be denoted as the "master-component". All other components must be defined with a <startGroup> and can be denoted as a "slave-component".

<startGroup> A <startGroup> should be used if a component (possibly including couplers) should only be executed at a subset of simulation time steps.

<time> Start-, step- and stop-time (in seconds) at which this slave-component should be executed. The times are relative to the times of the master-component. Thus a start-time of 0.0 always refers to the start time of the master-component and a stop-time of "infinity" always refers to the end time of the master-component.

<component name="myComponentName"> Component specification block. "myComponentName" is free to be defined by the user. It must match exactly with the reference in the <control> block above. The name of a component must be unique.

<library> Reference to the component to be executed. Currently "flowfm", "wave" and "RTCTools_BMI" are supported. The name must match exactly the name of the related dll/so (excluding prefixes (e.g. "lib") and suffixes (e.g. ".dll" or ".so")).

The library should be located in the search path, or it may include an absolute or relative path. Multiple <component> blocks may refer to the same component to be executed.

<process> Optional list of the ids of the mpi processes that should be used to run the component. If not specified, then the component will run only in process “0” (i.e. non-parallel). The processes may be specified as a space separated list with series compressed using colons e.g. “16:31” represents processes “16 17 18” up to “31”.

<mpiCommunicator> D-Flow FM specific flag. Mandatory only when this D-Flow FM component should run a parallel (partitioned) model. Note that this is *unrelated* to the <parallel> tag as introduced above.

<workingDir> Specification of the working directory of this <component>, relative to the location of the “dimr_config.xml” file. The workingDir is the base/root directory of all input and output files for the component. All other files will be located RELATIVE TO this folder. If not specified, then workingDir will be equal to the folder of the configuration file.

<inputFile> Specification of the input file of this <component>, relative to <workingDir>: D-Flow FM: mdu-file, D-Waves: mdw-file, D-RTC: .

<coupler name="myCouplerName"> Coupler specification block. ”myCouplerName” is free to be defined by the user. It must match exactly with the reference in the <control> block above. The name of a coupler must be unique.

<sourceComponent> Identifies which component provides the data.

<targetComponent> Identifies which component needs to receive the data. The coupler runs on the superset of the processes configured for the source and target components.

<item> For each quantity to be exchanged, the name in the source component and the name in the target component are specified. To support recursive components, a directory syntax is used with forward slashes. If a name includes a forward slash, then it needs to be escaped using a backward slash, like \/; if a name includes a backward slash, then it needs to be escaped with a backward slash, like \\.

<sourceName> Identifies which parameter will be sent at the source component side.

<targetName> Identifies which parameter will be received at the target component side.

15.1.4 Online process order

When D-Flow FM runs online in alternation with D-Waves and D-RTC, process steps can be identified, where the order as prescribed in “dimr_config.xml” is respected as much as possible. The process order of the example “dimr_config.xml” file in the section above is:

1 D-Flow FM`::Init`
D-Flow FM is initialized. Grid- and Flow-data is written to the NetCDF com-file.
Even though D-Flow FM is not the first component in the example config-file, it must be the first component to be initialized, because the initialization results may be needed when other components are initialized. This is implemented as an exceptional rule: The master-component is always the first component to be initialized.

2 `D-RTC::Init`
D-RTC is initialized using (only) D-RTC input. Data from other components is not initialized yet; default values are used.

3 `D-Waves::Init`
D-Waves is initialized. Grid- and Flow-data created by D-Flow FM::Init is read from the com-file. Grid conversion factors are generated. The factors for the conversion from the (structured!) wave grid to the (unstructured) flow grid are calculated inside D-Waves. The factors for the conversion from the (unstructured) flow grid to the (structured) wave

grid are calculated by ”ESMF_RegridWeightGen” via the execution of script <ESMF_-RegridWeightGen_in_Delft3D-WAVE.bat> (Windows) or <ESMF_RegridWeightGen_in_-Delft3D-WAVE.sh> (Linux).

4 `D-RTC::Step`
A D-RTC computation is performed at time “0.0”: Data is communicated (by DIMR) from D-Flow FM to D-RTC, the actual D-RTC computation is executed, data is communicated (by DIMR) from D-RTC to D-Flow FM.
5 `D-Waves::Step`
A D-Waves calculation is performed at time “0.0”: Flow data is read (by D-Waves) from the com-file and converted to the wave grid(s). SWAN input files are written, a SWAN calculation is started by executing script <swan.bat> (Windows) or <swan.sh> (Linux), SWAN output files are read, wave-data is converted to the flow grid and written to the com-file (by D-Waves).
6 D-Flow FM`::Step`
A D-Flow FM calculation is performed: The com-file is checked for wave data to be used/updated. The simulation time will proceed from “0.0” to “60.0” (next time that another component should be executed). Flow-data is written to the com-file (by D-Flow FM).
7 `D-RTC::Step,` D-Flow FM`::Step`
A D-RTC computation is performed after every “60.0” seconds. Then a D-Flow FM computation is performed and the simulation time will proceed another “60.0” seconds. This continues untile the simulation time has progressed for “3600.0” seconds.
8 `D-RTC::Step, D-Waves::Step,` D-Flow FM`::Step`
A D-RTC computation is performed, then a D-Waves computation, then a D-Flow FM computation. The simulation time will proceed another “60.0” seconds and the next D-RTC computation can start.

9 `D-RTC::Finish`
D-RTC is finished at the end of the simulation.
10 `D-Waves::Finish`
D-Waves is finished at the end of the simulation.
11 D-Flow FM`::Finish`
D-Flow FM is finished at the end of the simulation.

15.1.5 Related files

Below is an overview of the related files in the default directory structure. In this example the runid is set to foo.

<testcaseroot>
`dimr_config.xml` Configuration file, input for DIMR
<fm> Work directory for D-Flow FM
`foo.mdu` D-Flow FM input file
<dflowfmoutput> D-Flow FM output directory
`foo_com.nc` Communication file, written/read by both D-Flow FM and D-Waves
<rtc> Work directory for D-RTC
`settings.json` D-RTC input file (must have exactly this name)
<xml_dir> D-RTC directory containing xml input/output files and csv output file
<xsd_dir> D-RTC directory containing xsd input files
<wave> Work directory for D-Waves
`foo.mdw` D-Waves input file
`TMP_ESMF*_source.nc` Temporary input file for ESMF_Regridder, created by D-Waves
`TMP_ESMF*_destination.nc` Temporary input file for ESMF_Regridder, created

by D-Waves
`TMP_ESMF*_weights.nc` Resulting weights file, created by ESMF_Regridder, read by D-Waves
`PET0.RegridWeightGen.Log` ESMF_Regridder log file
`swn-diag.foo` SWAN log file

15.2 Forcing by radiation stress gradients

The momentum equation in x-direction, averaged over the wave motion and expressed in GLM co-ordinates is given by (GLM: Generalized Lagrangian Mean):

$$\frac{\partial \bar{u}_j^L}{\partial t} + \bar{u}_i^L \frac{\partial \bar{u}_j^L}{\partial x_j} + ... + g\frac{\partial \bar{\zeta}}{\partial x_j} - \frac{1}{\rho}\frac{\partial \bar{\tau}_{ij}^L}{\partial x_i} = F_j^L, \tag{15.1}$$

where for i and j the summation rule applies, $i, j = \{1, 2, 3\}$. As shown by Groeneweg (1999) the right-hand side of Equation (15.1) contains a term related to a Stokes correction of the shear stresses. In the current implementation this term is neglected.

The wave-induced force, i.e. the right-hand side of Equation (15.1), can be expressed in the wave parameters of the wave model that is being applied. For linear current refraction the expression can be derived analytically. To account for wave dissipation due to for instance bottom friction, wave breaking and whitecapping and wave growth due to wind one can rely on mild slope formulations with dissipation terms.

As shown by Dingemans *et al.* (1987), using the gradients of the radiation stresses in numerical models can result in spurious currents. Dingemans *et al.* (1987) showed that the divergence free part of the radiation stress is not capable of driving currents and can therefore be neglected if one is primarily interested in wave-driven currents. The remaining part of the radiation stress gradients is closely related to the wave energy dissipation, i.e. the right-hand side of Equation (15.1) can be written as:

$$F_i = \frac{Dk_i}{\omega}, \tag{15.2}$$

where D is the total energy dissipation due to waves, k_i is the wave number in i-direction and ω is the wave frequency; see Dingemans (1997) for many details and discussions on this subject.

2D implementation

For a depth averaged model the momentum equations in x- and y-direction, leaving out most of the terms, can be written as:

$$\frac{\partial U}{\partial t} + \ldots + \frac{gU\sqrt{U^2+V^2}}{C_{2D}^2 h} + \ldots = \ldots + F_x, \tag{15.3}$$

$$\frac{\partial V}{\partial t} + \ldots + \frac{gV\sqrt{U^2+V^2}}{C_{2D}^2 h} + \ldots = \ldots + F_y, \tag{15.4}$$

where F_x and F_y are the depth averaged wave-induced forcings and given by the gradients of the radiation stress tensor S, or following Dingemans *et al.* (1987) approximated by wave energy dissipation:

$$F_x = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{yx}}{\partial y} = D\frac{k_x}{\omega}, \tag{15.5}$$

$$F_y = -\frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y} = D\frac{k_y}{\omega}. \tag{15.6}$$

The dissipation rate D (a negative quantity) is computed by the wave model and read from the communication file. In SWAN, the dissipation rate may be computed from the bottom friction (orbital motion), depth-induced breaking and whitecapping.

You can choose to apply the radiation stress or the dissipation rate to determine the wave-induced forces.

3D implementation

There is no coupling available yet for 3D D-Flow FM models and D-Waves. The effect of the divergence free part of the radiation stresses is (the remaining part of the radiation stress gradients, after the wave dissipation has been subtracted) is added to the momentum equations in D-Flow FM (effect spread over the water column). This provides most adequate results, e.g. in situations with undertow.

15.3 Stokes drift and mass flux

In surface waves, fluid particles describe an orbital motion. The net horizontal displacement for a fluid particle is not zero. This wave induced drift velocity, the so-called Stokes-drift, is always in the direction of wave propagation. A particle at the top of the orbit beneath a wave crest moves slightly faster in the forward direction than it does in the backward direction beneath a wave trough. The mean drift velocity is a second order quantity in the wave height. The drift leads to additional fluxes in the wave averaged mass continuity equation.

The wave-induced mass fluxes M_x^S and M_y^S are found by integration of the components of the Stokes drift u^S and v^S over the wave-averaged total water depth:

$$M_x^S = \int_0^{\overline{h}} \rho_o u^S dz = \frac{E}{\omega} k_x \tag{15.7}$$

$$M_y^S = \int_0^{\overline{h}} \rho_0 v^S dz = \frac{E}{\omega} k_y \tag{15.8}$$

with E the wave energy defined as:

$$E = \frac{1}{8} \rho_0 g H_{rms}^2. \tag{15.9}$$

The mass fluxes M_x^S and M_y^S are computed by an interface program and are written to the communication file.

Remarks:

- ◇ The mass flux effect is only taken into account when D-Flow FM is used from within Delft3D-MOR.
- ◇ The velocities written to the communication file for use in Delft3D-MOR, D-Waves, and D-Water Quality are based on the *total flux* velocities.
- ◇ The Eulerian velocities, which may be used in comparisons with measurements at a fixed location, are written to the hydrodynamic map and history files.

2D implementation

The depth-averaged Stokes drift is given by:

$$U^S = \frac{M_x^S}{\rho_0 h}, \tag{15.10}$$

$$V^S = \frac{M_y^S}{\rho_0 h}. \tag{15.11}$$

3D implementation

There is no coupling available yet for 3D D-Flow FM models and D-Waves.

15.4 Streaming

Streaming is a 3D feature. There is still no coupling available for 3D D-Flow FM models and D-Waves.

15.5 Enhancement of the bed shear-stress by waves

The boundary layers at the bed associated with the waves and the current interact non-linearly. This has the effect of enhancing both the mean and oscillatory bed shear-stresses. In addition the current profile is modified, because the extra turbulence generated close to the bed by the waves appears to the current as being equivalent to an enhanced bottom roughness. The bed shear-stress due to the combination of waves and current is enhanced beyond the value which would result from a linear addition of the bed shear-stress due to waves, $\boldsymbol{\tau}_w$, and the bed shear-stress due to current $\boldsymbol{\tau}_c$. For sediment transport modelling it is important to predict the maximum bed shear-stress, $\boldsymbol{\tau}_{\max}$, while the current velocity and the turbulent diffusion are determined by the combined wave-current bed shear-stress $\boldsymbol{\tau}_m$.

Various, often very complex, methods exist to describe the bottom boundary layer under combined current and wave action and the resulting virtual roughness. Soulsby *et al.* (1993a) developed a parameterisation of these methods allowing a simple implementation and comparison of various wave-current interaction models: Fredsøe (1984); Myrhaug and Slaattelid (1990); Grant and Madsen (1979); Huynh-Thanh and Temperville (1991); Davies *et al.* (1988); Bijker (1967); Christoffersen and Jonsson (1985); O' Connor and Yoo (1988); Van Rijn *et al.* (2004). All these methods have all been implemented in D-Flow FM and can be applied in 2D and 3D modelling. However, as there are minor, but specific differences in determining certain quantities, such as determining the shear-stress at the bottom, we prefer to discuss the 2D and 3D implementation separately.

2D implementation

Following Soulsby *et al.* (1993b), Figure 15.1 gives a schematic overview of the bed shear-stresses for wave current interaction.

Soulsby *et al.* (1993b) fitted one standard formula to all of the models, each model having its own fitting coefficients. The parameterisation of Soulsby for the time-mean bed shear-stress is of the form:

$$|\boldsymbol{\tau}_m| = Y\left(|\boldsymbol{\tau}_c| + |\boldsymbol{\tau}_w|\right), \tag{15.12}$$

with

$$Y = X\left\{1 + bX^p(1-X)^q\right\}, \tag{15.13}$$

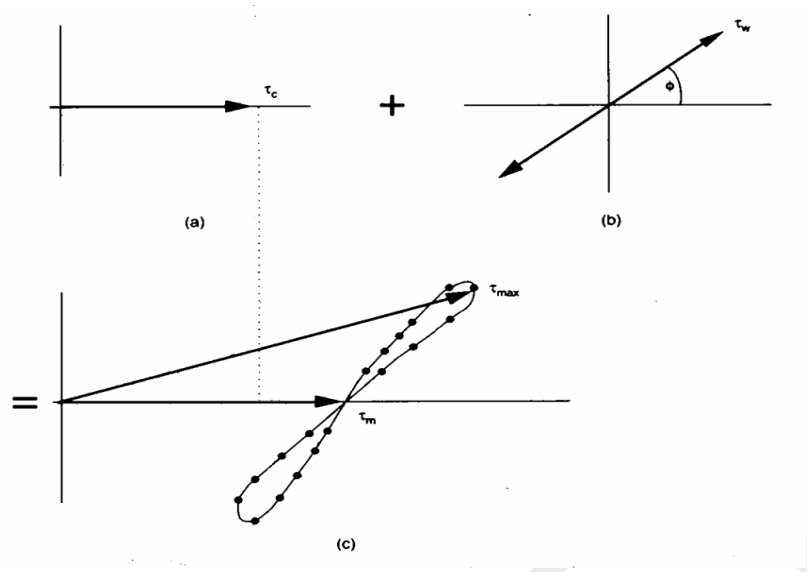


Figure 15.1: *Schematic view of non-linear interaction of wave and current bed shear-stresses (from Soulsby et al. (1993b, Figure 16, p. 89))*

and for the maximum bed shear-stress:

$$|\boldsymbol{\tau}_{\max}| = Z\left(|\boldsymbol{\tau}_c| + |\boldsymbol{\tau}_w|\right), \tag{15.14}$$

with

$$Z = 1 + aX^m(1-X)^n. \tag{15.15}$$

and:

$$X = \frac{|\boldsymbol{\tau}_c|}{|\boldsymbol{\tau}_c| + |\boldsymbol{\tau}_w|}, \tag{15.16}$$

The value of the parameters a, b, p, q, m and n depends on the friction model which is parameterised, and:

$\|\boldsymbol{\tau}_c\|$	magnitude of the bed stress due to current alone
$\|\boldsymbol{\tau}_w\|$	magnitude of the bed stress for waves alone
$\|\boldsymbol{\tau}_m\|$	magnitude of the mean bed stress for combined waves and current
$\|\boldsymbol{\tau}_{\max}\|$	magnitude of the maximum bed stress for combined waves and current.

Remark:

◇ The stresses $\boldsymbol{\tau}_m$ and $\boldsymbol{\tau}_{\max}$ are assumed to have the same direction as $\boldsymbol{\tau}_c$.

Following Soulsby *et al.* (1993b) the expressions for the parameters χ $(= a, b, p, q, m, n)$ and $\mathcal{J}$ $(= I, J$; also depending on the friction model) have the form:

$$\chi = \left(\chi_1 + \chi_2 \left|\cos\phi\right|^{\mathcal{J}}\right) + \left(\chi_3 + \chi_4 \left|\cos\phi\right|^{\mathcal{J}}\right)\ {}^{10}\log\left(\frac{f_w}{C_{2D}}\right), \tag{15.17}$$

in which:

C_{2D}	drag coefficient due to current
f_w	wave friction factor
ϕ	the angle between the current direction and the direction of wave propagation.

Table 15.1: *Fitting coefficients for wave/current boundary layer model*

Model[1]	a_1	a_2	a_3	a_4	m_1	m_2	m_3	m_4	n_1	n_2	n_3	n_4	I
FR84	-0.06	1.70	-0.29	0.29	0.67	-0.29	0.09	0.42	0.75	-0.27	0.11	-0.02	0.80
MS90	-0.01	1.84	-0.58	-0.22	0.63	-0.09	0.23	-0.02	0.82	-0.30	0.19	-0.21	0.67
HT91	-0.07	1.87	-0.34	-0.12	0.72	-0.33	0.08	0.34	0.78	-0.23	0.12	-0.12	0.82
GM79	0.11	1.95	-0.49	-0.28	0.65	-0.22	0.15	0.06	0.71	-0.19	0.17	-0.15	0.67
DS88	0.05	1.62	-0.38	0.25	1.05	-0.75	-0.08	0.59	0.66	-0.25	0.19	-0.03	0.82
BK67	0.00	2.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.50	0.00	0.00	1.00
CJ85	-0.01	1.58	-0.52	0.09	0.65	-0.17	0.18	0.05	0.47	-0.03	0.59	-0.50	0.64
OY88	-0.45	2.24	0.16	-0.09	0.71	0.27	-0.15	0.03	1.19	-0.66	-0.13	0.12	0.77
	b_1	b_2	b_3	b_4	p_1	p_2	p_3	p_4	q_1	q_2	q_3	q_4	J
FR84	0.29	0.55	-0.10	-0.14	-0.77	0.10	0.27	0.14	0.91	0.25	0.50	0.45	3.00
MS90	0.65	0.29	-0.30	-0.21	-0.60	0.10	0.27	-0.06	1.19	-0.68	0.22	-0.21	0.50
HT91	0.27	0.51	-0.10	-0.24	-0.75	0.13	0.12	0.02	0.89	0.40	0.50	-0.28	2.70
GM79	0.73	0.40	-0.23	-0.24	-0.68	0.13	0.24	-0.07	1.04	-0.56	0.34	-0.27	0.50
DS88	0.22	0.73	-0.05	-0.35	-0.86	0.26	0.34	-0.07	-0.89	2.33	2.60	-2.50	2.70
BK67	0.32	0.55	0.00	0.00	-0.63	0.05	0.00	0.00	1.14	0.18	0.00	0.00	3.00
CJ85	0.47	0.29	-0.09	-0.12	-0.70	0.13	0.28	-0.04	1.65	-1.19	-0.42	0.49	0.60
OY88	-0.06	0.26	0.08	-0.03	-1.00	0.31	0.25	-0.26	0.38	1.19	0.25	-0.66	1.50
VR04	$Y = 0.0$ and $Z = 1.0$												

[1] FR84=Fredsøe (1984), MS90=Myrhaug and Slaattelid (1990), HT91=Huynh-Thanh and Temperville (1991), GM79=Grant and Madsen (1979), DS88=Davies *et al.* (1988), BK67=Bijker (1967), CJ85=Christoffersen and Jonsson (1985), OY88=O' Connor and Yoo (1988), VR04=Van Rijn *et al.* (2004)

As the radiation stress is always in the wave direction, we can derive ϕ from:

$$|\cos\phi| = \frac{|UF_x + VF_y|}{|\boldsymbol{U}|\,|\boldsymbol{F}|}. \tag{15.18}$$

Values of the parameters a, b, p, q and J in Equation (15.17) have been optimised by Soulsby *et al.* (1993b), see Table 15.1 and Figure 15.2.

The bed shear-stress due to flow alone may be computed using various types of formulations like Chézy, Manning or White-Colebrook. The bed shear-stress due to current alone can be written in the form:

$$\boldsymbol{\tau}_c = \frac{g\rho_0 \boldsymbol{U}\,|\boldsymbol{U}|}{C_{2D}^2}. \tag{15.19}$$

The magnitude of the wave-averaged bed shear-stress due to waves alone is related to the wave orbital velocity near the bottom $\boldsymbol{u}_{orb}$ and the friction coefficient f_w:

$$|\boldsymbol{\tau}_w| = \frac{1}{2}\rho_0\, f_w\, u_{orb}^2. \tag{15.20}$$

The orbital velocity is computed from the linear wave theory and is given by:

$$u_{orb} = \frac{1}{4}\sqrt{\pi}\frac{H_{rms}\omega}{\sinh(kH)}, \tag{15.21}$$

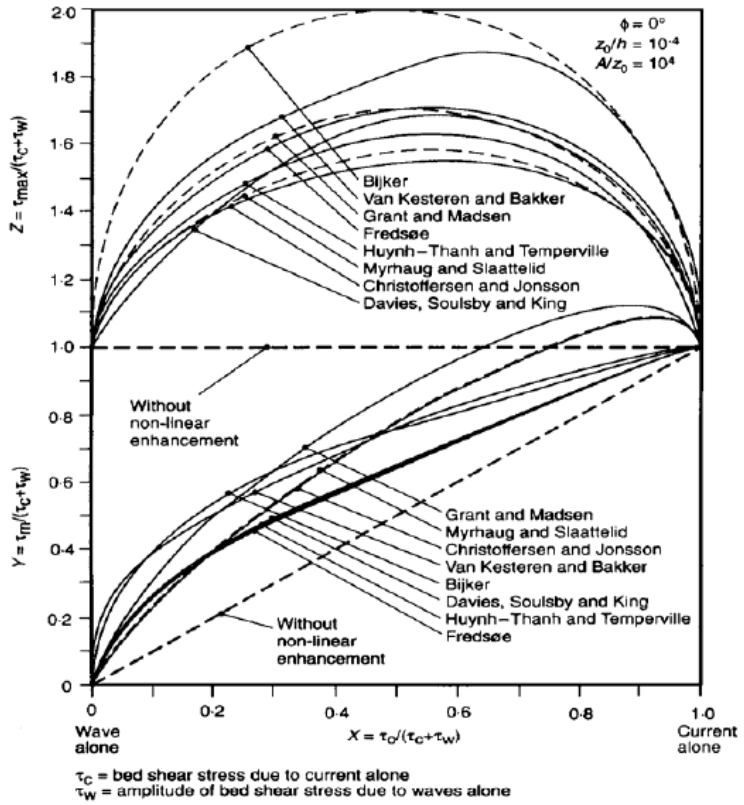


Figure 15.2: *Inter-comparison of eight models for prediction of mean and maximum bed shear-stress due to waves and currents (from Soulsby et al. (1993b, Figure 17, p. 90))*

where the root-mean-square wave height H_{rms} and the wave period $T(=2\pi/\omega)$ are read from the communication file. The variation of the wave friction factor with relative orbital excursion at the bed under purely oscillatory flow is given by Swart (1974) ($\equiv$ Equations (18.70), (18.109) and (18.150)):

$$f_w = \begin{cases} 0.00251 \exp\left[5.21 \left(\frac{A}{k_s}\right)^{-0.19}\right], & \frac{A}{k_s} > \frac{\pi}{2}, \\ 0.3, & \frac{A}{k_s} \leq \frac{\pi}{2}, \end{cases} \tag{15.22}$$

with:

$$A = \frac{u_{orb}}{\omega}, \tag{15.23}$$

k_s is the Nikuradse roughness length-scale and ω is the wave angular frequency.

As the bed is in rest and the equations are formulated in GLM co-ordinates, we must correct the bed shear-stress used in the momentum equations for the Stokes drift. The total or effective bed shear stress is given by:

$$\boldsymbol{\tau}_b = \frac{|\boldsymbol{\tau}_m|}{|\boldsymbol{U}|} \left(\boldsymbol{U} - \boldsymbol{U}^S\right), \tag{15.24}$$

where the components of the depth-averaged Stokes drift $\boldsymbol{U}^S$ are given by Eqs. (15.10) and (15.11).

3D implementation

There is no coupling available yet for 3D D-Flow FM models and D-Waves.

16 Coupling with D-RTC (RTC-Tools)

This chapter is on the *coupling* of hydrodynamics and real-time control of hydraulic structures.

16.1 Introduction

parallel/sequential coupling, which is shared

The Delta Shell framework implements the concept of an *Integrated model* in order to couple different models, such as: hydrodynamics coupled with the controlling of structures, waves, morphology and/or water quality.

Two types of coupling are distinguished: *offline* and *online* coupling. In case of an *Integrated model* with *offline* coupling, the entire hydrodynamic simulation is done first, i.e., *separately* from the second simulation. The file-based hydrodynamic output serves as input for the second simulation. As such, the hydrodynamic flow drives the controlling of structures or the simulation of waves or water quality. In this case there is no feedback on the hydrodynamic simulation. For many applications, this is good practice.

An *online* coupling, on the other hand, exchanges data *every time* after computing a specified time interval. This tight coupling allows for direct feedback of the various processes on one another. This is crucial for controlling structures.

Note: *Offline* is also referred to as *sequential* coupling and *online* as *parallel* coupling.

A coupled flow-rtc model can be run either as an Integrated Model from within Delta Shell, or from the commandline using the d_hydro program.

In case of a flow-rtc coupling

- ◇ the flow model will exchange for example *Water levels*
- ◇ subsequently, the rtc model will evaluate for example the *Crest level* of a controlled structure, based on the exchanged *water levels*
- ◇ in case of an *online* coupling this *Crest level* will influence the simulation of the flow of water

16.2 Getting started

16.2.1 User interface: the first steps

First, the user must add a *real-time control* model to the *flow-fm* model. The **Project** window will look like this.

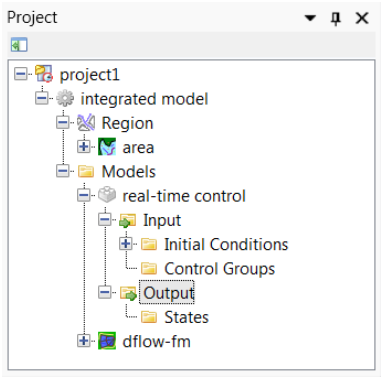


Figure 16.1: *An* Integrated model *in the* ***Project*** *window*

Secondly, the user will model the control flow for an hydraulic structure. This may look like this.

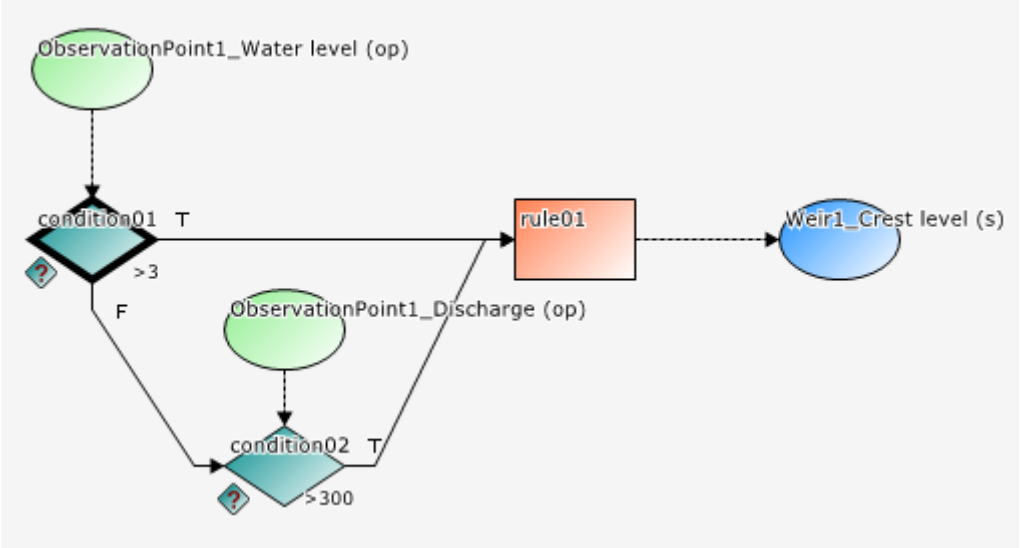


Figure 16.2: *Example of a* Control flow *in D-RTC*

Full documentation on D-RTC is available in its own User Manual. This chapter is limited to the details of running coupled flow-rtc models.

16.2.2 Input D-Flow FM

The hydraulic structures that are normally driven by time series in <∗.tim> files, will now be fed by D-RTC. Replace the timeseries file name by the `REALTIME` keyword in the <structures.ini> file (section B.11):

```
[structure]
type         = weir         # Type of structure
id           = weir01       # Name of the structure
polylinefile = weir01.pli   # *.pli; Polyline geometry definition for 2D structure
crest_level  = REALTIME     # Crest level in [m]
```

Also, the MDU file may optionally contain an observation file and/or a cross section file, such that D-RTC's triggers can be set to the observed time series at these locations.

```
[output]
ObsFile       = obs.xyn
CrsFile       = river_crs.pli
```

16.2.3 Input D-RTC

The input of D-RTC consists of several <∗.xml> files and a toplevel <settings.json>. We refer to the D-RTC User Manual for further details.

16.2.4 Input d_hydro

In **??**, details on a coupled flow-rtc-wave model are presented.

16.2.5 Online process order

This is discussed in Section 15.1.4.

17 Coupling with D-Water Quality (Delwaq)

17.1 Introduction

D-Water Quality is a multi-dimensional water quality model framework developed by Deltares over the past decades. It solves the advection-diffusion-reaction equation on a predefined computational grid and for a wide range of model substances. D-Water Quality offers flexible configuration of the substances to be included, as well as the processes to be evaluated. D-Water Quality is not a hydrodynamic model, so information on flow fields is obtained from hydraulic models such as D-Flow 1D (SOBEK 3) and D-Flow FM.

Here, only the *coupling* is discussed. Full documentation on D-Water Quality is available.

17.2 Offline versus online coupling

parallel/sequential coupling, which is shared

The Delta Shell framework implements the concept of an *Integrated model* in order to couple different models, such as: hydrodynamics coupled with the controlling of structures, waves, morphology and/or water quality.

Two types of coupling are distinguished: *offline* and *online* coupling. In case of an *Integrated model* with *offline* coupling, the entire hydrodynamic simulation is done first, i.e., *separately* from the second simulation. The file-based hydrodynamic output serves as input for the second simulation. As such, the hydrodynamic flow drives the controlling of structures or the simulation of waves or water quality. In this case there is no feedback on the hydrodynamic simulation. For many applications, this is good practice.

An *online* coupling, on the other hand, exchanges data *every time* after computing a specified time interval. This tight coupling allows for direct feedback of the various processes on one another. This is crucial for controlling structures.

Note: *Offline* is also referred to as *sequential* coupling and *online* as *parallel* coupling.

The *online* coupling is scheduled for a future release.

17.3 Creating output for D-Water Quality

Creating output for D-Water Quality by D-Flow FM can be enabled in Delta Shell in the main window under the tab ‘Output Parameters’. Change the “WAQ output interval” to a nonzero value. The MDU-equivalent is the keyword `[output]`, `WaqInterval`, where three numbers can be put and they are in the order of "WAQinterval, WAQ output-start-time, WAQ output-end-time". Each number should be a whole number of seconds, and must be a multiple of the “User time step” (see tab “Time frame”). Moreover, if the start and end output time is not explicitly specified, they are automatically set to start and end time of the simulation, respectively.

D-Flow FM will create a special output folder named <DFM_DELWAQ_*mdu_name*>. In this folder a <.hyd>-file will be created that gives an overview of the coupling with references to the files containing the hydrodynamic exchange data.

Load the <.hyd>-file in the D-Water Quality GUI to prepare the input for a water quality calculation. For further information on how to run D-Water Quality please consult its user manual.

The coupling between D-Flow FM and D-Water Quality has currently been tested with good results for 2D and 3D (sigma-layer) meshes.

The D-Water Quality GUI fully supports coupling with results from D-Flow FM. Postprocessing can be done in Delft3D-QUICKPLOT.

17.4 Current limitations

When using domain decomposition, D-Flow FM will create a special output folder per domain named <DFM_DELWAQ_*mdu_name_nnnn*>. Since D-Water Quality can accept results for a single domain only, you have to merge the results into one domain using a tool called ddcouplefm, which can be obtained by contacting support.

It can be useful to model the water quality processes on a coarser mesh than the hydrodynamic grid, and for this grid aggregation would be usefull. This is however not yet available for the coupling between D-Flow FM and D-Water Quality.

18 Sediment transport and morphology

Note: The implementation of sediment transport and morphological processes is currently a β-functionality of D-Flow FM.

18.1 General formulations

18.1.1 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 "mud" (cohesive suspended load transport), "sand" (non-cohesive bedload and suspended load transport) and "bedload" (non-cohesive bedload only or total load transport) fractions.

A model may contain a mixture of up to 99 suspended (i.e. "sand" and "mud") fraction and an arbitrary amount of "bedload" fractions if computer memory and simulation time allows.

The only difference between "bedload" and "sand" fractions lies in the fact that the suspended load advection-diffusion equation is not solved for the "bedload" fraction.

If the suspended load is known to be negligible (either due to sediment diameter or sediment transport formula chosen), the "bedload" approach is more efficient.

Sediment interactions are taken into account although especially in the field of sand-mud interactions still a couple of processes are lacking.

18.1.2 Suspended transport

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

$$\frac{\partial c^{(\ell)}}{\partial t}+\frac{\partial uc^{(\ell)}}{\partial x}+\frac{\partial vc^{(\ell)}}{\partial y}+\frac{\partial\left(w-w_s^{(\ell)}\right)c^{(\ell)}}{\partial z}+ \\ -\frac{\partial}{\partial x}\left(\varepsilon_{s,x}^{(\ell)}\frac{\partial c^{(\ell)}}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{s,y}^{(\ell)}\frac{\partial c^{(\ell)}}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{s,z}^{(\ell)}\frac{\partial c^{(\ell)}}{\partial z}\right)=0, \quad (18.1)$$

where:

$c^{(\ell)}$	mass concentration of sediment fraction (ℓ) [kg/m^3]
u, v and w	flow velocity components [m/s]
$\varepsilon_{s,x}^{(\ell)}$, $\varepsilon_{s,y}^{(\ell)}$ and $\varepsilon_{s,z}^{(\ell)}$	eddy diffusivities of sediment fraction (ℓ) [m^2/s]
$w_s^{(\ell)}$	(hindered) sediment settling velocity of sediment fraction (ℓ) [m/s]

The local flow velocities and eddy diffusivities are based on the results of the hydrodynamic computations. Computationally, the three-dimensional transport of sediment is computed in exactly 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 local mixture density, and hence on turbulence damping, can

also be taken into account. In addition, if a net flux of sediment from the bed to the flow, or vice versa, occurs then the resulting change in the bathymetry should influence subsequent hydrodynamic calculations. The formulation of several of these processes (such as, settling velocity, sediment deposition and pickup) 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 18.2 and section 18.3.

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 18.4.3) and bed composition models (section 18.6.4).
- Small negative sediment concentrations (-1×10^{-3} 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.

18.1.3 Effect of sediment on fluid density

The effect of sediment on fluid density is not implemented in D-Flow FM yet.

18.1.4 Sediment settling velocity

The settling velocity $w_s^{(\ell)}$ for sand and mud are strongly different in formulation; see Sections 18.2.1 and 18.3.1 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:

$$w_s^{(\ell)} = \left(1 - \frac{c_s^{tot}}{C_{soil}}\right)^5 w_{s,0}^{(\ell)}. \tag{18.2}$$

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:

$$c_m^{tot} = \sum_{\ell=1}^{lsed} c_s^{(\ell)}. \tag{18.3}$$

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).

18.1.5 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-ε turbulence closure model.
4 k-τ turbulence closure model (β-functionality.

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 chapter 9 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:

$$\varepsilon_s^{(\ell)} = \beta \varepsilon_f, \tag{18.4}$$

where:

$\varepsilon_s^{(\ell)}$	vertical sediment mixing coefficient for the sediment fraction (ℓ)
β	non-cohesive sediment: Van Rijn's 'beta' factor or effective 'beta' factor.
	cohesive sediment fractions and fine sand (< 150 μm): 1.0.
ε_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 18.2.2.
- ◇ For non-cohesive sediment the effect of waves is accounted for by using a modified or effective 'beta' factor of Van Rijn (k-ε model) or by using a separate formula to compute ε_f (algebraic or k-L) model. See also section 18.3.2.

18.1.6 Three-dimensional wave effects

Note: The three-dimensional sediment transport is not implemented in D-Flow FM yet.

These effects are important when computing the transport of sediment in wave and current situations; see Sections 18.2.5 and 18.3.4 for full details regarding their effect on cohesive and non-cohesive sediments respectively.

18.1.7 Initial and boundary conditions

To solve Equation (18.1) you need to prescribe initial and boundary conditions for each suspended sediment fraction.

18.1.7.1 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.

18.1.7.2 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.

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = 0, \quad \text{at } z = \zeta \tag{18.5}$$

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:

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = D^{(\ell)} - E^{(\ell)}, \quad \text{at } z = z_b \tag{18.6}$$

where:

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

The formulations of $D^{(\ell)}$ and $E^{(\ell)}$ strongly differ for cohesive and non-cohesive sediment; for the details you are referred to Sections 18.2.3 and 18.3.4 respectively.

Open inflow boundaries

D-Flow FM requires you to specify boundary conditions for all conservative constituents at all open inflow boundaries. When modelling in three dimensions you may choose to specify boundary concentrations that have a uniform, linear, or step distribution over the vertical. You may also choose to specify a “Thatcher-Harleman” return time to simulate the re-entry of material that flowed out of the model after the flow reverses direction.

All of these options are also available for sediment constituents, although they are probably more appropriate for fine, cohesive sediment than for sand-sized particles. To assist with modelling coarser material an additional option has been included. This option allows you to specify that, at all open inflow boundaries, the flow should enter carrying all “sand” sediment fractions at their “equilibrium” concentration profiles. This feature has been implemented as a Neumann boundary condition, that is, zero concentration gradient at the boundary. 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. This will generally be the desired situation if the model boundaries are well chosen. This feature can be activated for sand and mud fraction separately by setting `NeuBcSand` (previously, `EqmBc`) and/or `NeuBcMud` to true in the morphology input file.

Open outflow boundaries

No boundary condition is prescribed at outflow boundaries; effectively this means that the dispersive transport of sediment at the outflow boundary is neglected compared to the advective transport.

18.2 Cohesive sediment

Note: The cohesive sediment is not yet implemented in D-Flow FM.

18.2.1 Cohesive sediment settling velocity

In salt water cohesive sediment tends to flocculate to form sediment "flocs", with the degree of flocculation depending on the salinity of the water. These flocs are much larger than the individual sediment particles and settle at a faster rate. In order to model this salinity dependency you must supply two settling velocities and a maximum salinity. The first velocity, `WS0`, is taken to be the settling velocity of the sediment fraction in fresh water (salinity = 0). The second velocity, `WSM`, is the settling velocity of the fraction in water having a salinity equal to `SALMAX`. The settling velocity of the sediment flocs is calculated as follows:

$$w_{s,0}^{(\ell)} = \begin{cases} \frac{w_{s,\max}^{(\ell)}}{2}\left(1-\cos\left(\frac{\pi S}{S_{\max}}\right)\right) + \frac{w_{s,f}^{(\ell)}}{2}\left(1+\cos\left(\frac{\pi S}{S_{\max}}\right)\right), & \text{when } S \le S_{\max} \\ w_{s,\max}^{(\ell)}, & \text{when } S > S_{\max} \end{cases} \quad (18.7)$$

where:

$w_{s,0}^{(\ell)}$	the (non-hindered) settling velocity of sediment fraction (ℓ)
$w_{s,\max}^{(\ell)}$	WSM, settling velocity of sediment fraction (ℓ) at salinity concentration SALMAX
$w_{s,f}^{(\ell)}$	WS0, fresh water settling velocity of sediment fraction (ℓ)
S	salinity
$S_{\max}$	SALMAX, maximal salinity at which WSM is specified

Remarks:

- ◇ Modelling turbulence induced flocculation or the break-up of sediment flocs is not yet implemented.
- ◇ The influence of flocculation is disregarded by setting WSM = WS0.

18.2.2 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.:

$$\varepsilon_s^{(\ell)} = \varepsilon_f, \tag{18.8}$$

where:

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

18.2.3 Cohesive sediment erosion and deposition

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

$$E^{(\ell)} = M^{(\ell)} S\left(\tau_{cw}, \tau_{cr,e}^{(\ell)}\right), \tag{18.9}$$

$$D^{(\ell)} = w_s^{(\ell)} c_b^{\ell} S\left(\tau_{cw}, \tau_{cr,d}^{(\ell)}\right), \tag{18.10}$$

$$c_b^{(\ell)} = c^{(\ell)}\left(z = \frac{\Delta z_b}{2}, t\right), \tag{18.11}$$

where:

$E^{(\ell)}$	erosion flux [kg m^{-2} s^{-1}]
$M^{(\ell)}$	user-defined erosion parameter EROUNI [kg m^{-2} s^{-1}]
$S\left(\tau_{cw}, \tau_{cr,e}^{(\ell)}\right)$	erosion step function:

$$S\left(\tau_{cw}, \tau_{cr,e}^{(\ell)}\right) = \begin{cases} \left(\dfrac{\tau_{cw}}{\tau_{cr,e}^{(\ell)}} - 1\right), & \text{when } \tau_{cw} > \tau_{cr,e}^{(\ell)}, \\ 0, & \text{when } \tau_{cw} \leq \tau_{cr,e}^{(\ell)}. \end{cases} \tag{18.12}$$

$D^{(\ell)}$	deposition flux [kg m^{-2} s^{-1}]
$w_s^{(\ell)}$	fall velocity (hindered) [m/s]
$c_b^{(\ell)}$	average sediment concentration in the near bottom computational layer

$S\left(\tau_{cw}, \tau_{cr,d}^{(\ell)}\right)$ deposition step function:

$$S\left(\tau_{cw}, \tau_{cr,d}^{(\ell)}\right) = \begin{cases} \left(1 - \dfrac{\tau_{cw}}{\tau_{cr,d}^{(\ell)}}\right), & \text{when } \tau_{cw} < \tau_{cr,d}^{(\ell)}, \\ 0, & \text{when } \tau_{cw} \geq \tau_{cr,d}^{(\ell)}. \end{cases} \quad (18.13)$$

τ_{cw} maximum bed shear stress due to current and waves as calculated by the wave-current interaction model selected by the user.

$\tau_{cr,e}^{(\ell)}$ user-defined critical erosion shear stress TCEUNI [N/m^2]

$\tau_{cr,d}^{(\ell)}$ user-defined critical deposition shear stress TCDUNI [N/m^2]

Remark:

- ◇ Superscript (ℓ) implies that this quantity applies to sediment fraction (ℓ).

The calculated erosion or deposition flux is applied to the near bottom computational cell by setting the appropriate sink and source terms for that cell. Advection, particle settling, and diffusion through the bottom of the near bottom computational cell are all set to zero to prevent double counting these fluxes.

18.2.4 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 tot 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.

18.2.5 Influence of waves on cohesive sediment transport

The influence of wave on cohesive sediment is not implemented in D-Flow FM yet.

18.2.6 Inclusion of a fixed layer

If the thickness of the sediment layer becomes small then the erosion flux is reduced by a factor f_{FIXFAC} as defined in section 18.4.4. This reduction factor is related to the formulations implemented for non cohesive sediment transport (see Sections 18.3.5 and 18.4.4 for suspended and bedload transport respectively).

18.2.7 Inflow boundary conditions 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 equilibrium boundary conditions. The mud concentrations are in general more loosely coupled to local morphology than the concentrations of coarser non-cohesive sediment fractions; a unique "equilibrium" concentration (profile) does often not exist due to differences in critical shear stresses for erosion and sedimentation. So, D-Flow FM allows for a different approach. For cohesive material you can specify that, at all open inflow boundaries, the flow should enter carrying the same mud concentration as computed in the interior of the model. This feature is enabled by setting `NeuBcMud` in the morphology input file to true (Neumann boundary condition: concentration gradient perpendicular to open boundary equal to zero). Although this option may sometimes be very useful, one must be careful when applying it: the sediment concentration of the incoming flow may take on any value that does not lead to significant deposition in the first grid cell.

By setting `NeuBcMud = false`, the concentrations to be applied at the inflow boundaries are read from the $<*$.bcc$>$ file, which has to be created with the FLOW User Interface. If the parameter is set to true, the values specified in the $<*$.bcc$>$ file are overruled.

18.3 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 18.5)

18.3.1 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:

$$w_{s,0}^{(\ell)} = \begin{cases} \dfrac{(s^{(\ell)}-1)gD_s^{(\ell)2}}{18\nu}, & 65\ \mu\text{m} < D_s \leq 100\ \mu\text{m} \\ \dfrac{10\nu}{D_s}\left(\sqrt{1+\dfrac{0.01(s^{(\ell)}-1)gD_s^{(\ell)3}}{\nu^2}}-1\right), & 100\ \mu\text{m} < D_s \leq 1000\ \mu\text{m} \\ 1.1\sqrt{(s^{(\ell)}-1)gD_s^{(\ell)}}, & 1000\ \mu\text{m} < D_s \end{cases} \tag{18.14}$$

where:

$s^{(\ell)}$	relative density $\rho_s^{(\ell)}/\rho_w$ of sediment fraction(ℓ)
$D_s^{(\ell)}$	representative diameter of sediment fraction (ℓ)
ν	kinematic viscosity coefficient of water [m^2/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 18.5.1 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.

18.3.2 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:

18.3.2.1 Using the k-ε turbulence model

In the case of the k-ε 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:

$$\varepsilon_s^{(\ell)} = \beta_{eff}^{(\ell)} \varepsilon_f, \tag{18.15}$$

where:

$\varepsilon_s^{(\ell)}$	vertical sediment mixing coefficient of sediment fraction (ℓ)
$\beta_{eff}^{(\ell)}$	the effective Van Rijn's 'beta' factor of sediment fraction (ℓ) As the beta factor should only be applied to the current-related mixing this is estimated as: $$\beta_{eff}^{(\ell)} = 1 + \left(\beta^{(\ell)} - 1\right) \frac{\tau_c}{\tau_w + \tau_c}, \tag{18.16}$$ for non-cohesive sediment fractions
$\beta^{(\ell)}$	Van Rijn's 'beta' factor of the sediment fraction (ℓ), Equation (18.17)
τ_c	bed shear stress due to currents
τ_w	bed shear stress due to waves
ε_f	vertical fluid mixing coefficient calculated by the k-ε turbulence closure model

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

$$\beta^{(\ell)} = 1 + 2 \left(\frac{w_s^{(\ell)}}{u_{*,c}} \right)^2. \tag{18.17}$$

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 β-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 β-factor on flow conditions; this discrepancy is expected to be of little importance in practical situations.

◇ The k-ε 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.

18.3.2.2 Using the k-τ turbulence model

The k-τ model in combination with sediment transport is not supported in D-Flow FM yet.

18.3.3 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 level is given by:

$$a = \min\left[\max\left\{\text{AKSFAC} \cdot k_s, \frac{\Delta_r}{2}, 0.01h\right\}, 0.20h\right], \tag{18.18}$$

where:

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

Remark:

◇ Van Rijn's reference level 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 derived from current-related effective roughness height as determined in the D-Flow FM module (spatially varying) and $k_w = RWAVE \cdot \Delta r$.
◇ k_s and k_w specified by you (constant in space).

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 18.5.1). The reference concentration is adjusted proportional to the relative availability of the sediment fraction in the top-layer of the bed (see section 18.6.4 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.

18.3.4 Non-cohesive sediment erosion and deposition

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 level. This layer is identified as the reference layer and for brevity is referred to as the kmx-layer; see Figure 18.1.

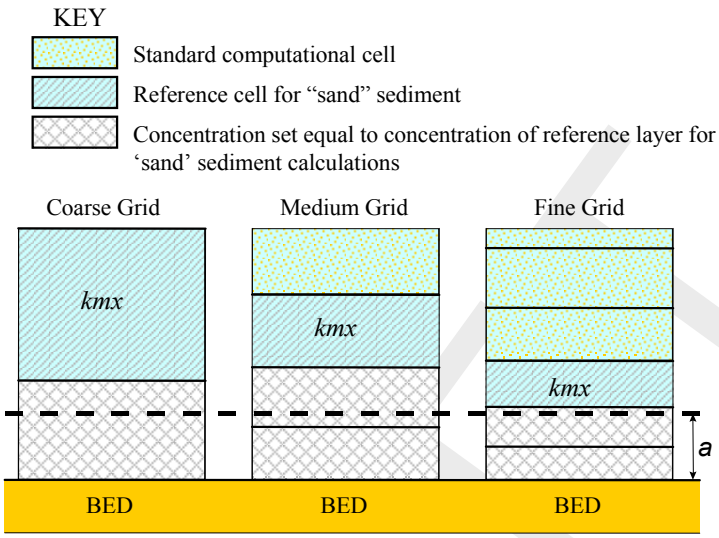


Figure 18.1: *Selection of the kmx layer; where a is Van Rijn's reference level*

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 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.

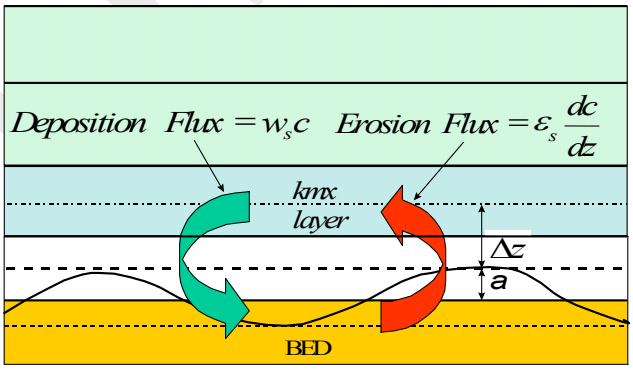


Figure 18.2: *Schematic arrangement of flux bottom boundary condition*

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 18.3).

$$c^{(\ell)} = c_a^{(\ell)} \left(\frac{a(h-z)}{z(h-a)} \right)^{A^{(\ell)}}, \tag{18.19}$$

where:

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

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

$$c_{kmx}^{(\ell)} = c_a^{(\ell)} \left(\frac{a(h-z_{kmx})}{z_{kmx}(h-a)} \right)^{A^{(\ell)}} \Rightarrow A^{(\ell)} = \frac{\ln\left(\frac{c_{kmx}}{c_a}\right)}{\ln\left(\frac{a(h-z_{kmx})}{z_{kmx}(h-a)}\right)} \tag{18.20}$$

The concentration at the bottom of the *kmx* layer is:

$$c_{kmx(bot)}^{(\ell)} = c_a^{(\ell)} \left(\frac{a(h-z_{kmx(bot)})}{z_{kmx(bot)}(h-a)} \right)^{A^{(\ell)}} \tag{18.21}$$

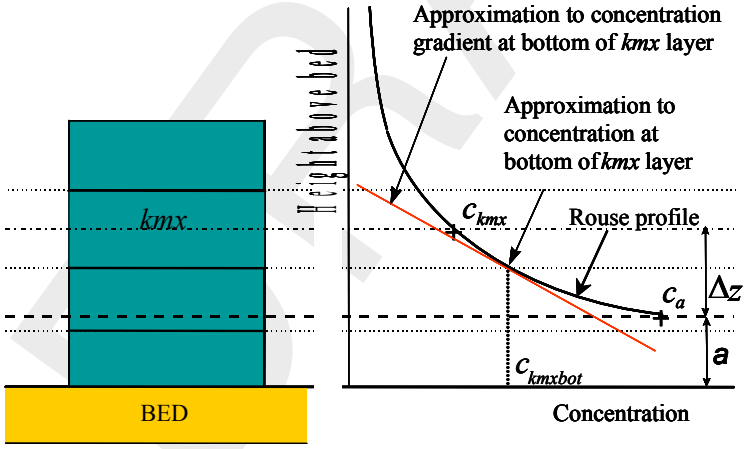


Figure 18.3: *Approximation of concentration and concentration gradient at bottom of kmx layer*

We express this concentration as a function of the known concentration c_{kmx} by introducing a correction factor α_1:

$$c_{kmx(bot)}^{(\ell)} = \alpha_1^{(\ell)} c_{kmx}^{(\ell)} \tag{18.22}$$

The concentration gradient of the Rouse profile is given by:

$$\frac{\partial c^{(\ell)}}{\partial z} = A^{(\ell)} c_a^{(\ell)} \left(\frac{a(h-z)}{z(h-a)} \right)^{A^{(\ell)}-1} \cdot \left(\frac{-ah}{z^2(h-a)} \right) \tag{18.23}$$

The concentration gradient at the bottom of the *kmx* layer is:

$$c'^{(\ell)}_{kmx(bot)} = A^{(\ell)} c_a^{(\ell)} \left(\frac{a(h - z_{kmx(bot)})}{z_{kmx(bot)}(h-a)} \right)^{A^{(\ell)}-1} \cdot \left(\frac{-ah}{z^2_{kmx(bot)}(h-a)} \right) \tag{18.24}$$

We express this gradient as a function of the known concentrations c_a and c_{kmx} by introducing another correction factor α_2:

$$c'^{(\ell)}_{kmx(bot)} = \alpha_2^{(\ell)} \left(\frac{c^{(\ell)}_{kmx} - c^{(\ell)}_a}{\Delta z} \right) \tag{18.25}$$

Erosive flux due to upward diffusion

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

$$E^{(\ell)} = \varepsilon_s^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z}, \tag{18.26}$$

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:

$$E^{(\ell)} \approx \alpha_2^{(\ell)} \varepsilon_s^{(\ell)} \left(\frac{c_a^{(\ell)} - c^{(\ell)}_{kmx}}{\Delta z} \right), \tag{18.27}$$

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(ℓ)
$c_a^{(\ell)}$	reference concentration of sediment fraction(ℓ)
$c^{(\ell)}_{kmx}$	average concentration of the kmx cell of sediment fraction(ℓ)
Δz	difference in elevation between the centre of the kmx cell and Van Rijn's reference level: $\Delta z = z_{kmx} - a$

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

$$E^{(\ell)} \approx \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_a^{(\ell)}}{\Delta z} - \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c^{(\ell)}_{kmx}}{\Delta z}. \tag{18.28}$$

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:

$$Source^{(\ell)}_{erosion} = \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c_a^{(\ell)}}{\Delta z} \tag{18.29}$$

$$Sink^{(\ell)}_{erosion} = \frac{\alpha_2^{(\ell)} \varepsilon_s^{(\ell)} c^{(\ell)}_{kmx}}{\Delta z} \tag{18.30}$$

Deposition flux due to sediment settling

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

$$D^{(\ell)} = w_s^{(\ell)} c_{kmx(bot)}^{(\ell)}, \tag{18.31}$$

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

We set:

$$c_{kmx(bot)}^{(\ell)} = \alpha_1^{(\ell)} c_{kmx}^{(\ell)}. \tag{18.32}$$

The deposition flux is approximated by:

$$D^{(\ell)} \approx \alpha_1^{(\ell)} c_{kmx}^{(\ell)} w_s^{(\ell)}. \tag{18.33}$$

This results in a simple deposition sink term:

$$Sink_{deposition}^{(\ell)} = \alpha_1^{(\ell)} c_{kmx}^{(\ell)} w_s^{(\ell)}. \tag{18.34}$$

The total source and sink terms is given by:

$$Source^{(\ell)} = \alpha_2^{(\ell)} c_a^{(\ell)} \left(\frac{\varepsilon_s^{(\ell)}}{\Delta z} \right), \tag{18.35}$$

$$Sink^{(\ell)} = \left[\alpha_2^{(\ell)} \left(\frac{\varepsilon_s^{(\ell)}}{\Delta z} \right) + \alpha_1^{(\ell)} w_s^{(\ell)} \right] c_{kmx}^{(\ell)}. \tag{18.36}$$

These source and sink terms are both guaranteed to be positive.

18.3.5 Inclusion of a fixed layer

The bedload transport is reduced if the thickness of the sediment layer becomes small (see section 18.4.4). 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_{FIXFAC} if erosion is expected to occur.

18.3.6 Inflow boundary conditions 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 equilibrium boundary conditions. Although equilibrium boundary conditions may be better defined for non-cohesive sediments than for cohesive sediments, we have implemented the open boundary condition in a consistent manner. For non-cohesive suspended material you can specify that, at all open inflow boundaries, the flow should enter carrying the same concentration of sediment as computed in the interior of the model. This feature is enabled by setting `NeuBcSand` in the morphology input file to true (Neumann boundary condition: concentration gradient perpendicular to open boundary equal to zero). This means that the sediment 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 will generally be the desired situation if the model boundaries are well chosen. This method gives the correct results even when the turbulent mixing profile is clearly non-parabolic.

By setting `NeuBcSand = false`, the concentrations to be applied at the inflow boundaries are read from the <*.bcc> file, which has to be created with the FLOW User Interface. If the parameter is set to true, the values specified in the <*.bcc> file are overruled. This parameter used to be called `EqmBc`.

18.4 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 18.5), subsequently the transport rates at the cell interfaces are determined, corrected for bed-slope effect and upwind bed composition and sediment availability.

18.4.1 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 18.5.1.

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 φ_τ is given by the following formula:

$$\tan(\varphi_\tau) = \frac{v - \alpha_I \frac{u}{U} I_s}{u - \alpha_I \frac{v}{U} I_s} \tag{18.37}$$

in which

$$\alpha_I = \frac{2}{\kappa^2} E_s \left(1 - \frac{1}{2}\frac{\sqrt{g}}{\kappa C}\right) \tag{18.38}$$

where:

g	gravitational acceleration
κ	Von Kármán constant
C	Chézy roughness
U	the depth-averaged velocity
E_s	coefficient to be specified by you as `Espir` 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.

18.4.2 Suspended sediment correction vector

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

18.4.3 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 ξ. The following formulations have been implemented:
  - ▫ No hiding and exposure correction ($\xi = 1$)
  - ▫ Egiazaroff formulation

$$\xi = \left(\frac{{}^{10}\log 19}{{}^{10}\log 19 + {}^{10}\log\left(D_i/D_m\right)} \right)^2 . \tag{18.39}$$

  - ▫ Ashida & Michiue formulation

$$\xi = \begin{cases} 0.8429 \frac{D_m}{D_i} & \text{if } D_i/D_m < 0.38889 \\ \left(\frac{{}^{10}\log 19}{{}^{10}\log 19 + {}^{10}\log\left(D_i/D_m\right)} \right)^2 & \text{otherwise} \end{cases} . \tag{18.40}$$

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

$$\xi = \left(\frac{D_m}{D_i} \right)^{\alpha} . \tag{18.41}$$

where α is given by the `ASKLHE` keyword in the morphology input file.

  - ▫ Wu, Wang & Jia formulation

$$\varphi^{(\ell)} = \sum_i \eta^{(i)} \frac{D^{(i)}}{D^{(\ell)} - D^{(i)}} \tag{18.42}$$

$$\xi^{(\ell)} = \left(\frac{1 - \varphi^{(\ell)}}{\varphi^{(\ell)}} \right)^m \tag{18.43}$$

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.

18.4.4 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:

$$S_b'' = f_{\text{FIXFAC}} S_b'', \tag{18.44}$$

where:

S_b''	magnitude of the bedload transport vector (before correction for bed slope effects)
f_{FIXFAC}	upwind fixed layer proximity factor: $f_{\text{FIXFAC}} = \frac{\text{DPSED}}{\text{THRESH}}$, limited to the range $0 \leq f_{\text{FIXFAC}} \leq 1$.
DPSED	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 18.2 and section 18.3.5.

18.4.5 Calculation of bedload transport at open boundaries

Bedload transport at open boundaries is not implemented yet.

18.4.6 Bedload transport at velocity points

As the control volume for bed level change calculations is centred on the water level points, see Figure 18.4, 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 18.4). In the example shown in Figure 18.4 the bedload transport normal component on the velocity point, S_u^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^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).

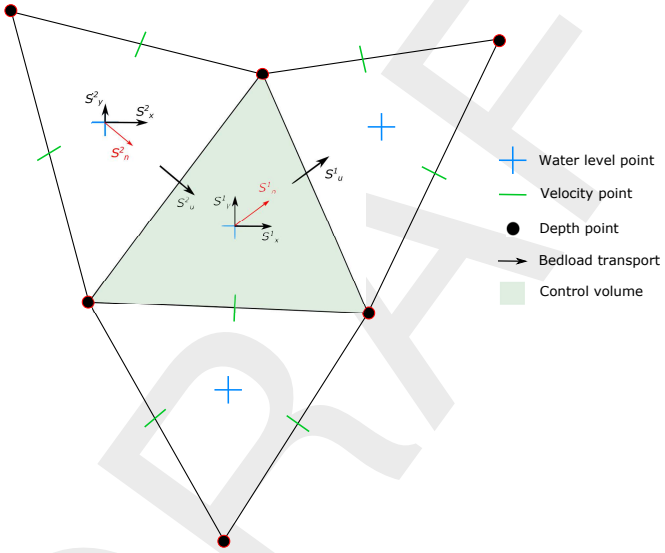


Figure 18.4: *Setting of bedload transport components at velocity points*

18.4.7 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:

$$\boldsymbol{S'}_b = \alpha_s \boldsymbol{S''}, \tag{18.45}$$

or, in vector component form:

$$S'_{b,x} = \alpha_s S''_{b,x}, \tag{18.46}$$

$$S'_{b,y} = \alpha_s S''_{b,y}, \tag{18.47}$$

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 slope. This is the default option for the bedload transport of all sediment transport formulae. In this case α_s is given by

$$\alpha_s = 1 + \alpha_{bs}\left(\frac{\tan(\phi)}{\cos\left(\tan^{-1}\left(\frac{\partial z}{\partial s}\right)\right)\left(\tan(\phi)+\frac{\partial z}{\partial s}\right)} - 1\right), \tag{18.48}$$

where α_{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 (18.49) 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. $u_{b,n} = 0$:

$$S_{b,n} = |S'_b|\,\alpha_{bn}\frac{u_{b,cr}}{|\boldsymbol{u}_b|}\frac{\partial z_b}{\partial n}, \tag{18.49}$$

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
$\lvert S'_b\rvert$	magnitude of the unadjusted bedload transport vector (adjusted for longitudinal bed slope only): $\lvert S'_b\rvert = \sqrt{\left(S'_{b,x}\right)^2 + \left(S'_{b,y}\right)^2}$.
α_{bn}	user-defined coefficient, ALFABN (default = 1.5)
$u_{b,cr}$	critical (threshold) near-bed fluid velocity
$\boldsymbol{u}_b$	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 (18.49) we substitute:

$$\frac{u_{b,cr}}{|\boldsymbol{u}_b|} = \sqrt{\frac{\tau_{b,cr}}{|\boldsymbol{\tau}_b|}}, \tag{18.50}$$

where:

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

resulting in:

$$S_{b,n} = |S'_b|\,f_{norm}, \tag{18.51}$$

where:

$$f_{norm} = \alpha_{bn}\sqrt{\frac{\tau_{b,cr}}{|\boldsymbol{\tau}_b|}}\frac{\partial z_b}{\partial n}. \tag{18.52}$$

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

$$\begin{aligned} S_{b,x} &= S'_{b,x} - S'_{b,y}f_{norm} \\ S_{b,y} &= S'_{b,y} + S'_{b,x}f_{norm} \end{aligned} \tag{18.53}$$

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 α_s is given by

$$\alpha_s = 1 - \alpha_{bs}\frac{\partial z}{\partial s}, \tag{18.54}$$

where α_{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:

$$\tan(\varphi_s) = \frac{\sin(\varphi_\tau) + \frac{1}{f(\theta)}\frac{\partial z_b}{\partial y}}{\cos(\varphi_\tau) + \frac{1}{f(\theta)}\frac{\partial z_b}{\partial x}}, \tag{18.55}$$

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

$$f(\theta) = A_{sh}\theta_i^{B_{sh}}\left(\frac{D_i}{H}\right)^{C_{sh}}\left(\frac{D_i}{D_m}\right)^{D_{sh}}, \tag{18.56}$$

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 α_s and φ_s hold as in the previous case except for $f(\theta)$ which now equals:

$$f(\theta) = \frac{c_L}{1+\mu c_L}\sqrt{\frac{\theta}{\max\left(\frac{1}{10}\theta, \xi\theta_{cr}\right)}}, \tag{18.57}$$

where Coulomb friction parameter c_L, lift-drag ratio μ and critical shields parameter θ_{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 ξ.

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 18.6. In all cases the bed slope has been defined as follows.

Longitudinal bed slope

This bed slope is calculated as:

$$\frac{\partial z_b}{\partial s} = \frac{\partial z_{(u)}}{\partial x}\frac{S''_{b,x}}{|S''_b|} + \frac{\partial z_{(v)}}{\partial y}\frac{S''_{b,y}}{|S''_b|}, \tag{18.58}$$

$$\left(\frac{\partial z_b}{\partial s}\right)_{\max} = 0.9\tan(\phi), \tag{18.59}$$

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
ϕ	internal angle of friction of bed material (assumed to be 30°)

Remarks:

- z_b is the depth down to the bed from a reference level (positive down), a downward bed slope returns a positive value).

Table 18.1: *Additional transport relations*

Formula	Bedload	Waves
18.5.1, Van Rijn (1993)	Bedload + suspended	Yes
18.5.2, Engelund-Hansen (1967)	Total transport	No
18.5.3, Meyer-Peter-Muller (1948)	Total transport	No
18.5.4, General formula	Total transport	No
18.5.5, Bijker (1971)	Bedload + suspended	Yes
18.5.6, Van Rijn (1984)	Bedload + suspended	No
18.5.7, Soulsby/Van Rijn	Bedload + suspended	Yes
18.5.8, Soulsby	Bedload + suspended	Yes
18.5.9, Ashida-Michiue (1974)	Total transport	No
18.5.10, Wilcock-Crowe (2003)	Bedload	No
18.5.11, Gaeuman et al. (2009) laboratory calibration	Bedload	No
18.5.12, Gaeuman et al. (2009) Trinity River calibration	Bedload	No

◇ 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:

$$\frac{\partial z_b}{\partial n} = -\frac{\partial z_{(u)}}{\partial x}\frac{S''_{b,y}}{|S''_b|} + \frac{\partial z_{(v)}}{\partial y}\frac{S''_{b,x}}{|S''_b|}. \tag{18.60}$$

18.5 Transport formulations for non-cohesive sediment

This special feature offers a number of standard sediment transport formulations for non-cohesive sediment. Table 18.1 gives a summary of the available additional formulae.

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

18.5.1 Van Rijn (1993)

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

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

$$c_a^{(\ell)} = 0.015\rho_s^{(\ell)}\frac{D_{50}^{(\ell)}\left(T_a^{(\ell)}\right)^{1.5}}{a\left(D_*^{(\ell)}\right)^{0.3}} \tag{18.61}$$

where:

$c_a^{(\ell)}$ mass concentration at reference level a

In order to evaluate this expression the following quantities must be calculated:

$D_*^{(\ell)}$ non-dimensional particle diameter:

$$D_*^{(\ell)} = D_{50}^{(\ell)} \left[\frac{(s^{(\ell)} - 1)g}{\nu^2} \right]^{1/3} \tag{18.62}$$

$T_a^{(\ell)}$ non-dimensional bed-shear stress:

$$T_a^{(\ell)} = \frac{(\mu_c^{(\ell)} \tau_{b,cw} + \mu_w^{(\ell)} \tau_{b,w}) - \tau_{cr}^{(\ell)}}{\tau_{cr}^{(\ell)}} \tag{18.63}$$

$\mu_c^{(\ell)}$ efficiency factor current:

$$\mu_c^{(\ell)} = \frac{f'^{(\ell)}_c}{f_c} \tag{18.64}$$

$f'^{(\ell)}_c$ gain related friction factor:

$$f'^{(\ell)}_c = 0.24 \left[{}^{10}\log \left(\frac{12h}{3D_{90}^{(\ell)}} \right) \right]^{-2} \tag{18.65}$$

$f_c^{(\ell)}$ total current-related friction factor:

$$f_c^{(\ell)} = 0.24 \left[{}^{10}\log \left(\frac{12h}{k_s} \right) \right]^{-2} \tag{18.66}$$

$\tau_{b,cw}$ 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 α_{cw} is not required.

$$\tau_{b,cw} = \rho_w u_*^2 \tag{18.67}$$

$\mu_w^{(\ell)}$ efficiency factor waves:

$$\mu_w^{(\ell)} = \max \left(0.063, \frac{1}{8} \left(1.5 - \frac{H_s}{h} \right)^2 \right) \tag{18.68}$$

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

$$\tau_{b,w} = \frac{1}{4} \rho_w f_w \left(\widehat{U}_\delta \right)^2 \tag{18.69}$$

f_w total wave-related friction factor:

$$f_w = \exp \left[-6 + 5.2 \left(\frac{\hat{A}_\delta}{k_{s,w}} \right)^{-0.19} \right] \tag{18.70}$$

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:

$$k_{s,w} = RWAVE \cdot \Delta_r, \text{ with } \Delta_r = 0.025 \text{ and } 0.01 \text{ m} \leq k_{s,w} \leq 0.1 \text{ m} \tag{18.71}$$

where:

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

$\tau_{cr}^{(\ell)}$ critical bed shear stress:

$$\tau_{cr}^{(\ell)} = (\rho_s^{(\ell)} - \rho_w) g D_{50}^{(\ell)} \theta_{cr}^{(\ell)} \tag{18.72}$$

$\theta_{cr}^{(\ell)}$ threshold parameter $\theta_{cr}^{(\ell)}$ 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:

$$\theta_{cr}^{(\ell)} = \begin{cases} 0.24 D_*^{-1}, & 1 < D_* \leq 4 \\ 0.14 D_*^{-0.64}, & 4 < D_* \leq 10 \\ 0.04 D_*^{-0.1}, & 10 < D_* \leq 20 \\ 0.013 D_*^{0.29}, & 20 < D_* \leq 150 \\ 0.055, & 150 < D_* \end{cases} \tag{18.73}$$

a Van Rijn's reference level

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

$D_{50}^{(\ell)}$ median sediment diameter

$D_{90}^{(\ell)}$ 90 % sediment passing size: $D_{90}^{(\ell)} = 1.5 D_{50}^{(\ell)}$

h water depth

k_a apparent bed roughness felt by the flow when waves are present. Calculated by D-Flow FM using the wave-current interaction formulation selected: $k_a \leq 10 k_s$

k_s user-defined current-related effective roughness height (space varying)

$k_{s,w}$ wave-related roughness, calculated from ripple height, see Equation (18.71)

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 δ.

$\widehat{U}_\delta$ peak orbital velocity at the bed: $\sqrt{2}\ RMS_{orbital\ velocity}$ 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

Δ_r estimated ripple height, see Equation (18.71)

δ_m thickness of wave boundary mixing layer following Van Rijn (1993): $3\delta_w$ (and $\delta_m \geq k_a$)

δ_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 D-Flow FM. 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:

$$D_s^{(\ell)} = \begin{cases} 0.64 D_{50}^{(\ell)} & \text{for } T_A^{(\ell)} \leq 1 \\ D_{50}^{(\ell)} \left(1 + 0.015 \left(T_A^{(\ell)} - 25\right)\right) & \text{for } 1 < T_A^{(\ell)} \leq 25 \\ D_{50}^{(\ell)} & \text{for } 25 < T_A^{(\ell)} \end{cases} \tag{18.74}$$

where $T_a^{(\ell)}$ is given by equation (18.63).

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:

$$|S_b| = 0.006 \rho_s w_s D_{50}^{(\ell)} M^{0.5} M_e^{0.7} \tag{18.75}$$

where:

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

$$M = \frac{v_{eff}^2}{(s-1)\, g D_{50}} \tag{18.76}$$

$$M_e = \frac{(v_{eff} - v_{cr})^2}{(s-1)\, g D_{50}} \tag{18.77}$$

$$v_{eff} = \sqrt{v_R^2 + U_{on}^2} \tag{18.78}$$

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:

$$S_{b,c} = \frac{S_b}{\sqrt{1 + r^2 + 2\,|r| \cos\varphi}} \tag{18.79}$$

$$|S_{b,w}| = r\,|S_{b,c}| \tag{18.80}$$

where:

$$r = \frac{(|U_{on}| - v_{cr})^3}{(|v_R| - v_{cr})^3} \tag{18.81}$$

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

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):

$$S_{s,w} = f_{\text{SUSW}} \gamma U_A L_T \tag{18.82}$$

where:

$S_{s,w}$	wave-related suspended transport [kg/(ms)]
f_{SUSW}	user-defined tuning parameter
γ	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^2] = $0.007 \rho_s D_{50} M_e$

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:

$$S_{bc,u} = \frac{u_{b,u}}{|u_b|}\,|S_{b,c}| \tag{18.83}$$

$$S_{bc,v} = \frac{u_{b,v}}{|u_b|}\,|S_{b,c}| \tag{18.84}$$

$$S_{bw,u} = S_{b,w} \cos\phi \tag{18.85}$$

$$S_{bw,v} = S_{b,w} \sin\phi \tag{18.86}$$

$$S_{sw,u} = S_{s,w} \cos\phi \tag{18.87}$$

$$S_{sw,v} = S_{s,w} \sin\phi \tag{18.88}$$

where ϕ 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.

18.5.2 Engelund-Hansen (1967)

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

$$S = S_b + S_{s,eq} = \frac{0.05\alpha q^5}{\sqrt{g}C^3\Delta^2 D_{50}} \tag{18.89}$$

where:

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

The transport rate is imposed as bedload transport due to currents S_{bc}. The following formula specific parameters have to be specified in the input files of the Transport module: calibration coefficient α and roughness height r_k.

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.

18.5.3 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:

$$S = 8\alpha D_{50}\sqrt{\Delta g D_{50}}(\mu\theta - \xi\theta_{cr})^{3/2} \tag{18.90}$$

where:

α	calibration coefficient (O(1))
Δ	the relative density $(\rho_s - \rho_w)/\rho_w$
μ	ripple factor or efficiency factor
θ_{cr}	critical mobility parameter ($= 0.047$)
ξ	hiding and exposure factor for the sediment fraction considered

and the Shields mobility parameter θ given by

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} \tag{18.91}$$

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

$$\mu = \min\left(\left(\frac{C}{C_{g,90}}\right)^{1.5}, 1.0\right) \tag{18.92}$$

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

$$C_{g,90} = 18\ {}^{10}\log\left(\frac{12(d+\zeta)}{D_{90}}\right) \tag{18.93}$$

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: calibration coefficient α 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.

18.5.4 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:

$$S = \alpha D_{50} \sqrt{\Delta g D_{50}} \theta^b (\mu\theta - \xi\theta_{cr})^c \tag{18.94}$$

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

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} \tag{18.95}$$

in which q is the magnitude of the flow velocity.

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

18.5.5 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:

$$\boldsymbol{S}_b = \boldsymbol{S}_{b0} + \boldsymbol{S}_{b,asymm} + \boldsymbol{S}_{s,asymm} + \boldsymbol{S}_{b,slope} + \boldsymbol{S}_{s,slope} \tag{18.96}$$

$$\boldsymbol{S}_s = \boldsymbol{S}_{s0} \tag{18.97}$$

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.

18.5.5.1 Basic formulation

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

$$S_b = bD_{50} \frac{q}{C} \sqrt{g} \left(1 - \phi\right) \exp\left(A_r\right) \tag{18.98}$$

$$S_s = 1.83 S_b \left(I_1 \ln\left(\frac{33.0h}{r_c}\right) + I_2\right) \tag{18.99}$$

where

C	Chézy coefficient (as specified in input of D-Flow FM module)
h	water depth
q	flow velocity magnitude
ϕ	porosity

and

$$A_r = \max\left(-50, \min\left(100, A_{ra}\right)\right) \tag{18.100}$$

$$b = BD + \max\left(0, \min\left(1, \frac{(h_w/h) - C_d}{C_s - C_d}\right)\right)(BS - BD) \tag{18.101}$$

$$I_1 = 0.216 \frac{\left(\frac{r_c}{h}\right)^{z_*-1}}{\left(1 - \frac{r_c}{h}\right)^{z_*}} \int_{r_c/h}^{1} \left(\frac{1-y}{y}\right)^{z_*} dy \tag{18.102}$$

$$I_2 = 0.216 \frac{\left(\frac{r_c}{h}\right)^{z_*-1}}{\left(1 - \frac{r_c}{h}\right)^{z_*}} \int_{r_c/h}^{1} \ln y \left(\frac{1-y}{y}\right)^{z_*} dy \tag{18.103}$$

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

$$A_{ra} = \frac{-0.27 \Delta D_{50} C^2}{\mu q^2 \left(1 + 0.5 \left(\psi \frac{U_b}{q}\right)^2\right)} \tag{18.104}$$

$$\mu = \left(\frac{C}{18\ {}^{10}\log(12h/D_{90})}\right)^{1.5} \tag{18.105}$$

$$z_* = \frac{w}{\frac{\kappa q \sqrt{g}}{C} \sqrt{1 + 0.5 \left(\psi \frac{U_b}{q}\right)^2}} \tag{18.106}$$

$$U_b = \frac{\omega h_w}{2 \sinh\left(k_w h\right)} \tag{18.107}$$

$$\omega = \frac{2\pi}{T} \tag{18.108}$$

$$f_w = \exp\left(-5.977 + \frac{5.123}{a_0^{0.194}}\right) \tag{18.109}$$

$$a_0 = \max\left(2, \frac{U_b}{\omega r_c}\right) \tag{18.110}$$

$$\psi = \begin{cases} C\sqrt{\frac{f_w}{2g}} & \text{if wave effects are included } (T > 0) \\ 0 & \text{otherwise} \end{cases} \tag{18.111}$$

where

C	Chézy coefficient (as specified in input of D-Flow FM module)
h_w	wave height (H_{rms})
k_w	wave number
T	wave period computed by the waves model or specified by you as T user.
U_b	wave velocity
w	sediment fall velocity [m/s]
Δ	relative density $(\rho_s - \rho_w)/\rho_w$
κ	Von Kármán constant (0.41)

The following formula specific parameters have to be specified in the input files of the Transport module: BS, BD, C_s, C_d, dummy argument, r_c, w, ε and T user.

18.5.5.2 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:

$$\boldsymbol{S}_b = \boldsymbol{S}_{b0} + \boldsymbol{S}_{b,asymm} + \boldsymbol{S}_{s,asymm} + \boldsymbol{S}_{b,slope} + \boldsymbol{S}_{s,slope} \tag{18.112}$$

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

$$S_{b;\mathrm{asymm}}(t) = \frac{\rho c_f \varepsilon_b}{(\rho_s - \rho)\, g\, (1-\phi) \tan\varphi} \left|u(t)\right|^2 u(t) \tag{18.113}$$

$$S_{s;\mathrm{asymm}}(t) = \frac{\rho c_f \varepsilon_s}{(\rho_s - \rho)\, g\, (1-\phi)\, w} \left|u(t)\right|^3 u(t) \tag{18.114}$$

from which the components in directions tangential and normal to flow links are obtained by multiplying with the cosine and sine of the wave angle θw and the bed slope components as:

$$S_{b;\mathrm{slope},\xi}(t) = \frac{\rho c_f \varepsilon_b}{(\rho_s - \rho)\, g\, (1-\phi) \tan\varphi} \frac{1}{\tan\varphi} \left|u(t)\right|^3 \frac{\partial z_b}{\partial \xi} \tag{18.115}$$

$$S_{s;\mathrm{slope},\xi}(t) = \frac{\rho c_f \varepsilon_s}{(\rho_s - \rho)\, g\, (1-\phi)\, w} \frac{\varepsilon_s}{w} \left|u(t)\right|^5 \frac{\partial z_b}{\partial \xi} \tag{18.116}$$

and similar for the η direction, where:

$u(t)$	near bed velocity signal [m/s]
ρ	density of water [kg/m^3]
ρ_s	density of the sediment [kg/m^3]
c_f	coefficient of the bottom shear stress [-] (constant value of 0.005)
ϕ	porosity [-] (constant value of 0.4)
φ	natural angle of repose [-] (constant value of $\tan\varphi = 0.63$)
w	sediment fall velocity [m/s]
ε_b	efficiency factor of bedload transport [-] (constant value of 0.10)
ε_s	efficiency factor of suspended transport [-] (constant value of 0.02, but in implemented expression for suspended bed slope transport the second ε_s is replaced by a user-defined calibration factor; see Equation (18.119)).

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 (18.113) and (18.114), is determined by using the following averaging expressions of the near bed velocity signal (calibration coefficients included):

$$\left\langle u\left|u\right|^2\right\rangle = FacA\left\langle \tilde{u}\left|\tilde{u}\right|^2\right\rangle + 3FacU\bar{u}\left\langle \left|\tilde{u}\right|^2\right\rangle \tag{18.117}$$

$$\left\langle u\left|u\right|^3\right\rangle = FacA\left\langle \tilde{u}\left|\tilde{u}\right|^3\right\rangle + 4FacU\bar{u}\left\langle \left|\tilde{u}\right|^3\right\rangle \tag{18.118}$$

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 (18.116) is implemented as:

$$S_{s;slope,\xi}(t) = \frac{\rho c_f \varepsilon_s}{(\rho_s - \rho)\, g\, (1-\phi)\, w} \frac{\varepsilon_{sl}}{w} \left|u(t)\right|^5 \frac{\partial z_b}{\partial \xi} \tag{18.119}$$

where:

ε_{sl}	user-defined calibration coefficient `EpsSL`

To activate this transport option, you have to create a separate file named <coef.inp> which contains on three separate lines the calibration coefficients: `FacA`, `FacU` and `EpsSL`. The other parameters are read from the transport input file or are specified as general sediment characteristics.

Note: the user-defined *FacU* value is currently treated as a dummy value, *FacU* = 0.0 will always be used.

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).

18.5.6 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:

$$S_b = \begin{cases} 0.053\sqrt{\Delta g D_{50}^3} D_*^{-0.3} T^{2.1} & \text{for } T < 3.0 \\ 0.1\sqrt{\Delta g D_{50}^3} D_*^{-0.3} T^{1.5} & \text{for } T \geq 3.0 \end{cases} \tag{18.120}$$

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

$$T = \frac{\mu_c \tau_{bc} - \tau_{bcr}}{\tau_{bcr}} \tag{18.121}$$

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

$$\tau_{bc} = \frac{1}{8}\rho_w f_{cb} q^2 \tag{18.122}$$

$$f_{cb} = \frac{0.24}{\left({}^{10}\log\left(12h/\xi_c\right)\right)^2} \tag{18.123}$$

$$\mu_c = \left(\frac{18\ {}^{10}\log\left(12h/\xi_c\right)}{C_{g,90}} \right)^2 \tag{18.124}$$

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

$$C_{g,90} = 18\ {}^{10}\log\left(\frac{12h}{3D_{90}}\right) \tag{18.125}$$

The critical shear stress is written according to Shields:

$$\tau_{bcr} = \rho_w \Delta g D_{50} \theta_{cr} \tag{18.126}$$

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

$$D_* = D_{50}\left(\frac{\Delta g}{\nu^2}\right)^{\frac{1}{3}} \tag{18.127}$$

The suspended transport formulation reads:

$$S_s = f_{cs} q h C_a \tag{18.128}$$

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:

$$f_{cs} = \begin{cases} f_0(z_c) & \text{if } z_c \neq 1.2 \\ f_1(z_c) & \text{if } z_c = 1.2 \end{cases} \tag{18.129}$$

$$f_0(z_c) = \frac{(\xi_c/h)^{z_c} - (\xi_c/h)^{1.2}}{(1-\xi_c/h)^{z_c}(1.2 - z_c)} \tag{18.130}$$

$$f_1(z_c) = \left(\frac{\xi_c/h}{1-\xi_c/h}\right)^{1.2} \ln(\xi_c/h) \tag{18.131}$$

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

$$z_c = \min\left(20, \frac{w_s}{\beta\kappa u_*} + \phi\right) \tag{18.132}$$

$$u_* = q\sqrt{\frac{f_{cb}}{8}} \tag{18.133}$$

$$\beta = \min\left(1.5, 1 + 2\left(\frac{w_s}{u_*}\right)^2\right) \tag{18.134}$$

$$\phi = 2.5\left(\frac{w_s}{u_*}\right)^{0.8}\left(\frac{C_a}{0.65}\right)^{0.4} \tag{18.135}$$

The reference concentration is written as:

$$C_a = 0.015\alpha_1 \frac{D_{50}}{\xi_c}\frac{T^{1.5}}{D_*^{0.3}} \tag{18.136}$$

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: calibration coefficient α_1, dummy argument, reference level (bedload layer thickness) or roughness height ξ_c [m] and settling velocity w_s [m/s].

18.5.7 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:

$$U_{rms} = \sqrt{2}\frac{\pi H_{rms}}{T_p \sinh(kH)} \tag{18.137}$$

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

$$D_* = \left(\frac{g\Delta}{\nu^2}\right)^{1/3} D_{50} \tag{18.138}$$

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

$$U_{cr} = \begin{cases} 0.19 D_{50}^{0.1}\ {}^{10}\log(4H/D_{90}) & \text{if } D_{50} \leq 0.5 \text{ mm} \\ 8.5 D_{50}^{0.6}\ {}^{10}\log(4H/D_{90}) & \text{if } 0.5 \text{ mm} < D_{50} \leq 2 \text{ mm} \end{cases} \tag{18.139}$$

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 level a (see section 18.3.3) in a 3D simulation (Soulsby, 1997, p.183):

$$S_{bx} = A_{cal} A_{sb} u \xi \tag{18.140}$$
$$S_{by} = A_{cal} A_{sb} v \xi \tag{18.141}$$

and the suspended transport magnitude is given by the following formula (this quantity is lateron converted to a reference concentration to feed the advection-diffusion equation for the suspended sediment transport as indicated in section 18.3.3):

$$S_s = A_{cal} A_{ss} \xi \sqrt{u^2 + v^2} \tag{18.142}$$

where

A_{cal} a user-defined calibration factor

A_{sb} bedload multiplication factor

$$A_{sb} = 0.005 H \left(\frac{D_{50}/H}{\Delta g D_{50}}\right)^{1.2} \tag{18.143}$$

A_{ss} suspended load multiplication factor

$$A_{ss} = 0.012 D_{50} \frac{D_*^{-0.6}}{(\Delta g D_{50})^{1.2}} \tag{18.144}$$

ξ a general multiplication factor

$$\xi = \left(\sqrt{U^2 + \frac{0.018}{C_D} U_{rms}^2} - U_{cr}\right)^{2.4} \tag{18.145}$$

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

$$C_D = \left(\frac{\kappa}{\ln(H/z_0) - 1}\right)^2 \tag{18.146}$$

where z_0 equals 6 mm and the Von Kármán constant κ 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: the calibration factor A_{cal}, the ratio of the two characteristic grain sizes D_{90}/D_{50} and the z_0 roughness height.

18.5.8 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

$$U_{rms} = \sqrt{2}U_{orb} = \sqrt{2}\frac{\pi H_{rms}}{T_p \sinh(kH)} \tag{18.147}$$

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 χ is a user-defined constant:

$$z_0 = \frac{D_{50}}{\chi} \tag{18.148}$$

The relative roughness is characterised using a_*:

$$a_* = \frac{U_{orb}T_p}{z_0} \tag{18.149}$$

which is subsequently used to determine the friction factor of the rough bed according to Swart (1974):

$$f_w = \begin{cases} 0.3 & \text{if } a_* \leq 30\pi^2 \\ 0.00251\exp(14.1a_*^{-0.19}) & \text{if } a_* > 30\pi^2 \end{cases} \tag{18.150}$$

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:

$$\tau_w = 0.5\rho f_w U_{orb}^2 \tag{18.151}$$

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

$$\tau_c = \rho C_D U^2 \tag{18.152}$$

Table 18.2: *Overview of the coefficients used in the various regression models (Soulsby et al., 1993a)*

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

where

$$C_D = \left(\frac{\kappa}{1 + \ln\left(z_0/H\right)} \right)^2 \tag{18.153}$$

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):

$$\tau_m = Y\left(\tau_w + \tau_c\right) \tag{18.154}$$

The formula for Y is given by:

$$Y = X\left[1 + bX^p\left(1 - X\right)^q\right] \tag{18.155}$$

where:

$$X = \frac{\tau_c}{\tau_c + \tau_w} \tag{18.156}$$

and b is computed using:

$$b = \left(b_1 + b_2\left|\cos\phi\right|^J\right) + \left(b_3 + b_4\left|\cos\phi\right|^J\right)\ {}^{10}\log\left(f_w/C_D\right) \tag{18.157}$$

and p and q are determined using similar equations. In this formula ϕ equals the angle between the wave angle and the current angle, and the coefficients are determined by the model index *modind* and tables 18.2 and 18.3 (related to Soulsby (1997, Table 9, p.91)):

Using the shear stresses given above, the following two Shields parameters are computed:

$$\theta_m = \frac{\tau_m}{\rho g \Delta D_{50}} \text{ and } \theta_w = \frac{\tau_w}{\rho g \Delta D_{50}} \tag{18.158}$$

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

$$D_* = \left(\frac{g\Delta}{\nu^2}\right)^{1/3} D_{50} \tag{18.159}$$

Table 18.3: *Overview of the coefficients used in the various regression models,* continued *(Soulsby* et al.*, 1993a)*

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

with which a critical Shields parameter is computed (Soulsby, 1997, eq.77, p.106):

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055\left(1 - \exp\left(-0.02D_*\right)\right) \tag{18.160}$$

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):

$$\Phi_{x1} = 12\left(\theta_m - \theta_{cr}\right)\sqrt{\theta_m + \varepsilon} \tag{18.161}$$

$$\Phi_{x2} = 12\left(0.95 + 0.19\cos\left(2\phi\right)\right)\theta_m\sqrt{\theta_w + \varepsilon} \tag{18.162}$$

$$\Phi_x = \max\left(\Phi_{x1}, \Phi_{x2}\right) \tag{18.163}$$

$$\Phi_y = \frac{12\left(0.19\theta_m\theta_w^2\sin\left(2\phi\right)\right)}{\left(\theta_w + \varepsilon\right)^{1.5} + 1.5\left(\theta_m + \varepsilon\right)^{1.5}} \tag{18.164}$$

where ε is a small constant (10^{-4}) to prevent numerical complications. From these expression are finally the actual bedload transport rates obtained:

$$S_{b,x} = \frac{\sqrt{g\Delta D_{50}^3}}{U}\left(\Phi_x u - \Phi_y v\right) \tag{18.165}$$

$$S_{b,y} = \frac{\sqrt{g\Delta D_{50}^3}}{U}\left(\Phi_x v - \Phi_y u\right) \tag{18.166}$$

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: 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 χ (about 12).

18.5.9 Ashida-Michiue (1974)

The transport rate is given by a generalised version of the Ashida-Michiue formulation:

$$S_{bc} = \alpha\sqrt{\Delta g D_{50}^3}\theta^m\left(1 - \xi\frac{\theta_c}{\theta}\right)^p\left(1 - \sqrt{\xi\frac{\theta_c}{\theta}}\right)^q \tag{18.167}$$

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

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} \tag{18.168}$$

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: α, θ_c, m, p and q.

18.5.10 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:

$$S_{bi} = \frac{W_i^* F_i U_*^3}{\Delta g} \tag{18.169}$$

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14\left(1 - \frac{0.894}{\phi^{0.5}}\right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases} \tag{18.170}$$

$$\phi = \frac{\tau}{\tau_{ri}} \tag{18.171}$$

$$\frac{\tau_{ri}}{\tau_{rm}} = \left(\frac{D_i}{D_m}\right)^b \tag{18.172}$$

$$\tau_{rm} = (0.021 + 0.015\exp(-20F_s))(\rho_s - \rho_w) g D_g \tag{18.173}$$

$$b = \frac{0.67}{1 + \exp\left(1.5 - \frac{D_i}{D_g}\right)} \tag{18.174}$$

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 transort rate of size fraction i
W_i^*	dimensionless bedload transport rate of size fraction i
Δ	the relative density of the sediment $(\rho_s - \rho_w)/\rho_w$
τ_{ri}	reference shear stress of grains of size D_i
τ_{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.

18.5.11 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 (σ_ϕ^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, it's derivation and calibration is described in Gaeuman *et al.* (2009).

The formulae for the calculation of S_{bi}, W_i^*, ϕ and τ_{ri} are the same as for the Wilcock-Crowe transport model (Equations (18.169), (18.170), (18.171) and (18.172)) but the calculation of τ_{rm} and b differs.

$$\tau_{rm} = \left(\theta_{c0} + \frac{0.015}{1 + \exp\left(10.1\sigma_\phi^2 - 14.14\right)} \right) (\rho_s - \rho_w)\, g D_g \tag{18.175}$$

$$b = \frac{1 - \alpha_0}{1 + \exp\left(1.5 - \frac{D_i}{D_g}\right)} \tag{18.176}$$

$$\sigma_\phi^2 = \sum_{i=1}^{n} \left({}^2\log\left(\frac{D_i}{D_g}\right)\right)^2 F_i \tag{18.177}$$

where θ_{c0} and α_0 are user specified parameters. 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.

18.5.12 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 τ_{rm} and b.

$$\tau_{rm} = \left(\theta_{c0} + \frac{0.022}{1 + \exp\left(7.1\sigma_\phi^2 - 11.786\right)} \right) (\rho_s - \rho_w)\, g D_g \tag{18.178}$$

$$b = \frac{1 - \alpha_0}{1 + \exp\left(1.9 - \frac{D_i}{3D_g}\right)} \tag{18.179}$$

where θ_{c0} and α_0 are user specified parameters. 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.

18.6 Morphological updating

The elevation of the bed is dynamically updated at each computational time-step. This is one of the distinct advantages over an offline morphological computation as it means that the hydrodynamic flow calculations are always carried out using the correct bathymetry.

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. This change in mass is then translated into a bed level change based on the dry bed densities of the various sediment fractions. Both the bed levels at the cell centres and cell interfaces are updated.

Remark:

- ◇ The depths stored at the depth points (which are read directly from the bathymetry specified as input) 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 calculated depths to the bed by setting the `MorUpd` (or equivalently `BedUpd`) flag in the morphology input file. It may be useful to turn bottom updating off if only the initial patterns of erosion and deposition are required, or an investigation of sediment transport patterns with a constant bathymetry is required.

Remark:

- ◇ The use of `MorUpd` or `BedUpd` only affects the updating of the depth values (at ζ and velocity points); the amount of sediment available in the bed will still be updated. Use the `CmpUpd` flag to switch off the updating of the bed composition. If you wish to prevent any change in both the bottom sediments *and* flow depths from the initial condition then this may also 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.

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 `MorStt` whereby you can specify a time interval (in minutes after the start time) after which the morphological bottom updating will begin. During the `MorStt` 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 the available bottom sediments 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 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. 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 is 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, 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.

18.6.1 Bathymetry updating including bedload transport

The change in the quantity of bottom sediments caused by the bedload transport is calculated using the expression:

$$\Delta^c_{SED} = \frac{\Delta t f_{\text{MORFAC}}}{A^c} \sum_i S^i_u W^i_u \tag{18.180}$$

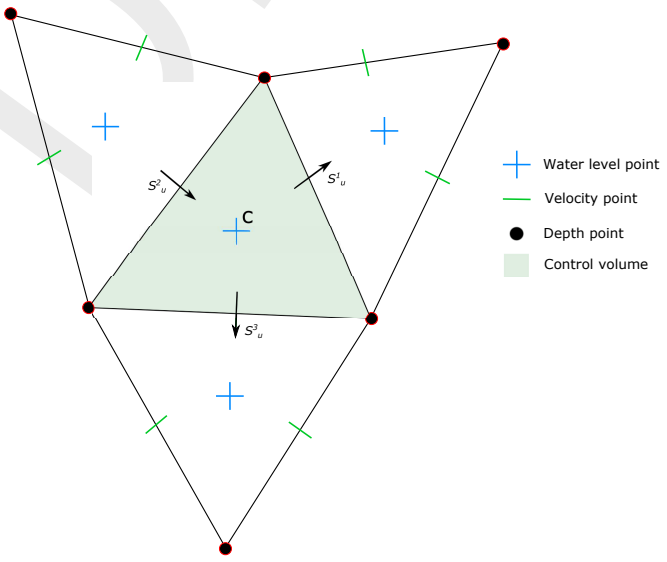


Figure 18.5: *Morphological control volume and bedload transport components*

where:

Δ^c_{SED}	change in quantity of bottom sediment at location c [kg/m^2]
Δt	computational time-step [s]
f_{MORFAC}	user-defined morphological acceleration factor, MORFAC
A^c	area of computational cell at location c [m^2]
S^i_u	computed bedload sediment transport vector in u direction (direction normal to face i), held at the velocity point [kg/(m s)]
W^i_u	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.

18.6.2 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 in the paragraph above are defined as cells at which the water depth is, respectively, more and less 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:

$$Thet = (h_1 - SedThr)/(HMaxTH - SedThr) \times ThetSD$$
$$\text{where } Thet = \min(Thet, ThetSD) \quad (18.181)$$

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.

18.6.3 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 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. The $<$mdu$>$ file should contain a keyword `Fildad` referring to the file used. The $<*$.dad$>$ file refers to the file containing the polygons.

18.6.4 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.

At input you must specify the amount of sediment available at the bed as the total (dry) mass of all sediment fractions in [kg/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.[1] The thickness of the total sediment 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.

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. However, the cohesive sediment is still not included in D-Flow FM.

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:

$$Source_{total} = f_r \, Source_{total}, \tag{18.182}$$

$$Sink_{total} = f_r \, Sink_{total}, \tag{18.183}$$

where f_r is a reduction factor determined by:

$$f_r = \min\left(\frac{\Delta_{sed}}{Thresh}, 1\right), \tag{18.184}$$

where Δ_{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.

18.7 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.

[1] The uniformly mixed bed can be used as input for both bed composition models. If you have more detailed 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 and associated initial bed composition file. In that case the bed composition given in the <*.sed> file will overruled, you have to specify dummy values though.

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 and bedload transport are not calculated for 'sand' and 'bedload' sediment fractions. 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. bathymetrical 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.

19 Tutorial

19.1 Introduction

In this brief introduction, basic information is provided on either the **setup of the tutorial** and some **basic grid concepts**.

19.1.1 Setup of the tutorial

In this three-hours tutorial you will experience the basic functionality of D-Flow FM. On the one hand you will learn how to capture a certain area with a computational grid. On the other hand you will set up and run a computation yourself. This involves for example inserting a bed level, imposing boundary conditions, running a D-Flow FM model and postprocessing with a D-Flow FM output file. This manual contains nine tutorials (with indication of the estimated time):

- ◇ Tutorial 1 (section 19.2): Creating a curvilinear grid (25 minutes).
- ◇ Tutorial 2 (section 19.3): Creating a triangular grid (20 minutes).
- ◇ Tutorial 3 (section 19.4): Coupling multiple distinct grids (15 minutes).
- ◇ Tutorial 4 (section 19.5): Inserting a bed level (15 minutes).
- ◇ Tutorial 5 (section 19.6): Imposing boundary conditions (25 minutes).
- ◇ Tutorial 6 (section 19.7): Defining output locations (15 minutes).
- ◇ Tutorial 7 (section 19.8): Defining computational parameters (10 minutes).
- ◇ Tutorial 8 (section 19.9): Running a model simulation (20 minutes).
- ◇ Tutorial 9 (section 19.10): Viewing the output of a model simulation (15 minutes).

This estimated times leave room for a 5 minutes introduction and a 15 minutes break after tutorial 4. The necessary input files for a tutorial can be found in the directories *tutorial01* till *tutorial09*. You can put your output files in a separate directory, e.g. *finished*.

19.1.2 Basic grid concepts

In D-Flow FM, grids (sometimes denoted as 'networks') consist of net cells and are described by **net nodes** (corners of a cell), **net links** (edges of a cell, connecting net nodes), **flow nodes** (the cell circumcentre) and **flow links** (a line segment connecting two flow nodes).

This grid topology is illustrated in Figure 19.1. Important properties of the mesh are the *orthogonality* and *smoothness*. The *orthogonality* is defined as the cosine of the angle φ between a flowlink and a netlink. Ideally 0, angle $\varphi = 90^\circ$. The *smoothness* of a mesh is defined as the ratio of the areas of two adjacent cells. Ideally 1, the areas of the cells are equal to each other. A nearly ideal setup is shown in Figure 19.2.

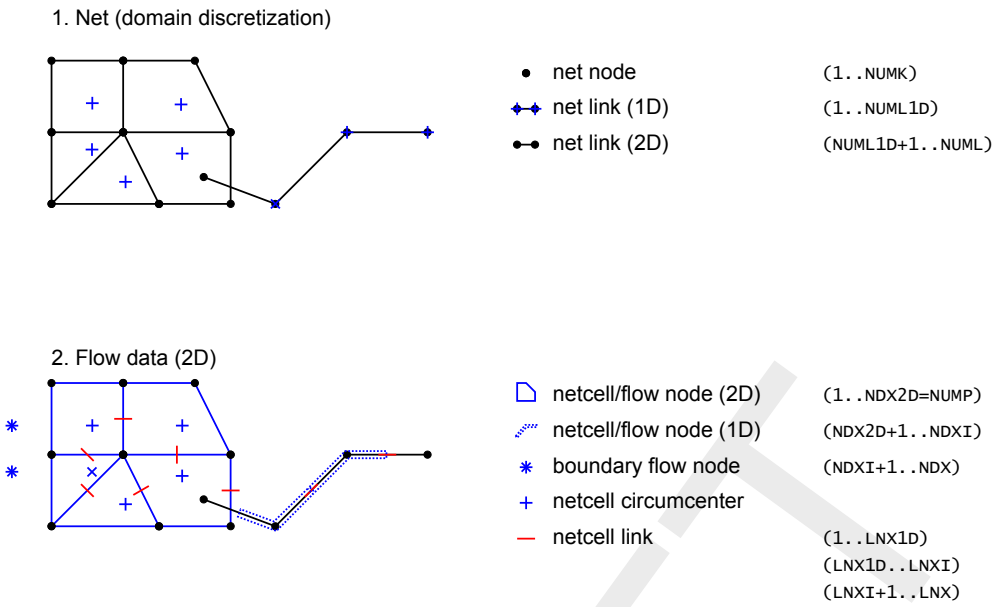


Figure 19.1: *Topology and definitions for a grid as used in D-Flow FM.*

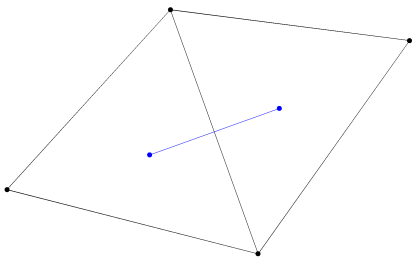
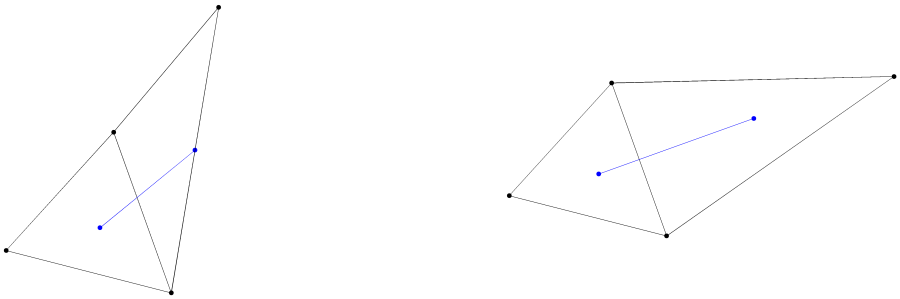


Figure 19.2: *Perfect orthogonality and nearly perfect smoothness along the edge connecting two triangles. Black lines/dots are network links/nodes, blue lines/-dots are flow links/nodes.*

It is rather easy to generate grids that violate the orthogonality and smoothness requirements. In Figure 19.3, two different setups of two grid cells are shown with different grid properties. Figure 19.3a shows how orthogonality can be detoriated by skewing the right triangle with respect to the left triangle. While having the same area (perfect smoothness), the mutually oblique orientation results in poor orthogonality. In this particular case the circumcentre of the right triangle is outside the area of the triangle because it is an obtuse triangle, which is bad for computations with D-Flow FM. The opposite is shown in Figure 19.3b in which the right triangle has strongly been elongated, disturbing the smoothness property. However, the orthogonality is perfect (both triangle are acute). Nonetheless, both grids need to be improved to assure accurate model results.



(a) *Perfect smoothness, but poor orthogonality.* ***(b)*** *Perfect orthogonality, but poor smoothness*

Figure 19.3: *Poor grid properties due to violating either the smoothness or the orthogonality at the edge connecting two triangles. Black lines/dots are network links/nodes, blue lines/dots are flow links/nodes.*

19.2 Tutorial 1: Creating a curvilinear grid

In the upcoming tutorials, the Westernscheldt and the harbour of Antwerp will be used as an example case for generating a grid and setting up a computation.

With D-Flow FM both structured grids and unstructured grids are possible. In practice, a large part of a model domain might be based on a structured grid. Therefore, it is important that a D-Flow FM user also has sufficiently expertise in generating structured grids. In this exercise we therefore will apply D-Flow FM for the generation of a curvilinear grid.

The generation of a grid is an iterative process. However, the Undo functionality is limited in RGFGRID. By clicking on *Esc* it is sometimes possible to undo the last action. Therefore, it is important to frequently save intermediate results in RGFGRID.

To start RGFGRID in the Delta Shell Graphical User Interface the following steps have to be carried out:

- Double click on the Delta Shell icon on the desktop of your computer.
- Click on *New Model* in the main toolbar at the top of the Delta Shell GUI.
- A new window pops up in which you have to select *Flow Flexible Mesh Model* → *OK*.
- Double click on *Grid*, see Figure 19.4. RGFGRID will now start.

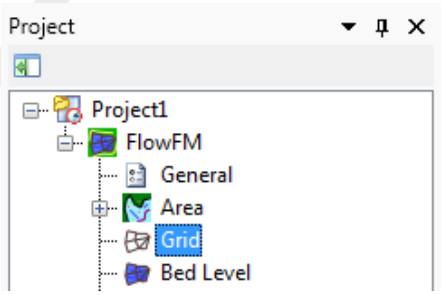


Figure 19.4: *Start RGFGRID by a double-click on* Grid*.*

- Choose from the main menubar *Coordinate System* → *Cartesian Coordinates*. This is the default setting, which means that you do not have to change anything.

To generate a curvilinear grid from splines, a grid is iteratively developed. The approach is as

follows:

- Import a land boundary via *File* → *Attribute Files* → *Open Land Boundary* and select the file <tutorial01\scheldtriver.ldb>
- Select *Edit* → *Splines* → *New* and draw a spline at the left boundary of the river (use the leftmousebutton) with at least three vertices. Finalise the spline by one rightmouseclick.
- Select the lefthandside spline through choosing *Edit* → *Splines* → *Select*.
- Choose the option *Edit* → *Splines* → *Attach to Land Boundary*. Select the the two outer points delimiting the spline to be snapped. The vertices which will be snapped are now marked by a square. Press the rightmousebutton to perform the snapping.
- A window appears for extra snapping: Press *Yes* several times. You will see the spline evolve towards the land boundary. Press *No* when you are satisfied with the result.
- Repeat the previous three steps for the righthandside spline.
- Draw a third spline along the river axis; see Figure 19.5.

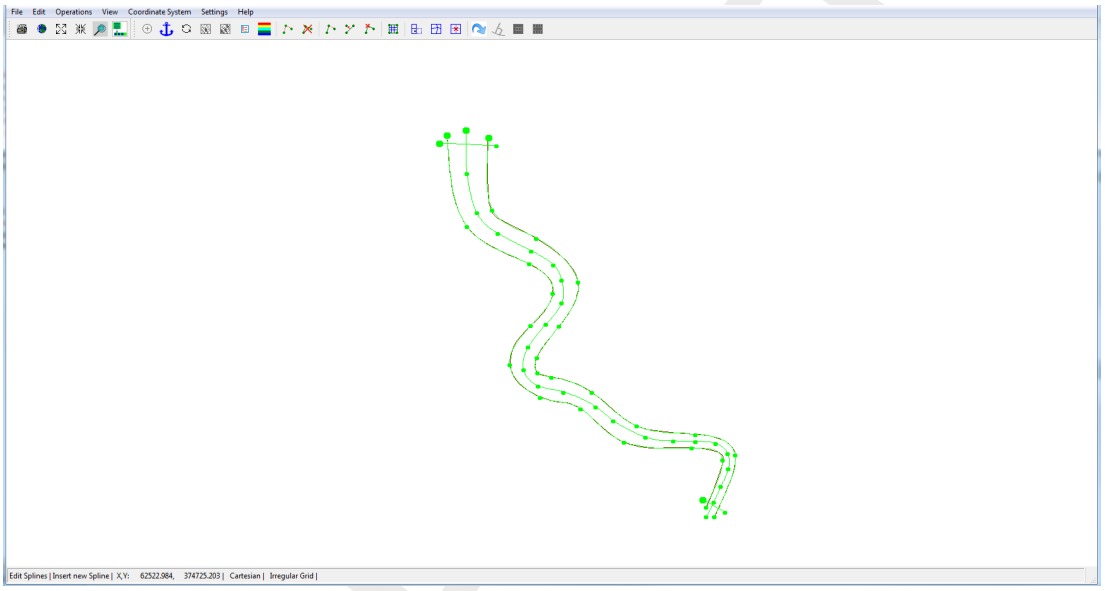


Figure 19.5: *Splines in Tutorial01*

- Draw two cross-splines, each containing exact two vertices: one spline at the North side and one spline at the South side of the river (see Figure 19.7). The channel is now enveloped by four splines and there is an extra spline along the river axis.
- Choose *Settings* → *Grow Grid from Splines...* . You will be able to set several settings of the operator. The first seven entries should be changed into the values shown in Figure 19.6.

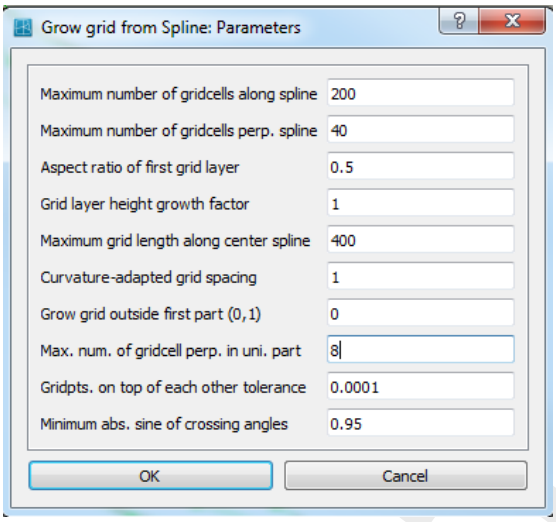


Figure 19.6: *Settings for the* Grow Grid from Splines *procedure.*

A brief explanation:

- ◇ Using the parameter *Max. num. of gridcells perp. in uni. part*, the user can give an indication of the number of cells across the width between the longitudinal splines.
- ◇ By using the parameters *Maximum grid length along center spline*, the user can give an indication of the length of the cells in longitudinal direction. Based on the value of the parameter *Aspect ratio of first grid layer*, the algorithm establishes a suitable grid, under the restrictions of the prevailing maximum numbers of gridcells (first two entries).
- ◇ The option *Grid layer height growth factor* enables the user to demand for a non-equidistant grid in cross-sectional direction. The value represents the width-ratio of two adjacent cells. Using the option *Grow grid outside first part (0/1)*, one can extend a grid outside the longitudinal splines, for instance to capture winterbed regions.

➢ After entering the values of Figure 19.6, choose *Operations* → *Grow Grid from Splines*. This will deliver the grid as shown in Figure 19.7.

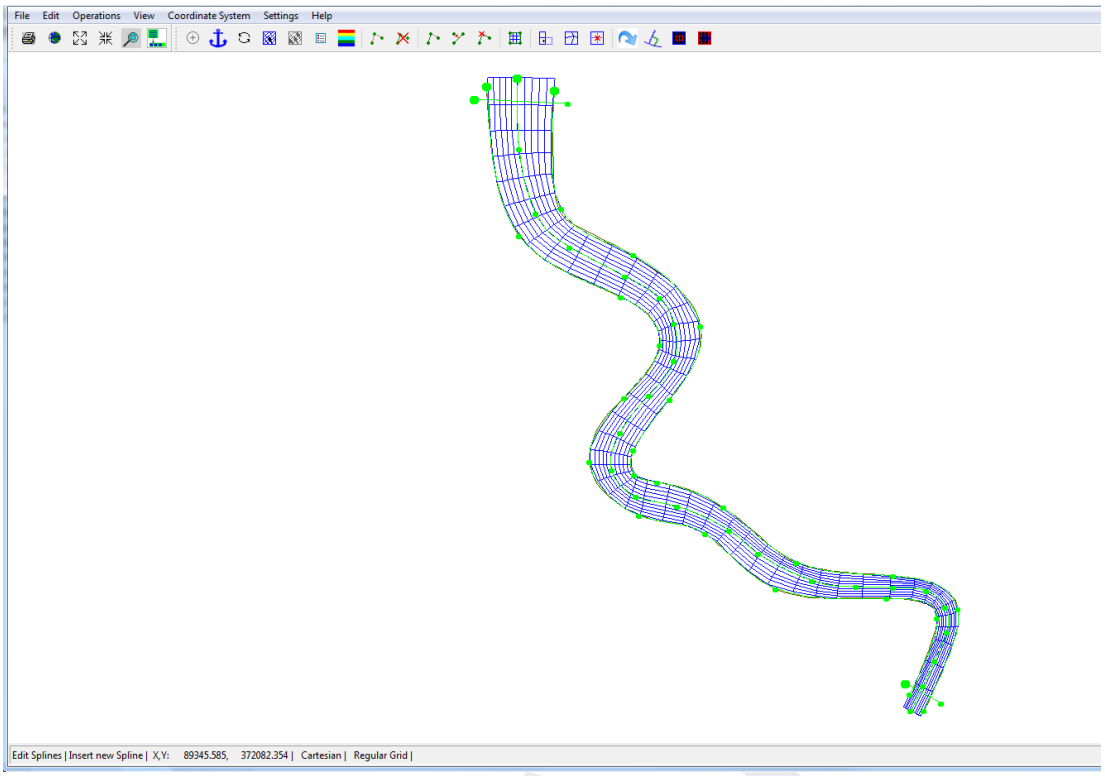


Figure 19.7: *Generated curvilinear grid after the new* Grow Grid from Splines *procedure.*

- To be able to further improve the grid, choose *Operations* → *Convert grid* → *Regular to Irregular*. Strictly, the grid is now not curvilinear anymore, but unstructured.
- Choose *View* → *Grid Property Style* → *Coloured Edge* and then *View* → *Grid Properties* → *Orthogonality*. The result is shown in Figure 19.8. We remark that no orthogonalisation iterations have been performed yet. Try to reach the level of orthogonality as shown in Figure 19.8.

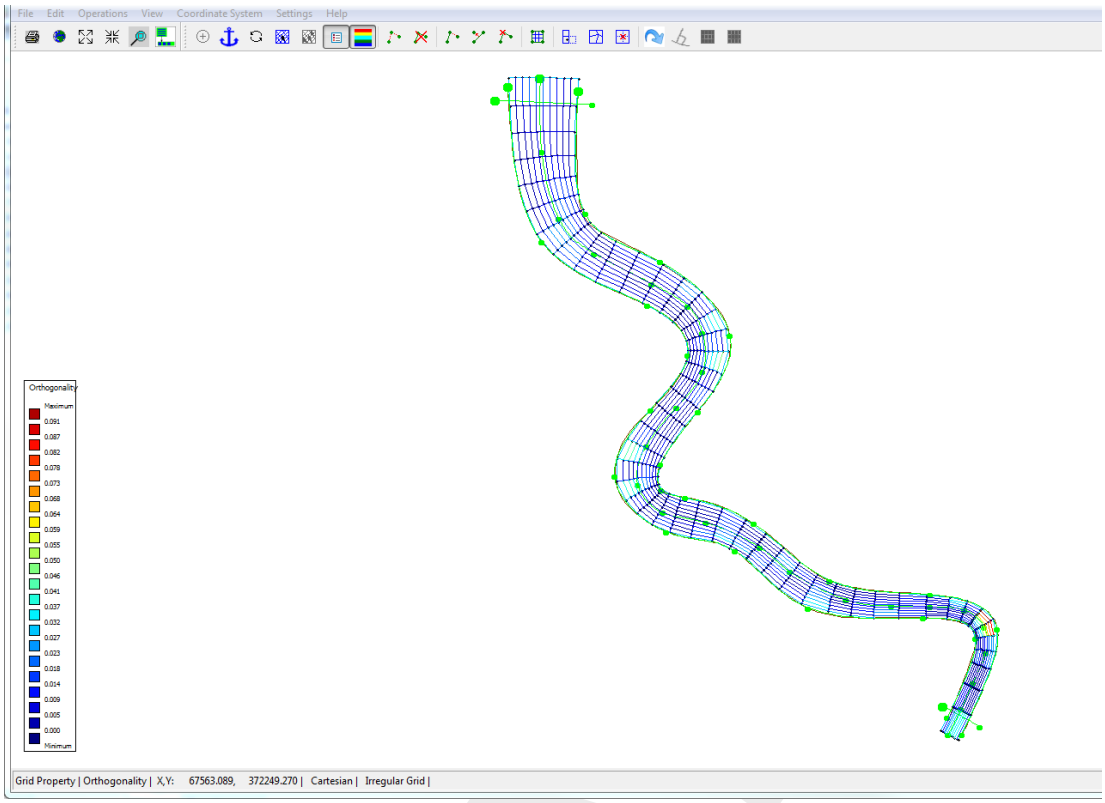


Figure 19.8: *Orthogonality of the generated curvilinear grid after the* Grow Grid from Splines *procedure.*

To save the grid and close RGFGRID the following steps have to be carried out:

- Choose from the menubar *File* → *Export* → *UGRID (D-Flow FM)...* and save the grid with name <scheldt01_net.nc> in the folder <tutorial01>.The grid has now been saved.
- Choose *File* → *Attribute Files* → *Save splines with Intermediate Points* and save the splines with the name<scheldt01.spl> in folder *tutorial01*. The splines and the grid have now been saved.
- Choose *File* → *Save Project*.
- Close RGFGRID by choosing *File* → *Exit*

Folder <tutorial01\finished> contains splines and a grid for this tutorial exercise that has been prepared by Deltares.

Now your are back in the Delta Shell GUI. It appears that the land boundary is not visible anymore, because it was selected in RGFGRID. However, also in the Delta Shell GUI a land boundary can be activated via:

- Open *Area* under *Project1* →*FlowFM* →*Area*.
- Import the land boundary from <tutorial01\scheldtriver.ldb> by choosing *Import* via the right mouse button on *Project1* →*FlowFM* →*Area* →*Land Boundaries* (see Figure 19.9).
- Do not apply a coordinate transformation by pressing *OK*.

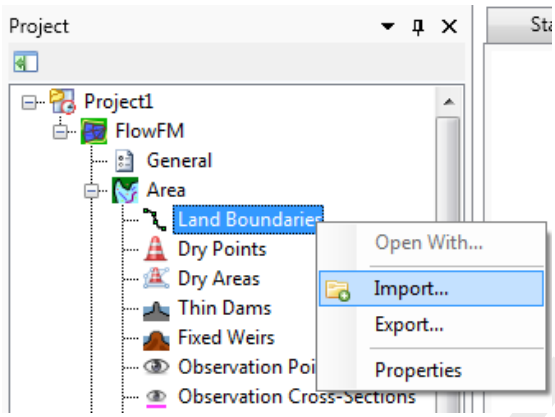


Figure 19.9: *Importing a land boundary*

Now the grid and land boundary are visible in the central map of the Delta Shell GUI, see Figure 19.10.

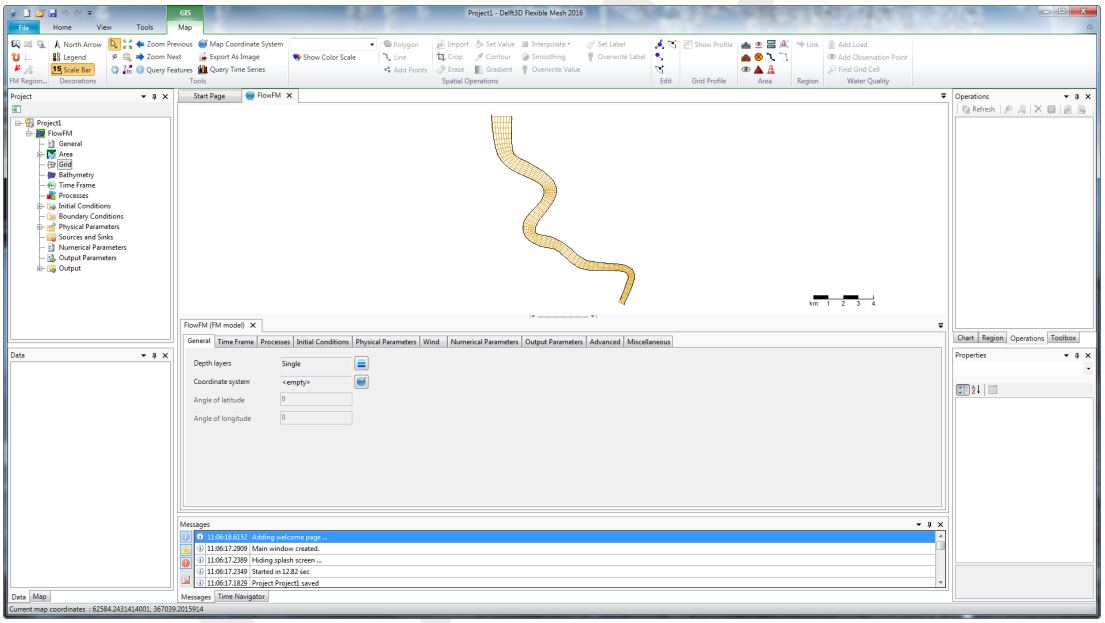


Figure 19.10: *After closing RGFGRID the grid is visible in the Delta Shell GUI.*

19.3 Tutorial 2: Creating a triangular grid

We will continue with the grid created in the previous tutorial for the Scheldt river. The river is separated from the harbour, west of the river, by a sluice. The small area between the sluice and the Scheldt will benefit from an unstructured grid because of its irregular geometry. The unstructured grid for this irregular geometry is created first in this section.

The following steps have to be carried out:

- Import the land boundary from <tutorial02\scheldtharbour.ldb> by choosing *Import* via the right mouse button on *Project1* →*FlowFM* →*Area* →*Land Boundaries* (see Figure 19.9). Do not apply a coordinate transformation, press *OK*.
- Import the grid file by choosing *Import* via the right mouse button on *Project1* →*FlowFM*

→*Grid*. Choose the grid file <scheldt01_net.nc> in the folder <tutorial02>.

➢ Start RGFGRID by double clicking on *Grid*, see Figure 19.4. Set the Coordinate System (if necessary), as has been explained in section 19.2 (Figure 19.4).

➢ Choose from the menubar *Edit* → *Polygons* → *New*. The intention is to mark the area of interest (i.e. the area for which we want to generate the grid) by means of a polygon, see Figure 19.11.

➢ Start drawing the polygon at a distance from the curvilinear grid that is similar to the width of the curvilinear grid cells (since we want to have a smooth transition in grid resolution). Specify the second point at a relatively small distance from the first one.This distance is later used as the first indication of the size of the triangular gridcells to be placed.

➢ Mark the characteristic locations of the area (follow the landboundary) and place the final points at the same distance away from the river grid as the first point. The distance between the last two points should be similar to the distance between the first two points. The result is shown in Figure 19.11.

➢ Choose *Edit* → *Polygons* → *Refine (linear)* and click on the first and last points of the polyline (in Figure 19.11 we would select point 1 first and then point 15). Now, the polygon is divided into a finer set of line elements (based on the length of the first and last segment of the polyline).

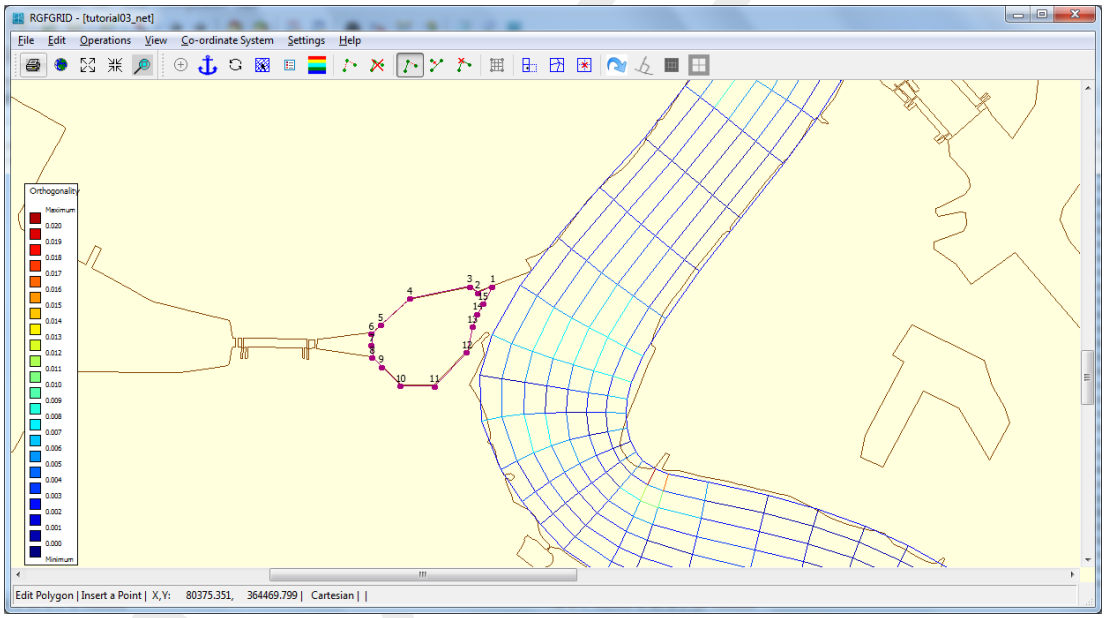


Figure 19.11: *Polygon that envelopes the area in which an unstructured grid is aimed to be established.*

Remarks:

◇ The distance between the points of the polygon is derived from the distance of the two polyline segments at both sides of the *selected* segment. The length of the polyline segments varies linearly from the segment length at the one side of the selected segment towards the segment length at the other side of the selected segment.

◇ You can play around to see how this works. If needed, you can add extra polyline points by choosing *Edit* → *Polygon* → *Insert point*. Choose *Edit* → *Polygon* → *Move point* if a point move would make sense.

◇ You can snap the refined polygon to the landboundary through *Edit* → *Polygons* → *Attach to Land Boundary*. Select two points for this.

Now we continue with this tutorial by carried out the following steps:

➢ Choose *Operations* →*Domain* →*New* to indicate that the new grid to be generated grid should be created next to the already existing one (and not replace it).

➢ Choose *Operations* → *Grow Grid from Polygons*. The result is shown in Figure 19.12.
➢ Improve the orthogonality through *Operations* → *Orthogonalise grid*. With the default settings also the smoothness is improved.

Since the solver only supports one grid, we need to merge the newly created grid with the original grid of the river. The newly created grid is currently selected. Next:

➢ Choose *Edit* →*Multi Select* and click on the river Scheldt grid to select it as well. After selection both grids should be coloured blue with black dots on the nodes.
➢ Choose *Operations* →*Grid* →*Merge Grids* to merge the nodes of the (two) highlighted grids. Now, the grids have been merged. However, nothing will visually change.

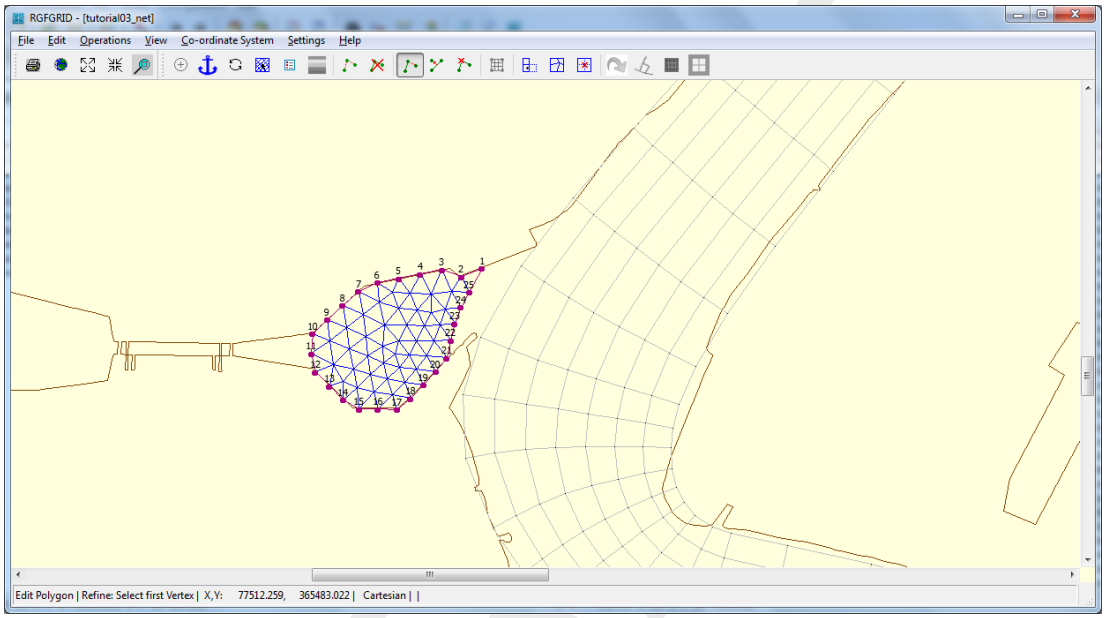


Figure 19.12: *Unstructured grid, after having refined the polygon.*

To save the grid and go back to the Delta Shell GUI:

➢ Choose from the menubar *File* → *Export* → *UGRID (D-Flow FM)...* and save it with name <scheldt02_net.nc> in the folder <tutorial02>. The grid has now been saved. We remark that folder <tutorial02\finished> contains a grid for this tutorial exercise that has been prepared by Deltares.
➢ Choose *File* → *Save Project*.
➢ Close RGFGRID by clicking on *File* →*Exit*.

19.4 Tutorial 3: Coupling multiple separate grids

From the previous tutorial we have ended up with two separate grids that are not connected yet. Obviously, these two grids should properly be integrated into one single grid. Before we can couple the two grids, we should first make sure that the typical grid size is of the same order of magnitude for both grids at the location where the connection is to be laid. Hence, basically two operations are to be done:

◇ Split the grid cells in the Scheldt river grid over the full width. Hence, the grid cell size in the river will match the gridcell size of the unstructured grid.
◇ Merge the two grids and put connections in between.

The splitting can be established as follows:

- Import the land boundary file <scheldtharbour.ldb> and the grid file <scheldt02_net.nc> from the folder <tutorial03> in DeltaShell under *Project1* →*FlowFM* →*Area* and *Project1* →*FlowFM* →*Grid*, respectively.
- Start RGFGRID and set the Coordinate System (if necessary), as has been explained in section 19.2 (Figure 19.4).
- Choose *Edit* → *Irregular Grid* → *Split Row or Column*.
- Select the locations where the grid lines should be split by clicking on the left boundary of the Scheldt river.
- Try to achieve the picture shown in Figure 19.13, in particular the typical grid size in the curved area. *N.B. Ignore the red lines in this picture for now!*

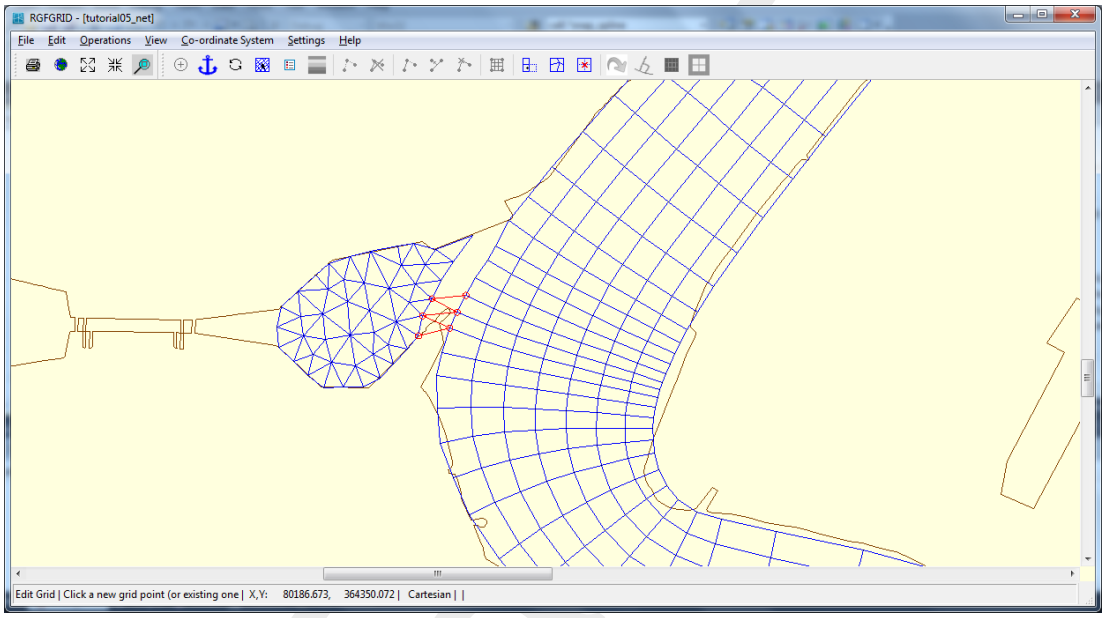


Figure 19.13: *Connection of the river grid and the unstructured grid. The red lines show the inserted grid lines used to couple the two grids manually.*

Connecting edges between the two parts of the grid can be created as follows:

- Since the two visually separate grid parts have already been merged into one logical grid in the previous tutorial, we can now physically connect them by laying new gridlines between them. Therefore, select *Edit* → *Irregular Grid* → *Insert Node*. Insert new gridlines in a zigzag-like style: see the red grid lines in Figure 19.13. Now, you will benefit from the (more or less) equal resolutions in the river and unstructured regions.
- Finally, you will end up with a picture like shown in Figure 19.14. You can visualize the orthogonality through *View* → *Grid Property Style* → *Coloured Edge* and *View* → *Grid property* → *Orthogonality*.

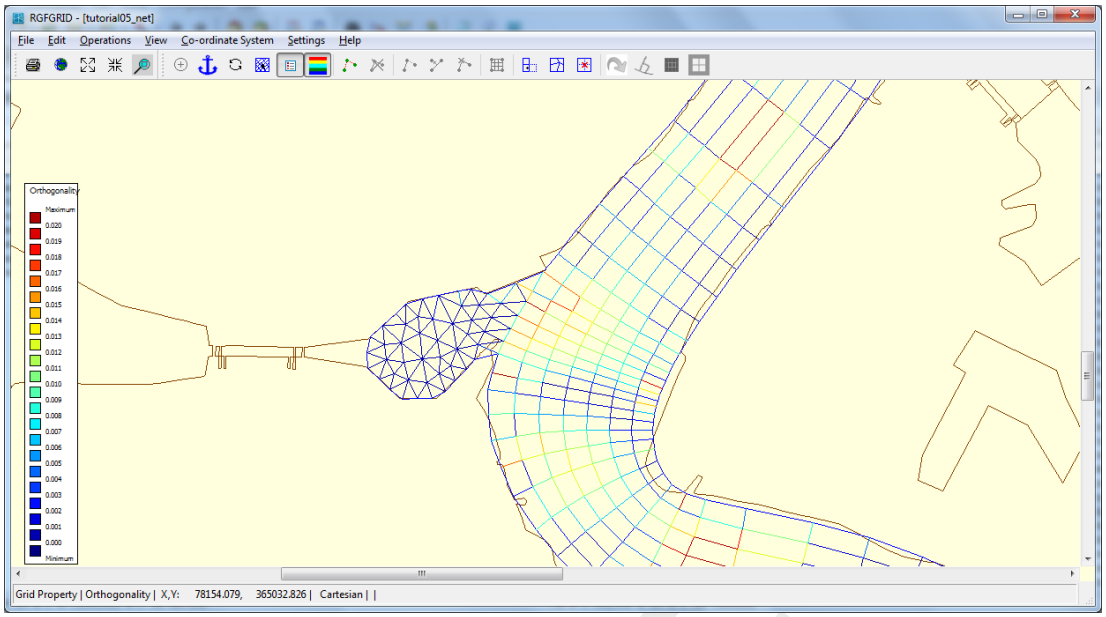


Figure 19.14: *Orthogonality of the integrated grid, containing the curvilinear part, the triangular part and the coupling between the two grids.*

To save the grid and close RGFGRID is done as follows:

- *File* → *Export* → *UGRID (D-Flow FM)...* and save the it with name <scheldt03_net.nc> in folder <tutorial03_result>.
  The grid has now been saved.
- Choose *File* → *Save Project*.
- Close RGFGRID by clicking on *Exit*.

19.5 Tutorial 4: Inserting a bed level

In previous tutorial exercises we focused on the grid generation. The next step is to couple the bed level data to the grid. The grid for this tutorial exercise is available in file <westernscheldt03_net.nc> in the directory <tutorial04>. A harbour has been added to the grid, as well as the Westerscheldt part at the North side. Bed levels are available in the file <westernscheldt_bed_level.xyz>.

The file with bed levels should first be projected onto the unstructured grid by means of interpolation. To this purpose, the following actions should be carried out:

- Start Delta Shell as already explained in previous tutorial exercises.
- Create a D-Flow FM model by choosing *New Model* → *Flow Flexible Mesh model* → *OK*.
  The project tree of a D-Flow FM model is shown in Figure 19.15.

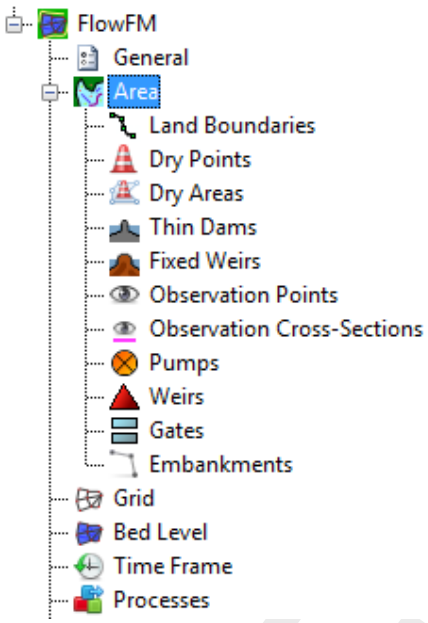


Figure 19.15: *Project tree.*

- Import the grid file by rightmouseclicking on *Grid* → *Import* (see Figure 19.15) and choose the available grid file <westernscheldt03_net.nc> from folder <tutorial04>,
- Import the land boundary file: *Area* by rightmouseclicking on *Land boundaries* → *Import* and import the land boundary file <sealand.ldb>, *Grid transformation* → *OK*,
- Import a sample file containing the measured bed levels: in the drop down menu at the top of the screen (See Figure 19.16), choose *Bed Level*. Then choose *Import* from the *Spatial Operators* menu, and select the file <westernscheldt_bed_level.xyz> which contains measured bed level data for the Westernscheldt, from the North Sea up to Antwerp, *Grid transformation* → *OK*.

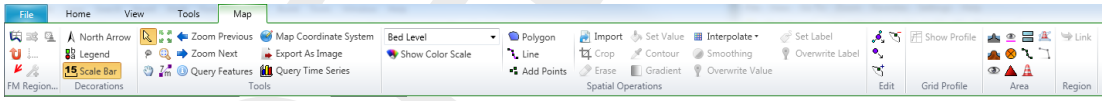


Figure 19.16: *Map-ribbon with the* Spatial Operations *menu.*

Now we are going to project the bed level data onto the nodes:

- Choose *Interpolate* (see Figure 19.16).
- Choose *interpolate selected set*.
- The window **Interpolation operation** appear. Select the *Overwrite* option for *Pointwise operation*, then press *OK*. The result will look like Figure 19.17. If you do not see a colorbar, click *Show Color Scale* (see Figure 19.16).

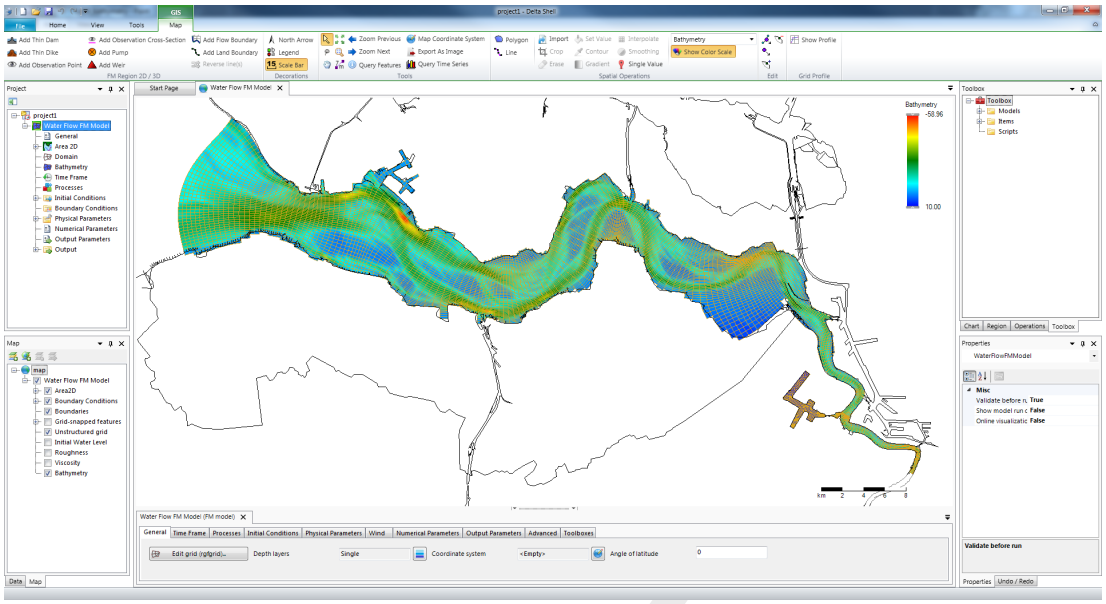


Figure 19.17: *Interpolated bed levels values at the grid (estuary).*

- Have a look at the sluice and the docks of the harbour. You can see that the bed level in this area is unrealistically high. This unrealistic value has been assigned because of undesired extrapolation, since no bed level data has been available in this area. To repair this, first draw a polygon that envelops the sluice and the docks. Do this by clicking *Polygon* (see Figure 19.16). The resulting polygon can be observed in Figure 19.18.
- Choose *Set value* (see Figure 19.16): specify an appropriate value, for instance “-10” m. The result will look like as shown in Figure 19.18.

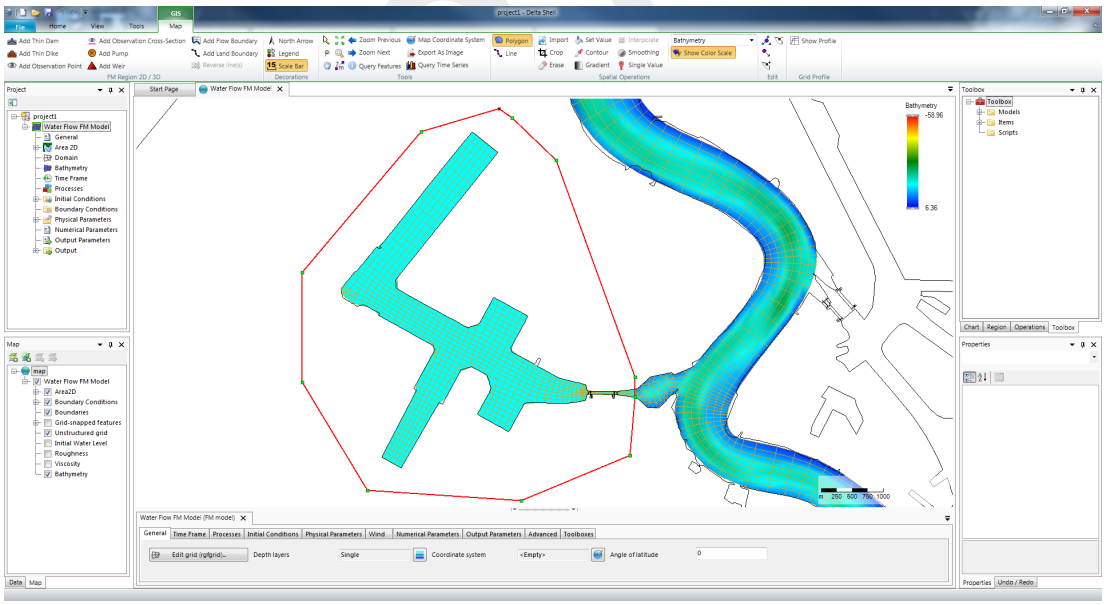


Figure 19.18: *Interpolated bed levels values at the grid (harbour).*

N.B. The mesh file (<∗_net.nc>) will contain the grid together with the bed level data in the nodes.

To save the mesh and bed level, and save the model within the Delta Shell GUI the following should be done:

➢ To save the mesh file you have to rightmouseclick on *Grid* → *Export* in the project bar. Choose *Grid exporter* and save the file as <westernscheldt04_net.nc> in folder *tutorial04*.The grid including the bed level has now been saved.
➢ To close Delta Shell click on *File* → *Exit*. Then, the following question arises: "Save changes to the project: Project?" Click on *No*. Now, the current D-Flow FM model has now been closed.

Folder <tutorial04\finished> contains a bed level for this tutorial exercise that has been prepared by Deltares.

19.6 Tutorial 5: Imposing boundary conditions

Along both the sea boundary and the Scheldt river boundary, appropriate boundary conditions have to be imposed. The boundary conditions can be prescribed in many ways, for instance as water levels, velocities (tangential and normal direction), discharge and Riemann. In this tutorial exercise we will impose boundary conditions for the Western Scheldt in the following way:

◇ At the sea boundary: a periodic water level boundary, described as a harmonic signal with a mean 0.5 m+NAP, an amplitude 2.5 m and a frequency of 28.984 $°h^{-1}$,
◇ At the river boundary: a constant discharge boundary, described by a constant 2500 $m^3 s^{-1}$.

Let us start with a new D-Flow FM model and import the network and land boundaries, which is done as follows:

➢ Click on *New Model* → *Delft3D Flexible Mesh Model* → *OK*.
➢ Load the grid file from the folder <tutorial05> by rightmouseclicking on *Grid* → *Import* (see Figure 19.15) and select file <westernscheldt04_net.nc>.
➢ Import the land boundary file via *Project1* →*FlowFM* →*Area* (see Figure 19.15) by rightmouseclicking on *Land boundaries* → *Import* and import the land boundary file <sealand.ldb>, *Grid transformation* → *OK*.

In order to define boundary conditions one has to follow this strategy:

1 draw a polyline along the boundary;
2 fill a file with essential information;
3 link the boundary files with the model setup.

The boundary conditions can be imposed as follows:

➢ Choose *Add (2D) Flow Boundary* (top of screen, see Figure 19.19) and insert a polyline along the sea boundary. To close the polyline, doubleclick. In the Project bar at the left, under *Boundary Conditions*, this boundary has now been added. Figure 19.19 shows how this will look like.
Tip: to remove a wrongly placed point in the polyline, use *Remove point from geometry* (top of screen, above *Edit*, see Figure 19.16). It is also possible to replace or add a point.

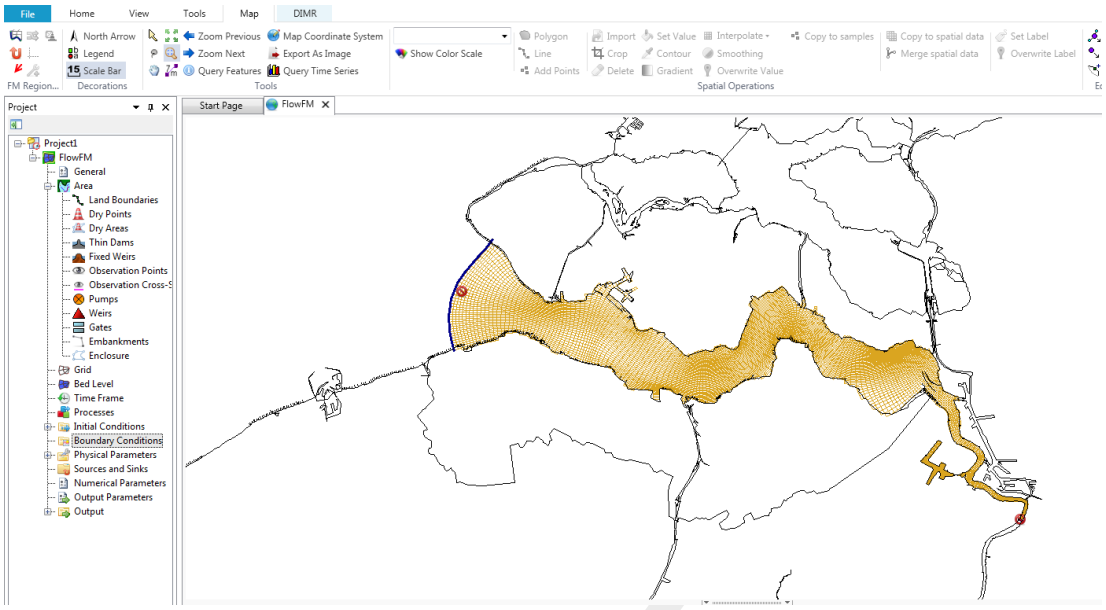


Figure 19.19: *Location of the two open boundaries at the sea and river side.*

- Draw another polyline at the river entrance south of Antwerp, see the right bottom corner of Figure 19.19).
- To impose boundary conditions at the seaboundary, double click at *Boundary01*, see Figure 19.20.

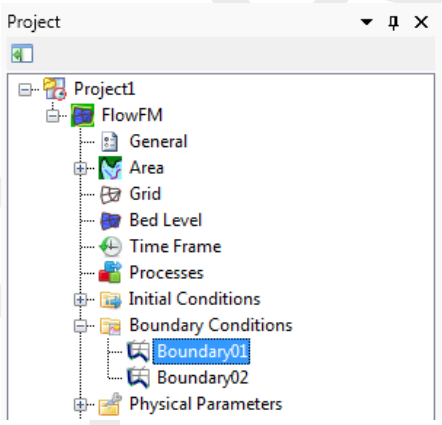


Figure 19.20: *Selection of Boundary01.*

- Choose *Water level*, press + and choose *Forcing type: Astronomical*.
- Selected the first boundary support point *Boundary01_0001* by clicking on the plus-sign behind it, repeat this for the last boundary support point.
- Choose *Select components. . .* (at the lefthandside of the screen).
- Choose the components *A0* and *M2*, and press *OK*,
- Select *All support points* and press *OK*. All support points will now have components *A0* and *M2* defined.
- Fill in the amplitudes of the components in the table, see Figure 19.21.

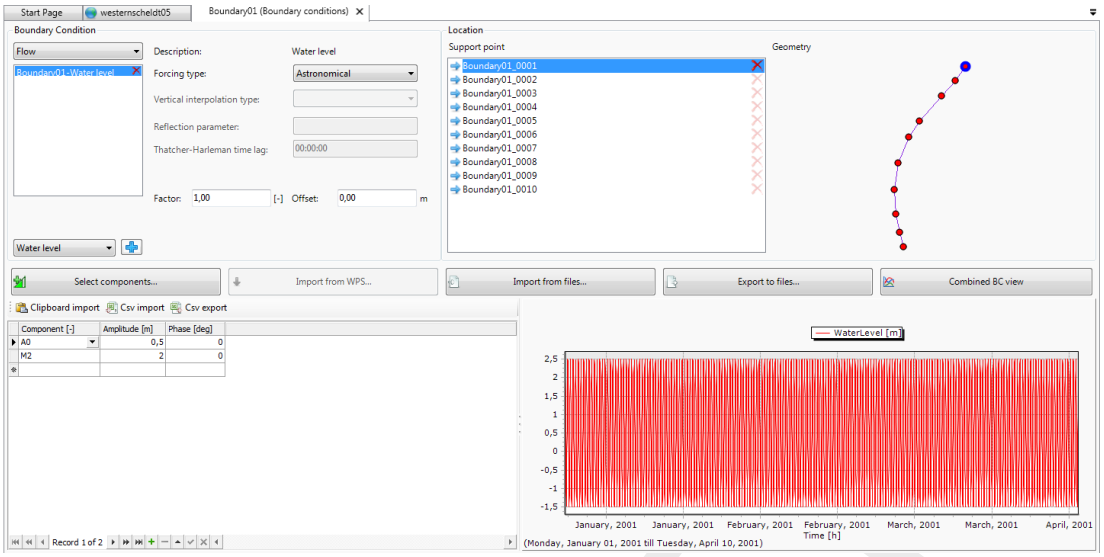


Figure 19.21: *Boundary conditions seaside.*

We have now prescribed an astronomical water level signal, consisting of two components. The first component has an amplitude equal to 0.5 m with a frequency of 0 degrees/hour, i.e. a constant value of 0.5 m+NAP. The second component has an amplitude of 2.5 m with a frequency of 28.984 degrees/hour. Basically, the signal $h(t) = 0.5 + 2.5\ \cos(28.984\, t)$ has been prescribed now, with h in meters w.r.t. the reference level (in case: NAP) and t in hours.

➢ To impose boundary conditions at the riverboundary, double click at *Boundary02*, Choose *Discharge* and press *+*. Choose *Forcing type: Time Series*.

➢ To impose a contant discharge of 2500 $m^3\ s^{-1}$, fill in the table like Figure 19.22. Make sure you insert the same times!

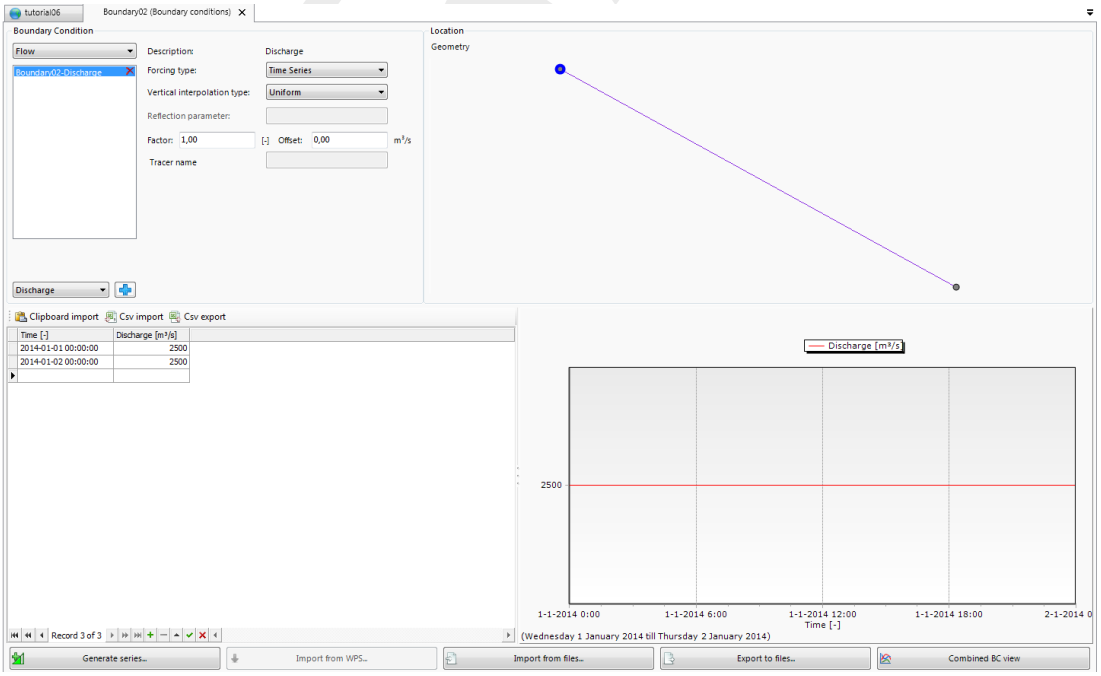


Figure 19.22: *Boundary condition riverside.*

To be able to load this D-Flow FM model in the future, it is necessary to save the model:

- In the project tree, rightclick on *FlowFM* and select *Rename*. Rename the model to “westernscheldt05”.
- Save the model in folder <tutorial05_result>. In the project tree rightclick on *westernscheldt05*. Choose *Export* select *Flow Flexible Mesh model*, press *OK* and save the model as <westernscheldt05>.

The model might now be loaded in the next tutorial exercise, without inserting all network files or land and flow boundaries individually again.

- Now close the D-Flow FM model by rightmouseclicking In the project bar on *westernscheldt05* → *Delete* → *OK*.

19.7 Tutorial 6: Defining output locations

Often one would like to monitor computational results at certain specific cross-sections or locations (i.e. ’observation points’). In this tutorial exercise we will add cross-sections and observation points in a D-Flow FM model.

We will start with importing an existing D-Flow FM model without cross-sections and observation points:

- Import the D-Flow FM Model from the folder <tutorial06> by choosing (in the top ribbon) *Import* → *Flow Flexible Mesh Model* and press *OK*. Then choose <westernscheldt05.mdu> and click on *Open*.

Inserting cross-sections and observation points is rather straightforward. The following actions are necessary, in which we start with inserting cross sections:

- Choose *Add Observation Cross-Section (2D)* (see item *Area* in the ribbon).
- Draw as many cross-sections as you like. Finalize each cross-section by doubleclicking the left mouse button.
- To view how many cross sections have been made, double click on *Area* → *Observation Cross-Sections*, see Figure 19.23.

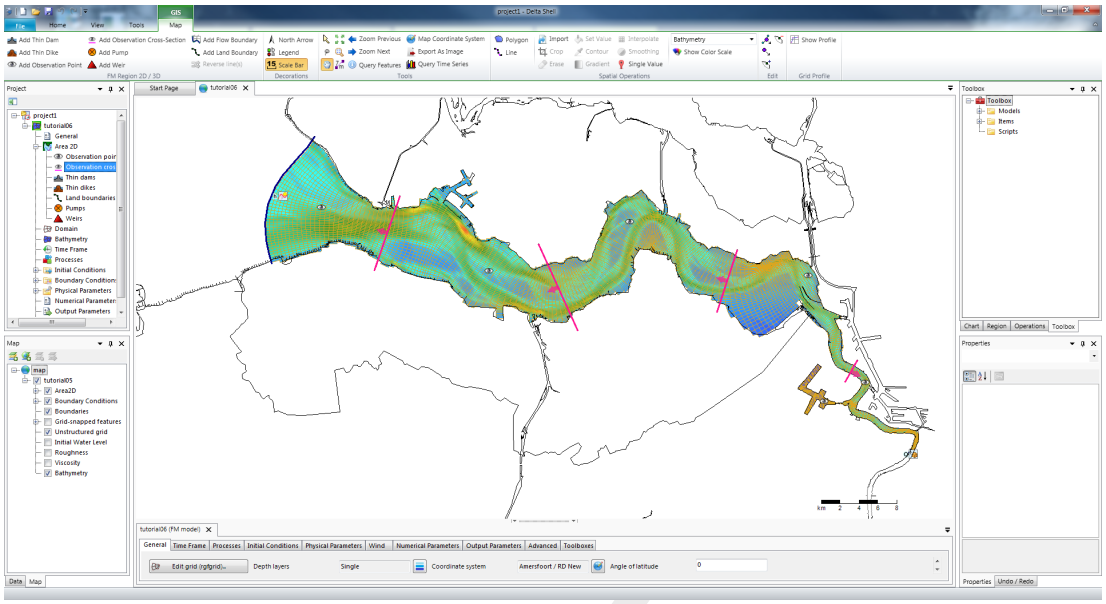


Figure 19.23: *Overview cross sections and observation points.*

Now we will add observation points:

- Choose *Add Observation Point*. Draw as many observation points as you like.
- To view how many observation points have been made, double click on *Area* → *Observation points*.
- Save the current FM model in the folder <tutorial06> by rightmouseclicking in the project tree on *westernscheldt05*.
- Choose *Export*, choose *Flow Flexible Mesh Model* and press *OK*, then save the model with name “westernscheldt06”). The observation points and cross sections have now been saved in the new <mdu>-file.
- **Tip**: It is also possible to save only the observations points for instance to a certain folder. To try this, rightmouseclick on *Observation points* → *Export* → *Observation points to <xyn>-file*. Then, choose a filename and a folder.
- Close the current Flexible Mesh model by rightmouseclicking In the project bar on *westernscheldt05* → *Delete* → *OK*.

19.8 Tutorial 7: Defining computational parameters

Before we can run the model, all computational parameters need to be set. For example, this involves the *Time Frame*, *Initial Conditions* and the *Output Parameters*. These can be specified in the grey box at the bottom of Delta Shell. All other parameters are set by default, and will not be consider in this tutorial exercise.

We will start with importing an existing D-Flow FM model:

- Import the D-Flow FM Model from the folder <tutorial07>, by choosing *Home* → *Import* → *Flow Flexible Mesh Model* → *OK*. Choose <westernscheldt06.mdu> and press *Open*.

Several parameters will be set. We will start with the *Time Frame*, see Figure 19.24:

- At the Time Frame section: fill in the parameters of Figure 19.24.

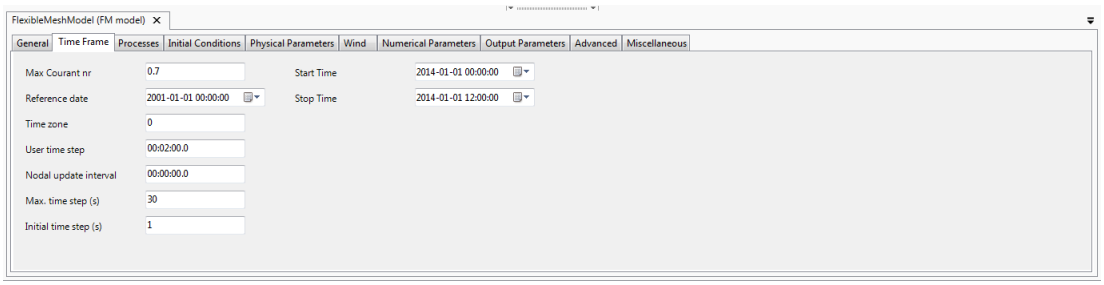


Figure 19.24: *The time frame of the simulation.*

➢ At the Initial Conditions section: fill in “0.5” m for the Initial water level, see Figure 19.25.

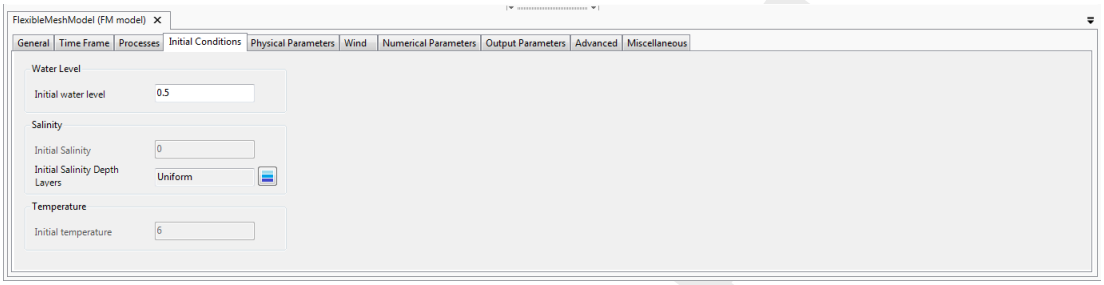


Figure 19.25: *Imposed initial conditions for the simulation.*

➢ At the Output Parameters section: fill in the parameters of Figure 19.26.

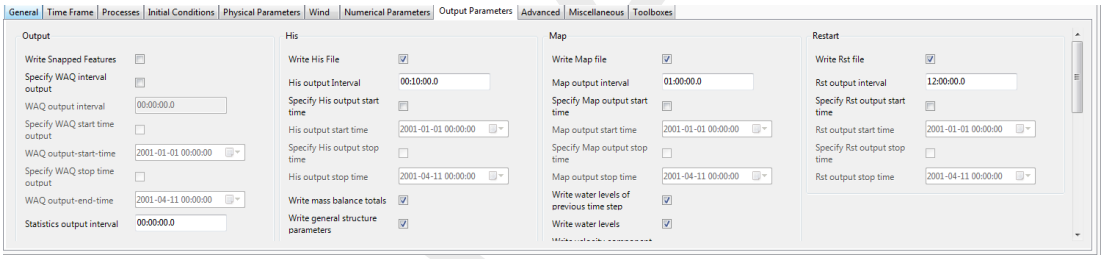


Figure 19.26: *Optional output parameters for the computation.*

As an explanation, the computation will generate history-files and map-files:

- ◇ In history-files, timeseries are stored at the cross-sections and observation locations, at a frequency specified via the parameter *His Output Interval*.
- ◇ The map-files collect data over the entire domain, at a frequency specified via the parameter *Map Output Interval*.

  Note: Be aware that these periods are clipped by the parameter *User time step*, which has been specified under *Time Frame*. That means, if *User time step* $>$ *His Output Interval*, then the period with which his-files are written is given by *User time step*.
- ◇ Restart files will be written when *Write Rst File* is selected.
  The period with which these files are written can then be specified at *Rst Output Interval*. This period is not clipped by *User time step*. To start a computation with a restart file is not part of this tutorial.

➢ Save the current D-Flow FM model in the folder <tutorial07> by rightmouseclicking in the project tree on *westernscheldt06*, choose *Export* and save the model as <westernscheldt07>.

The computational parameters have now been saved in the <mdu>-file.

➢ Now close the current FM model (In the project bar, rightmouseclick on *westernscheldt06* → *Delete* → *OK*).

19.9 Tutorial 8: Running a model simulation

Up till now we have saved the D-Flow FM model by means of a <mdu>-file. For running computations, it is necessary to save the entire project, which will be done in this tutorial exercise:

➢ Import the D-Flow FM Model from the folder <tutorial08>, by choosing *Import* → *Flow Flexible Mesh Model* → *OK*. Choose <westernscheldt07.mdu> and *Open*.

For saving the entire project, the following should be done:

➢ Choose *File* → *Save As* to save <tutorial08.dsproj> in the folder <tutorial08> and click *Save*.
The project has now been saved in a folder called <tutorial08\tutorial08.dsproj_data> and a project file <tutorial08\tutorial08.dsproj> has been created (See Figure 19.27).
Within this folder you will find all input files of the model (some are ASCII), output files of the model (when it has been run) and, if applicable, zip-folders containing the restart files.

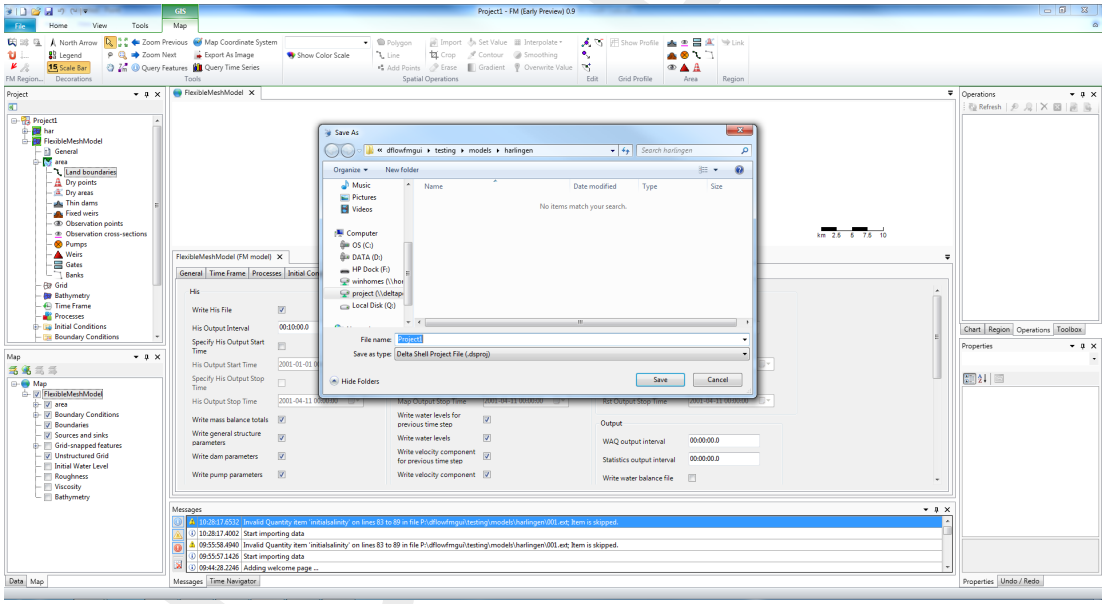


Figure 19.27: *Menu for saving a project.*

To start a computation, the following needs to be done:

➢ In the project tree select the model you want to run by means of clicking the first attribute of the desired model (which has been named *westernscheldt07*, see Figure 19.28).

Choose *Run Model*. Now, the simulation will start running.

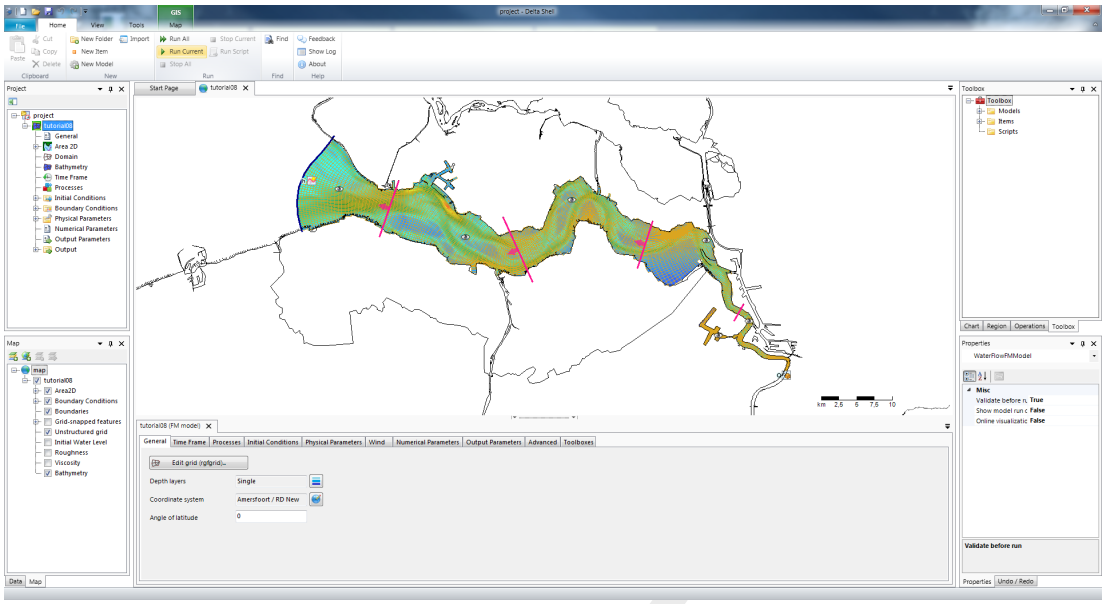


Figure 19.28: *View of Delta Shell when running a model.*

The output of the run is being stored in the folder *tutorial07\finished*. Now:

- Save the project with generated output in the folder <tutorial08> (*File* → *Save As* and save the project with name “tutorial08.dsproj”). Press *Yes* to overwrite the project.
- Now close the current D-Flow FM model (In the project bar, rightmouseclick on *westernscheldt07* → *Delete* → *OK*).

19.10 Tutorial 9: Viewing the output of a model simulation

The output of the model can be observed within Delta Shell. At first a project has to be imported:

- Choose *File* → *Open*. Select the file <tutorial9.dsproj> from the folder <tutorial09> and choose *Open*. The project is now activated.
- Doubleclick on *westernscheldt07*.

To view the output of the history files (observation points and cross-sections):

- Click with leftmousebutton on an observation point (while being in *select* mode. Your mouse looks like an arrow in this mode).
- Choose at the top part of the screen *Query Time Series*, see Figure 19.29 (option available within the Map-ribbon).

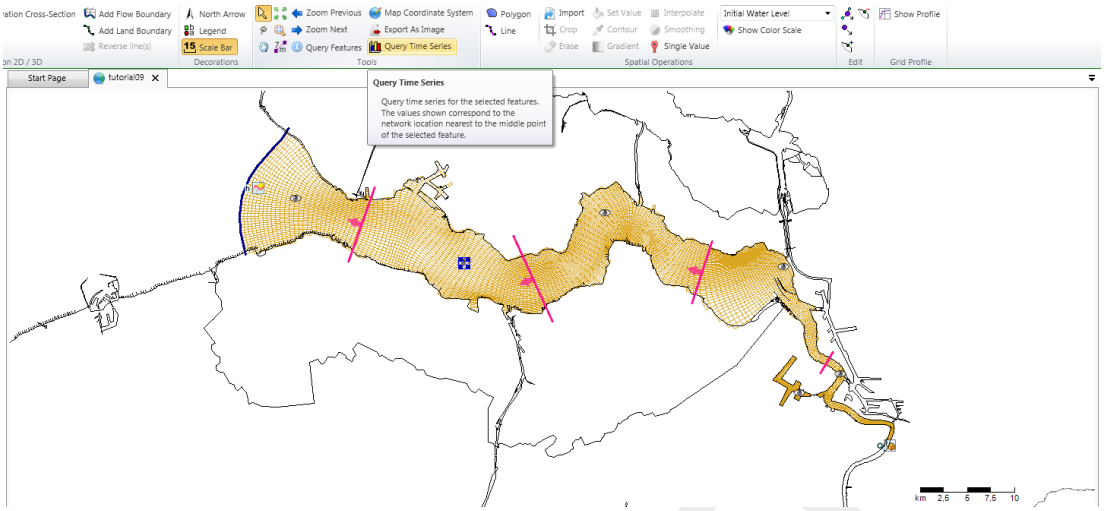


Figure 19.29: *View of Delta Shell, available to select a location for timeseries in.*

➢ Choose *Water level (waterlevel)* → *OK*. You can now observe the water levels in the observation point you selected, see Figure 19.30. You can choose other parameters as well to observe. Also cross-sections can be observed this way.

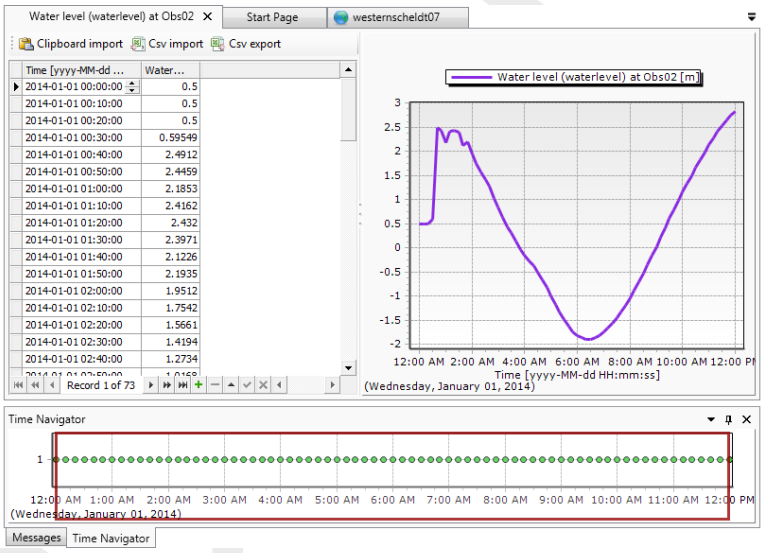


Figure 19.30: *View of Delta Shell, time-series for observation point "Obs03".*

To view the output of the map files:

➢ Open the Time Navigator, by choosing from the ribbon *Time Navigator*. The Time Navigator will appear at the bottom of Delta Shell.
➢ If necessary; select, below the Data window, the tab *Map* (lower left corner of the main window).
➢ Choose in the Map-tree *Add New Wms Layer* (see Figure 19.31) and choose *http://openstreetmap.org*.

Figure 19.31: *WMS layer icon at the top of the map-tree viewer.*

Now, the model can be observed with OpenStreetMap in the background. See Figure 19.32.

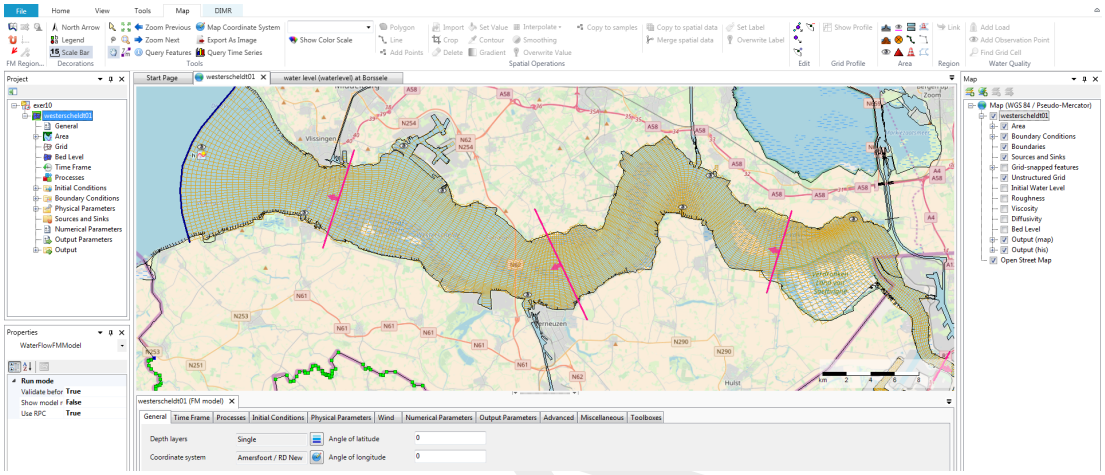


Figure 19.32: *View of Delta Shell in combination with OpenStreetMap.*

➢ Open *Output* in the map tree to the left. Choose *waterlevel(s1)* to observe water levels, see Figure 19.33.

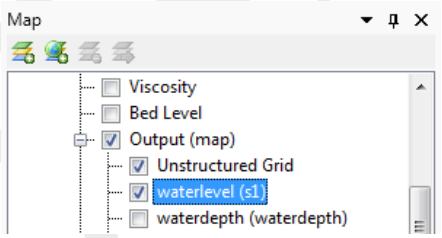


Figure 19.33: *Select* waterlevel(s1) *from the map tree*

➢ To adjust the legend, rightmouseclick on *Output(map)* →*waterlevel (s1)* and select *Properties*. Now the window **Layer Properties Editor** appears in which the legend can be adjusted.
➢ Set classes to “11”
➢ Select *Custom range* and set the legend values for minimum and maximum value to “-2.5” to “-0.5”.
➢ Press *Generate*
➢ Press *OK*, see Figure 19.33.
➢ Click the play button in the *Time Navigator* to check whether the water levels change in time. Choose another parameter, e.g. water depth, to observe afterwards too.
➢ Now close the current D-Flow FM model (In the project bar, rightmouseclick on *westernscheldt07* → *Delete* → *OK*).

20 Calibration and data assimilation

Note: Calibration of D-Flow FM with OpenDA is a β-functionality.

20.1 Introduction

A flow model in D-Flow FM will generally benefit from parameter *calibration* to closer match observation data. When the model runs in an operational system *data assimilation* can be used to into the running model. For the automatic calibration and data assimilation, the open source toolbox **OpenDA** is available.

OpenDA basically provides three types of building blocks: an optimisation algorithm that performs the calibration or data assimilation, communication routines for passing information between OpenDA and D-Flow FM, and methods for handling observation data. The communication between OpenDA and D-Flow FM is realised using a Black Box approach. A number of wrapper objects (so called dataObjects) are available for reading and writing D-Flow FM input and output files.

This chapter contains a description of how the OpenDA toolbox could be deployed to apply calibration and data assimilation. The OpenDA tools can run D-Flow FM models and analyze the model results. A more extensive design description of the D-Flow FM wrappers for OpenDA can be found in the D-Flow FM TRM (2015).

More information on OpenDA can be found on the website `http://www.openda.org`.

General information on the installation of OpenDA to get started is provided in section 20.2. section 20.4 gives an overview of the black box wrapper for D-Flow FM. section 20.4 describes the OpenDA configuration and the related D-Flow FM files. The generation of noise and how this noise is added to forcings and boundaries is given in section 20.5. Examples case for calibration and data assimilation using the ensemble Kalman filter are described in section 20.6.

20.2 Getting started with OpenDA

The required D-Flow FM wrapper is enclosed in the official OpenDA release since version 2.2.2. The following three elements are needed for a calibration or data assimilation run with D-Flow FM:

1. The D-Flow FM Command Line Interface (CLI) installation. All OpenDA algorithms start D-Flow FM with a shell script `start_dflowfm.sh` or a batch script `start_dflowfm.bat`. Both scripts assume that D-Flow FM executable is available on the search path (i.e. it should be executable from the command line). If this is not the case change the environment variable `PATH` to include the installation path of the D-Flow FM executable.
2. An OpenDA installation including the OpenDA core, the D-Flow FM specific wrapper code and examples.
3. A Java Runtime Environment (JRE) version 7 (or higher) is needed to run OpenDA (2.2.2). OpenDA can use one of the system installed JREs or alternatively an JRE can be installed directly in the OpenDA directory at the same level as the <bin> directory.

For Linux it is required to run `source settings_local.sh` to setup OpenDA. The OpenDA GUI can be started from the <bin> directory using `oda_run_gui.bat` (Windows) or `oda_run.sh` with the `-gui` command line option (Linux).

20.3 The OpenDA black box model wrapper for D-Flow FM

For a D-Flow FM model to function within the OpenDA toolbox we need to establish two things:

1 the control to propagate the model over time and
2 access to the model state, physical parameters, boundary conditions and external forcings.

In the black box approach the standard D-Flow FM command line executable is used to propagate the model over time. Access to the model state, physical parameters, boundary conditions and external forcings is obtained by reading from and writing to the D-Flow FM input and output files. Inside OpenDA all data is available in the form of exchange items which all have an unique identifier.

Calibration and data assimilation typically need multiple model evaluations with altered parameters, forcings, boundary conditions or the initial model state. In the black box approach this is achieved by creating multiple work directories containing altered model input files and starting the D-Flow FM executable in each work directory. D-Flow FM model results are than read from the work directories and compared to observation data.

For calibration this is an iterative process. Results from model evaluations $1, \ldots, n$ are required to obtain a better estimate for parameter values, which are then evaluated in run $n+1$.

In case of an ensemble Kalman filter (EnKF) run, the D-Flow FM computations (one run for each ensemble member) is stopped each time an observation is available, the input files for each ensemble member are modified according to the ensemble Kalman filter algorithm, after which the D-Flow FM run is restarted.

Next to the D-Flow FM model configuration OpenDA has its own configuration for selecting the algorithm, observations and interfacing with the D-Flow FM input an output files.

20.4 OpenDA configuration

20.4.1 Main configuration file and the directory structure

The OpenDA main configuration file has the `.oda` extension. All OpenDA configuration files use the xml format. It is advised to use a schema aware xml editor, when making changes to the OpenDA configuration. These editors provide direct access to the documentation that is stored in the schema and can validate the correctness of the xml files.

All other xml config file names and directories are configurable. However, there is a commonly used directory layout and naming convention. All the examples are configured using this convention. For example, the directory structure for the simple_waal_kalman example is given in Table 20.1.

All the work directories are available in the <stochModel> directory, after performing a run with OpenDA they contain the D-Flow FM results.

It is a good practice to name the main configuration file corresponding to the algorithms executed by OpenDA. The following files are used in the provided examples:

- ◇ <Simulation.oda>: performs a regular D-Flow FM simulation run, only the executable is started by OpenDA. This algorithm is useful to check the configuration.
- ◇ <Dud.oda>: Dud (Doesn't Use Derivative) is one of the optimisation algorithms available for calibration purposes.

```
<simple_waal_kalman>
├── <algorithm> ..... calibration method or data-assimilation algorithm
│   ├── <enkfAlgorithm.xml> ..... algorithm specific configuration
│   └── ...
├── <stochModel> ..... model and its uncertainty description
│   ├── <bin> ..... .bat and .sh scripts for calling D-Flow FM
│   ├── <input_dflowfm> ..... D-Flow FM template configuration
│   │   └── ...
│   ├── <work0/> ..... work directory for propagated mean
│   ├── <work1/> ..... work directory for first ensemble member
│   ├── ...
│   ├── <dflowfmModel.xml> ..... exchange items configuration
│   ├── <dflowfmStochModel.xml> ..... predictor, state and parameter
│   ├── <dflowfmWrapper.xml> ..... actions and data objects configuration
│   └── ...
├── <stochObserver> ..... observations and uncertainty
│   ├── <noosObservations.xml> ..... observations and uncertainty
│   ├── <waterlevel_Obs01.noos> ..... raw observation file
│   └── ...
├── <Enkf.oda> ..... main configuration file
└── ...
```

Table 20.1: *Directory structure of the OpenDA Ensemble Kalman filtering configuration for the simple Waal D-Flow FM model.*

- ◇ <SequentialSimulation.oda>: performs a D-Flow FM simulation run through which the executable is stopped and restarted by OpenDA at the moments for which observed data are available.
- ◇ <Enkf.oda>: performs an ensemble Kalman filtering.

The main configuration for an OpenDA application has three mandatory components, which make up an OpenDA application: `stochModelFactory`, `stochObserver` and `algorithm`. Each component is configured by specifying its `className` attribute, `workingDirectory` and `configFile/configString`. There are optional components to enable writing OpenDA results, to define OpenDA restart input and output files and to enable timings. The `resultwriter` is typically useful for writing stochastic properties that are only available to OpenDA and not in D-Flow FM.

The main configuration file <Enkf.oda> for the `simple_waal` example:

```
<?xml version="1.0" encoding="UTF-8"?>
<openDaApplication
  xmlns="http://www.openda.org"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation
    ="http://www.openda.org http://schemas.openda.org/openDaApplication.xsd">
 <stochObserver className="org.openda.observers.NoosTimeSeriesStochObserver">
  <workingDirectory>./stochObserver</workingDirectory>
  <configFile>noosObservations.xml</configFile>
 </stochObserver>
 <stochModelFactory className="org.openda.blackbox.wrapper.BBStochModelFactory">
  <workingDirectory>./stochModel</workingDirectory>
  <configFile>dflowfmStochModel.xml</configFile>
 </stochModelFactory>
 <algorithm className="org.openda.algorithms.kalmanFilter.EnKF">
  <workingDirectory>./algorithm</workingDirectory>
  <configString>EnkfAlgorithm.xml</configString>
```

```
 </algorithm>
 <resultWriter className="org.openda.resultwriters.MatlabResultWriter">
   <workingDirectory>.</workingDirectory>
   <configFile>Enkf_results.m</configFile>
   <selection>
     <resultItem id="pred_f"/>
     <resultItem id="pred_f_0"/>
     <resultItem id="pred_f_1"/>
     <resultItem id="pred_f_std"/>
     <resultItem id="pred_f_central"/>
     <resultItem id="pred_a_linear"/>
     <resultItem id="analysis_time"/>
     <resultItem id="obs"/>
   </selection>
 </resultWriter>
</openDaApplication>
```

Note that the directory layout in this section is created by setting the `workingDirectory` elements in `stochModelFactory`, `stochObserver` and `algorithm` parts of the configuration. Each of these components have their own configuration, which are described in the following sections.

20.4.2 The `algorithm` configuration

All provided methods for calibration and data assimilation are configurable through an xml file. The convention is to include the algorithm name in the fila name e.g <EnkfAlgorithm.xml>. For data assimilation algorithms the configuration typically specifies the ensemble size and the option to use stochastic parameters, forcing and initialisation. For calibration algorithms the configuration typically contains definition of the cost function and tolerances and stopping criteria. For a list of algorithms and their configuration options see the general OpenDA documentation.

20.4.3 The `stochObserver` configuration

The access to observations is standardized in OpenDA using a `stochObserver` object. The configuration and the observation data are placed in the <stochObserver> directory. OpenDA contains a number of different `stochObserver` objects that can handle different types of data files. In this manual, we discuss the `NoosTimeSeriesStochObserver` and the more generic `IoObjectStochObserver`. For a more complete list of available `stochObservers` see the OpenDA web site.

20.4.3.1 NoosTimeSeriesStochObserver

The NOOS file format is used to store time series. The format is created for use by the members of the North West European Shelf Operational Oceanographic System `http://www.noos.cc/`. An example of (a part of) a NOOS file is:

```
#-------------------------------------------------------
#-------------------------------------------------------
# Location : station01
# Position : (0.0,0.0)
# Source : twin experiment DFlowFM
# Unit : waterlevel
# Analyse time: null
# Timezone : null
#-------------------------------------------------------
199101010000   1.0000
199101010100   0.8944
199101010200   0.6862
```

```
199101010300   0.5956
199101010400   0.3794
199101010500   0.1372
199101010600   -0.1300
199101010700   -0.3044
199101010800   -0.3963
199101010900   -0.3739
199101011000   -0.1930
...
```

The file contains a header with meta data specifying among others the location name (`Location`) and the quantity (`Unit`). The data is written in two columns, the first gives the time of the observation using the '`YYYYMMDDhhmm`' format and the second column gives the measured value.

The file <noosObserver.xml> defines a number of time series, each coupled to a NOOS file containing the measurements.

```
<?xml version="1.0" encoding="UTF-8"?>
<noosObserver
  xmlns="http://www.openda.org"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation
    ="http://www.openda.org http://schemas.openda.org/schemas/noosObservations.xsd">
 <timeSeries status="use" standardDeviation="0.05">
  den_helder_waterlevel_astro.noos
 </timeSeries>
 <timeSeries status="use" standardDeviation="0.05">
  aberdeen_waterlevel_astro.noos
 </timeSeries>
</noosObserver>
```

OpenDA creates an exchange item for each observation time series. The default exchange item id (identifier) is created using the location (`Location`) and the quantity (`Unit`). The standard deviation (measurement error) is specified with `standDeviation` attribute.

20.4.3.2 IoObjectStochObserver

This observer uses a dataObject for handling the file IO. All exchange items that are provided by dataObject can be used by the observer. For instance the NetcdfDataObject can read and write to NetCDF files, and has an exchange item for each variable in the NetCDF file. The `lake_kalman` example uses this approach to use the `*.his` file from a D-Flow FM run as synthetic observations for a ensemble Kalman filter run. The <dflowfmStochObsConfig.xml> file reads:

```
<?xml version="1.0" encoding="UTF-8"?>
<ioObjectStochObserver
  xmlns="http://www.openda.org"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation
    ="http://www.openda.org http://schemas.openda.org/openDaStochObserver.xsd">
 <uncertaintyModule
    workingDirectory="."
    className="org.openda.uncertainties.UncertaintyEngine">
  <arg>stochObsUncertainties.xml</arg>
 </uncertaintyModule>
 <ioObject
    workingDirectory="."
    className="org.openda.exchange.dataobjects.NetcdfDataObject">
  <fileName>lake2d_his.nc</fileName>
 </ioObject>
```

```
</ioObjectStochObserver>
```

In the configuration of `UncertaintyEngine` OpenDA object, a selection of these exchange items `id`'s is made and a standard deviation is specified.

```
<?xml version="1.0" encoding="UTF-8"?>
<uncertainties
   xmlns="http://www.wldelft.nl"
   xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
   xsi:schemaLocation
     ="http://www.wldelft.nl http://schemas.openda.org/uncertainties.xsd"
   version="1.0">
 <uncertaintyType>ProbabilityDistributionFunction</uncertaintyType>
 <probabilityDistributionFunction id="S1.waterlevel" isActive="true">
   <normal mean="0" stdv="0.05" stdvIsFactor="false"/>
 </probabilityDistributionFunction>
 <probabilityDistributionFunction id="S2.waterlevel" isActive="true">
   <normal mean="0" stdv="0.05" stdvIsFactor="false"/>
 </probabilityDistributionFunction>
 <probabilityDistributionFunction id="S3.waterlevel" isActive="true">
   <normal mean="0" stdv="0.05" stdvIsFactor="false"/>
 </probabilityDistributionFunction>
 <probabilityDistributionFunction id="S4.waterlevel" isActive="true">
   <normal mean="0" stdv="0.05" stdvIsFactor="false"/>
 </probabilityDistributionFunction>
</uncertainties>
```

20.4.4 The `stochModel` configuration

The stochModel configuration usually consists of three <∗.xml> files in the <stochModel> directory. These are called:

- <dflowfmWrapper.xml>: This file specifies the actions to perform in order to run a D-Flow FM simulation and list the D-Flow FM input and output files that can be used to let OpenDA interact with the model. For each file the dataObject is specified which is used for handling the specified file.
- <dflowfmModel.xml>: This file contains a list of the exchange items which are provided by the configured dataObject. The model time information is constructed by the `timeInfoExchangeItems` element. It also contains a number of alias values which can be used in three stochModel configuration files.
- <dflowfmStochModel.xml>: In this file defines the predictor, the selection of observations which are compared to the model results. For calibration this file also specifies which parameters can be changed. For data assimilation this files contains the definition of the model state and the noise (uncertainty) specification for the boundaries and forcings.

20.4.5 D-Flow FM files and the OpenDA dataObjects configuration

The dataObjects for reading and writing provide so-called exchange items that allow OpenDA to manipulate specific parts of the files of D-Flow FM. The D-Flow FM files that can be manipulated by OpenDA and the corresponding OpenDA class names are given in Table 20.2.

Table 20.2: *D-Flow FM files that can be manipulated and the corresponding OpenDA class names to be used in the* `dflowfmWrapper.xml` *file.*

D-Flow FM filetype	OpenDA dataObject & exchange items
<*.mdu>	`org.openda.model_dflowfm.DFlowFMTimeInfo` IDs: `start_time, end_time`
<*.amu>	`org.openda.model_dflowfm.DFlowFMMeteoFile` ID: `x_wind`
<*.amv>	`org.openda.model_dflowfm.DFlowFMMeteoFile` IDs: `y_wind`
<*.amp>	`org.openda.model_dflowfm.DFlowFMMeteoFile` ID: `air_pressure`
<*.tim>	`org.openda.model_dflowfm.DFlowFMTimeSeriesDataObject` IDs: `BOUNDARY_ID.#:QUANTITY`
<*.xyz>	`org.openda.model_dflowfm.DFlowFMXyzFile` IDs: `FILENAME_#`
<*_his.nc>	`org.openda.exchange.dataobjects.NetcdfDataObject` IDs: `STATION_ID.VARIABLE_NAME`
<*_map.nc>	`org.openda.model_dflowfm.DFlowFMRestartFileWrapper` IDs: `VARIABLE_NAME`

<*.cld>	`org.openda.model_dflowfm.DFlowFMCalibrationFactorFile`
	IDs: `CalFactor-CALIBRATION_DEFINTION_NUMBER`,
	`CalFactor-CALIBRATION_DEFINTION_NUMBER-q{DISCHARGE}`,
	`CalFactor-CALIBRATION_DEFINTION_NUMBER-h{WATERLEVEL}`

<*.ttd>	`org.openda.model_dflowfm.DFlowFMTrachytopeFile`
	IDs: `RoughNr_{ROUGHNESSNR}_FormulaNr{FORMULANR}_{FORMULAPARAME`
	`RoughNr_{ROUGHNESSNR}_DISCHARGE{DISCHARGE}_FormulaNr{FORMULA`
	`RoughNr_{ROUGHNESSNR}_WATERLEVEL{WATERLEVEL}_FormulaNr{FORMU`

All the dataObjects and their configuration are described tn the following sections.

20.4.5.1 Start and end time in the model definition file (`.mdu`)

The start and end time are set in <*.mdu>-file the by OpenDA using the `start_time` and `end_time` exchange items. These are provided by the `DFlowFMTimeInfo` data object.

D-Flow FM reference	Exchange Item Id	Remark
`TStart`	`start_time`	`RefDate` and `Tunit` needed for interpretation
`TStop`	`end_time`	`RefDate` and `Tunit` needed for interpretation

20.4.5.2 External forcings (`.xyz`)

All D-Flow FM external forcings are specified via the <*.ext> forcings file. Here a spatial forcing can be defined by using a `.xyz`-file (e.g. the bed friction coefficients). For instance the file <nikuradse.xyz> contains:

```
x1 y1 0.9994357525438934
x2 y2 0.9994357525438934
x3 y3 2.0021214673505600
x4 y4 2.0021214673505600
x5 y5 2.0021214673505600
x6 y6 2.0021214673505600
```

When performing calibration of a spatial field it is often required to group points in a select number of regions. The calibration then does not change the individual values but applies a factor to all values in the group. The best approach is to create a file with multipliers (e.g <friction_multiplier.xyz>) which are initially all equal to one.

```
x1 y1 1.0
x2 y2 1.0
x3 y3 1.0
x4 y4 1.0
x5 y5 1.0
x6 y6 1.0
```

The multiplication (or addition) with the values in `nikuradse.xyz` should be configured in the `*.ext` file.

Group from keywords in file

One option to construct groups is to use keywords directly in the <friction_multiplier.xyz> file:

```
x1 y1 1.0 #friction_3
x2 y2 1.0 #friction_3
x3 y3 1.0 #friction_1
x4 y4 1.0 #friction_1
x5 y5 1.0 #friction_4
x6 y6 1.0 #friction_4
```

In the OpenDA wrapper config the dataObject is than configured as:

```
<ioObject className="org.openda.model_dflowfm.DFlowFMXyzFile">
  <file>friction_multiplier.xyz</file>
  <id>frictionCoefFile</id>
  <arg>idsFromKeywordsInFile</arg>
</ioObject>
```

This will create exchange items with identifier `friction_3`, `friction_1` and `friction_4`.

Group from template file

An other options is to use a template file (<friction_multiplier_template.xyz>) with exactly the same (x,y) coordinates as in (<friction_multiplier.xyz>). The third column is used to define groups by using these values as group numbers:

```
x1 y1 3.0
x2 y2 3.0
x3 y3 4.0
x4 y4 4.0
x5 y5 1.0
x6 y6 1.0
```

In the OpenDA wrapper config the dataObject must be configured as:

```
<ioObject className="org.openda.model_dflowfm.DFlowFMXyzFile">
  <file>friction_multiplier.xyz</file>
  <id>frictionCoefFile</id>
  <arg>idsFromTemplateFile=friction_multiplier_template.xyz</arg>
</ioObject>
```

This will create an exchange item for each group with identifier 'FILE_BASENAME + _ + number from template file', e.g. `friction_multiplier_3`, `friction_multiplier_4` and `friction_multiplier_1`.

20.4.5.3 Boundary time series (`.tim`)

Boundary conditions are specified as a combination of a <∗.pli> file and one or more `.tim` files. The `DFlowFMTimeSeriesDataObject` dataObject creates exchange items for all boundary conditions. It starts with reading the name of the external forcing file name from the <.mdu>-file (key `ExtForceFile`). The <∗.ext>-file contains formatted blocks, one for each forcing. Forcings are defined along polylines, given in `.pli`-files. A <∗.pli>-file is accompanied by a <∗.cmp>- or a (number of) <∗.tim>-file(s).

Noise can be added by means of an extra block in the `.ext`-file. As an example, noise is added to a boundary with a discharge imposed as:

```
QUANTITY =dischargebnd
FILENAME =sw_east_dis.pli
FILETYPE =9
METHOD =3
OPERAND =O

QUANTITY =dischargebnd
FILENAME =sw_east_dis_noise.pli
FILETYPE =9
METHOD =3
OPERAND =+
```

The discharge is set by the first block (operand=`O`), the information in the <∗.pli>-files is identical and noise is added as a time series: the <_noise.pli> file is always accompanied by a (number of) <∗.tim> file(s). The `location`-information on the first line of the `.pli`-file combined with the quantity is used to construct the exchange item identifier: `location.1.dischargebnd`. The numbering is used to discern between multiple <∗.tim>-files possibly linked to a single <∗.pli>-file.

20.4.5.4 Meteorological boundary conditions (<∗.amu>, <∗.amv>, <∗.amp>)

OpenDA can read and write to the D-Flow FM <∗.amu>, <∗.amv> and <∗.amp> files using the `org.openda.model_dflowfm.DFlowFMMeteoFile` dataObject. These contain the x- and y components of the wind and the air pressure at the free surface on an equidistant

grid. In a typical data assimilation use noise fields are added to the wind. For the this purpose OpenDA can generate a spatial noise field on an equidistant grid (see section 20.5). D-Flow FM can combine fields defined in files on different to single field on the computational grid.

20.4.5.5 Result time series (<*_his.nc>)

The <*_his.nc>-file contains time series with D-Flow FM model results for a number of stations. The generic `org.openda.exchange.dataobjects.NetcdfDataObject` is used for handling this type of files. The `NetcdfDataObject` expects a NetCDF-file that contains dimensions `time` and `stations` plus a variable `station_id` of type string and dimension `stations`. For each variable in this NetCDF-file with dimensions `(time,stations)` an exchange item is created, that can be referred to as `station_id(i).variablename`. For instance:

```
dimensions:
time = UNLIMITED ; // (2882 currently)
stations = 3 ;
station_name_len = 40 ;
variables:
char station_id(stations, station_name_len) ;
(containing strings Obs1, Obs2, Obs3)
double waterlevel(time, stations) ;
(containing the computed values of the waterlevel)
```

results in three exchange items (a 1D vector in this case) with identifiers: `Obs1.waterlevel`, `Obs2.waterlevel` and `Obs3.waterlevel`.

20.4.5.6 Restart file (<*_map.nc>)

OpenDA provides the `org.openda.model_dflowfm.DFlowFMRestartFileWrapper` for reading and writing the <*_map.nc>-file. This file contains all information needed to restart a D-Flow FM computation. Not all variables are relevant for manipulation by OpenDA: variable names that start with 'time', 'NetLink', 'BndLink', 'FlowLink', 'NetElem', 'FlowElem', 'NetNode', 'wgs84' and 'projected_coordinate_system' are ignored. Variables of other types than float or double are also ignored. For all other variables an exchange item is created, where the name of the variable in the NetCDF is used as the exchange item id.

Note: for Kalman filtering it is essential that the model starts from the <*_map.nc> file. It is not possible to specify an initial field by setting the `initialwaterlevel` or `initialsalinity` quantities in the <*.ext> file. If you want to set an initial field using these settings, make a custom D-Flow FM run where `TStop` is equal to `TStart` and use the created <*_map.nc> file for the starting point of the Kalman filtering.

20.4.5.7 Calibration factor definition file (<*.cld>)

The calibraction factor definition file has the following layout. This file includes examples of the three different types of calibration definition factors and in comments the resulting names of the exchange items for OpenDA.

```
# [FileInformation]
#   FileType     = CalibrationFactorsDefinitionFile
```

```
#   FileVersion   = 1.0
# [CalibrationFactors]

# Non-Q-or-h-dependent
#
# calibration-class-nr   calibration-factor
#
34 0.9
#
# (will lead to exchange item CalFactor-34)

# Q-dependent calibration factors
#
# calibration-class-nr DISCHARGE "Cross-section name"
# calibration-class-nr Q1 ConstantValueAtQ1
# calibration-class-nr Q2 ConstantValueAtQ2
# calibration-class-nr Q3 ConstantValueAtQ3
# calibration-class-nr Q4 ConstantValueAtQ4
#
601 DISCHARGE "cross-section name"
601 0100 1.0
601 1000 1.0
601 5500 1.0

# (will lead to exchange items:
#  CalFactor-601-q0100, CalFactor-601-q1000, CalFactor-601-q5500) etc.

# Waterlevel dependent calibration factor
# calibration-class-nr WATERLEVEL "Observation station name"
# calibration-class-nr H1 ConstantValueAtH1
# calibration-class-nr H2 ConstantValueAtH2
# calibration-class-nr H3 ConstantValueAtH3
# calibration-class-nr H4 ConstantValueAtH4
#
3 WATERLEVEL "water-level station name"
3 0.45 1.0
3 0.9  1.0
# (will lead to exchange items:
# CalFactor-3-h0.45 and CalFactor-3-h0.9)
```

OpenDA provides the `org.openda.model_dflowfm.DFlowFMCalibrationFactorFile` for reading and writing the <*.cld>-file. In the OpenDA wrapper config `<dflowfmWrapper.xml>` the dataObject can be configured as:

```
<ioObject className="org.openda.model_dflowfm.DFlowFMCalibrationFactorFile">
  <file>FlowFM.cld</file>
  <id>calibFactorFileID</id>
</ioObject>
```

In the `dflowfmModel.xml` a listing of the exchange items which are to be used can be found. To select all of the available exchange items from the calibration factor definition file, the following code can be used:

```
<exchangeItems>
  <vector id="allElementsFromIoObject" ioObjectId="calibFactorFileID"/>
</exchangeItems>
```

To select just a few of the exchange items, these can also be selected individually:

```
<exchangeItems>
  <vector id="CalFactor-601-q0100" ioObjectId="calibFactorFileID"
    elementId="CalFactor-601-q0100"/>
```

```
  <vector id="CalFactor-601-q1000" ioObjectId="calibFactorFileID"
    elementId="CalFactor-601-q1000"/>
  <vector id="CalFactor-601-h0.45" ioObjectId="calibFactorFileID"
    elementId="CalFactor-601-h0.45"/>
  <vector id="CalFactor-601-q0.9" ioObjectId="calibFactorFileID"
    elementId="CalFactor-601-h0.9"/>
</exchangeItems>
```

20.4.5.8 Trachytopes roughness definition file (<∗.ttd>)

The trachytopes definition file has the following layout. This file includes examples of the three different types of calibration definition factors and in comments the resulting names of the exchange items for OpenDA.

```
# [FileInformation]
#   FileType     = TrachytopesRoughnessDefinitionFile
#   FileVersion  = 1.0
# [RoughnessDefinitions]
#
# Constant roughness definitions
# roughness-definition-code formula-number formula-parameters
# Nikuradse 0.2
7     51      0.2
# (Leads to exchange-item RoughNr_7_FormulaNr_51_A)

# Linear trachytopes: wooden barrier
9     201     5.0      1.25
# (Leads to exchange-items RoughNr_9_FormulaNr_201_A
# and RoughNr_9_FormulaNr_201_B})

#     Uniform chezy value 25
10    52      25
# (Leads to exchange-item RoughNr_10_FormulaNr_52_A)

# Discharge dependent trachytopes
# roughness-definition-code DISCHARGE cross-section-name
# roughness-definition-code Q1 formula-number formula-parametersatQ1
# roughness-definition-code Q2 formula-number formula-parametersatQ2
11    DISCHARGE   "m=1"
11    0.0     51      0.2
11    200.0   51      0.18
11    1000.0  51      0.1
%# (Leads to exchange-items RoughNr_11_DISCHARGE0.0_FormulaNr_51_A,
# RoughNr_11_DISCHARGE200.0_FormulaNr_51_A,
# RoughNr_11_DISCHARGE1000.0_FormulaNr_51_A)

# Water-level dependent trachytopes
# roughness-definition-code WATERLEVEL observation-station-name
# roughness-definition-code ZS1 formula-number formula-parametersatZS1
# roughness-definition-code ZS2 formula-number formula-parametersatZS2
11    WATERLEVEL   "obs1"
16    -1.2   151     4.0      0.1
16    -1     151     4.0      0.3
16     2     151     5.0      0.1
# (Leads to exchange-items RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_A,
# RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_B,
# RoughNr_16_WATERLEVEL-1_FormulaNr_151_A,
# RoughNr_16_WATERLEVEL-1_FormulaNr_151_B,
# RoughNr_16_WATERLEVEL2_FormulaNr_151_A,
# RoughNr_16_WATERLEVEL2_FormulaNr_151_B)
```

OpenDA provides the `org.openda.model_dflowfm.dflowfm.DFlowFMTrachytopeFile` for reading and writing the <*.cld>-file. In the OpenDA wrapper config `<dflowfmWrapper.xml>` the dataObject can be configured as:

```
<ioObject className="org.openda.model_dflowfm.dflowfm.DFlowFMTrachytopeFile">
<file>FlowFM.ttd</file>
<id>trachytopesFileID</id>
</ioObject>
```

In the `dflowfmModel.xml` a listing of the exchange items which are to be used can be found. To select all of the available exchange items from the calibration factor definition file, the following code can be used:

```
<exchangeItems>
<vector id="allElementsFromIoObject" ioObjectId="trachytopesFileID"/>
</exchangeItems>
```

To select just a few of the exchange items, these can also be selected individually:

```
<exchangeItems>
  <vector id="RoughNr_7_FormulaNr_51_A" ioObjectId="trachytopesFileID"
  elementId="RoughNr_7_FormulaNr_51_A"/>
  <vector id="RoughNr_11_DISCHARGE0.0_FormulaNr_51_A" ioObjectId="trachytopesFileID"
  elementId="RoughNr_11_DISCHARGE0.0_FormulaNr_51_A"/>
  <vector id="RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_A" ioObjectId="trachytopesFileID"
  elementId="RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_A"/>
  <vector id="RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_B" ioObjectId="trachytopesFileID"
  elementId="RoughNr_16_WATERLEVEL-1.2_FormulaNr_151_B"/>
</exchangeItems>
```

20.5 Generating noise

To add uncertainty to the external forcings and the boundary conditions, OpenDA has functionality for generating noise time series and spatial fields. The noise generation can be specified within the `state` definition in <dflowfmStochModel.xml>. For instance in the example `simple_waal_kalman`, a noise time series is created (ID `dischargenoise`), which is added to the inflow discharge (ID `eastboundary.1:dischargebnd`).

```
<?xml version="1.0" encoding="UTF-8"?>
<blackBoxStochModel
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation
    ="http://www.openda.org http://schemas.openda.org/blackBoxStochModelConfig.xsd"
  xmlns="http://www.openda.org">
 <modelConfig>
     <file>./dflowfmModel.xml</file>
 </modelConfig>
 <vectorSpecification>
  <state>
   <noiseModel
      id="boundaryNoiseModel"
      className="org.openda.noiseModels.TimeSeriesNoiseModelFactory"
      workingDirectory=".">
     <configFile>BoundaryNoise.xml</configFile>
     <exchangeItems>
      <exchangeItem
       id="dischargenoise"
       operation="add"
       modelExchangeItemId="eastboundary.1:dischargebnd"/>
     </exchangeItems>
   </noiseModel>
   <vector id="s1"/>
   <vector id="unorm"/>
```

```
  </state>
 </vectorSpecification>
</blackBoxStochModel>
```

The config file <BoundaryNoise.xml> contains the details of the noise:

```
<?xml version="1.0" encoding="UTF-8"?>
<mapsNoiseModelConfig>
 <simulationTimespan timeFormat="dateTimeString">
    199208311200,199209010000,...,199212090000
 </simulationTimespan>
 <timeSeries
   id="dischargenoise"
   location="eastboundary"
   quantity="discharge"
   standardDeviation="0.2"
   timeCorrelationScale="6.0"
   timeCorrelationScaleUnit="hours"/>"
</mapsNoiseModelConfig>
```

A noise time series is created (ID `dischargenoise`) with a correlation time of 6 hours and a standard deviation of 0.2. **Note:** currently OpenDA does not support the creation of D-Flow FM files, all files should exist in the <input_dflowfm>. In this case the boundary is defined in <sw_east_dis.pli>, but the noise is in a separate file <sw_east_dis_noise.pli>. Initially it contains zeros, but is filled with the noise values at run time. The time points in the file need to match the `simulationTimespan` in the OpenDA config. The total discharge at the boundary is constructed by D-Flow FM where the noise is added to original boundary values (see <simple_waal.ext>).

To generate a spatial correlation field the same approach can be used. In the `lake_kalman` example a noise field is added the wind. Instead of `timeSeries` a `noiseItem` is specified which contains the grid definition.

```
<?xml version="1.0" encoding="UTF-8"?>
<mapsNoiseModelConfig>
 <simulationTimespan timeFormat="dateTimeString">
    200106240000,200106240100,...,200106270000
 </simulationTimespan>
 <noiseItem id="2DNoise" quantity="wind-x" unit="m/s" height="10.0"
    standardDeviation="20.0"
    timeCorrelationScale="12.0" timeCorrelationScaleUnit="hours"
    initialValue="0.0"
    horizontalCorrelationScale="10" horizontalCorrelationScaleUnit="km">
   <grid type="cartesian" coordinates="XY">
    <x>0,3000,...,63000</x>
    <y>0,3000,...,63000</y>
   </grid>
 </noiseItem>
</mapsNoiseModelConfig>
```

The calculation of spatially correlated noise on a cartesian grid is quite fast as the x and y-direction are independent. The interpolation from an equidistant grid to the computational grid is performed within D-Flow FM. Again, note that an zero valued wind files should be present <input_dflowfm> folder, where the time stamps match with the ones given in `simulationTimespan` in the OpenDA configuration.

20.6 Examples of the application of OpenDA for D-Flow FM

In this section, some examples are elaborated for both the calibration of a model and the ensemble Kalman filtering (abbreviated as 'EnKF') of a model. All the examples can be found in the directory <examples/model_dflowfm_blackbox>.

20.6.1 Example 1: Calibration of the roughness parameter

The automatic calibration of a model needs two main choices from the user:

1 Which model parameters may be modified during the calibration process?
2 Which model results need to be compared to observations, to judge the model quality?

The remainder of this section will be in the form of a tutorial, to directly illustrate all steps in an example model. In this example you will use a small river model 'simple_waal' and use the bed roughness to calibrate this model for its three water level observation stations.

Step 1: Inspect the model

All the required model files can be found in the directory <simple_waal_calibration_roughness>. Consider the following steps:

1 Start D-Flow FM (standalone) in directory <input_dflowfm/>.
2 Select *Files* → *Load MDU-file*.
3 Load the model: select <simple_waal.mdu>.
4 You can run the model if you like (right mouse button).

The basic model is built to simulate a simple two-dimensional river with a spatially varying bed friction coefficient. It is driven by two boundary conditions: an upstream discharge inflow at the eastern boundary and a downstream water level at the western boundary. Inspect the model forcing in the following way:

1 Open the external forcings file <simple_waal.ext> in a text editor.
2 Notice how, in addition to the two boundaries, there are two blocks for the friction coefficient. The first one is a spatially varying roughness field in the <sw_nikuradse.xyz> file. The second refers to the <sw_frcfact_all.xyz> file that contains multipliers for the original friction coefficients. A third file <sw_frcfact_template.xyz> is present, which is used to define a number of subdomains.
3 In D-Flow FM, select *Files* → *Load sample file* and select <sw_frcfact_template.xyz>.
4 Notice how the loaded samples have three distinct values 1, 2 and 3, which act as identifiers: they approximately define the corner points of three subdomains of the entire river stretch. For each subdomain, a different roughness can be calibrated.

Step 2: Select the model parameters

Currently, the only calibratable parameters are the time-independent parameters in the external forcings file that use the `.xyz` sample file format. The most obvious parameter is the bed friction coefficient.

Step 3: Select the model results

The example directory <simple_waal> contains all the necessary configuration files for the so-called Black Box model wrapper for D-Flow FM to run a 'twin experiment'. In a twin experiment a model setup with given solution (the synthetic observations) is perturbed after which OpenDA is applied to re-estimate the original settings. The effects of the parameter variations may be judged by comparing time series output in the <*_his.nc> history file to observed data in NOOS time series format. The model output and observation data are compared by calculating a cost function. Which cost function is used is configured in the <dudAlgorithm.xml> in the <algorithm> directory. See the OpenDA documentation for the available options for the cost function.

The D-Flow FM model simulates a 1D river flow. The input files for D-Flow FM are located in the directory <simple_waal/stochModel/input>. D-Flow FM allows the user to specify regions with a different bed friction coefficient (constant for each region) and is able to handle the interpolation of the coefficients between these regions. In the experiment we try to re-estimate the values of the bed friction coefficients of an earlier run. As observations, the waterlevel at three locations (stations) along the river is used. These results are written to the main output file (<*_his.nc>) as time series.

In the directory <simple_waal>, there are two main configuration files of OpenDA present:

- `Simulation.oda`: runs a single run of the model, this configuration is mainly used to test the black box configuration files.
- `Dud.oda` runs a calibration experiment with algorithm DUD (Doesn't Use Derivative).

These files configure the main ingredients of an OpenDA run:

1. the stochObserver (`org.openda.observers.NoosTimeSeriesStochObserver`). Observations for this experiment were created by extracting the timeseries for all stations from the netcdf-file and convert them to NOOS format (script nchis2noos.sh) het script schrijft nog tijd sinds begin situatie.
2. the stochObserver (`org.openda.observers.NoosTimeSeriesStochObserver`). Observations for this experiment were created by extracting the time series for all stations from the netcdf-file and convert them to NOOS format (script nchis2noos.sh)
3. the stochModelFactory (org.openda.blackbox.wrapper.BBStochModelFactory). A black box model configuration consist of three configuration files that are described in more detail below.
4. the algorithm (org.openda.algorithms.Dud). Dud is a well known algorithm in calibration experiments, more information about it can be found on the OpenDA website or in the literature.

The configuration files for these 3 components are located in different sub directories to reflect the Object Oriented architecture of OpenDA. The fourth block in the configuration file specifies the result writer (org.openda.resultwriters.MatlabResultWriter). The resulting m-file may be loaded in Matlab to visualize results of the OpenDA run.

In this example, the data exchange between OpenDA and D-Flow FM is limited to the bed friction coefficients and the computed waterlevel at observation locations. The waterlevel at a observation location is expected to be written to NetCDF-file with the following features

1. dimension 'time' and 'stations' are defined
2. there exists a variable 'station_id(stations)' defined that contains strings with the station_id

For NetCDF-files that satisfy these two conditions OpenDA creates an 'exchange item' for each variable that has the dimensions (time, stations). The exchange item is referred to as 'station id(nr)'.'name of variable'.

20.6.2 Example 2: EnKF with uncertainty in the tidal components

The geometry for this test case is the same as used in the Delft3D model example for calibration that was presented in a Deltares webinar (recording, slides and all configuration files for this example are available at the OpenDA website).

Regularly, D-Flow FM uses 1 component file to specify all tidal component (one component at a line). In order to add different noise models to different components, you must split the component file and add one <∗.tim>-files for noise for each component.

Again, all configuration files are available, but not much effort has been put into the exact configuration of the EnKF algorithm or the noise model specifications. The results of the SequentialSimulation show that this test case suffers much less from the inexact restart. The whole workflow is highlighted in more detail below.

A few remarks are made:

- ◇ the directories <bin> and <jre> should be on the same level,
- ◇ the computation is started through running the file oda_run_gui.bat,
- ◇ the bare D-Flow FM model is located in the directory <input_dflowfm>,
- ◇ the observations are in `.noos`-format, and are located in the directory <stochObserver>.

Step 2: Start the EnKF computation

The OpenDA run is launched through the core `oda_run_gui.bat` file. Once having opened this file, a user interface appears. Within the user interface, an <∗.oda>-file can be opened from a certain case directory (in this case, we have <estuary_kalman>). One can choose `Enkf.oda`, `SequentialSimulation.oda` or `Simulation.oda`. In this case, we choose for `Enkf.oda`.

Step 3: Examine the applied noise

The basic necessary component of an EnKF computation comprises the noise applied to some variable. In this case, the noise is applied to the waterlevel boundary representing the tidal motion. Within the directory <input_dflowfm>, this noise is explicitly declared through a separate polyline and a separate data file for the boundary. The configuration of the noise is accomplished through two <∗.xml>-files in the directory <stoch_model>.

Step 4: Run the EnKF computation

By means of the user interface, the EnKF computation can be launched. After having opened the file <EnKF.oda>, the *Run*-button can be pressed. The computation is being performed. Along the computation's duration, multiple <work> directories are generated in the directory <stochModel>, i.e. <work0>, <work1>, <work2>, etc.

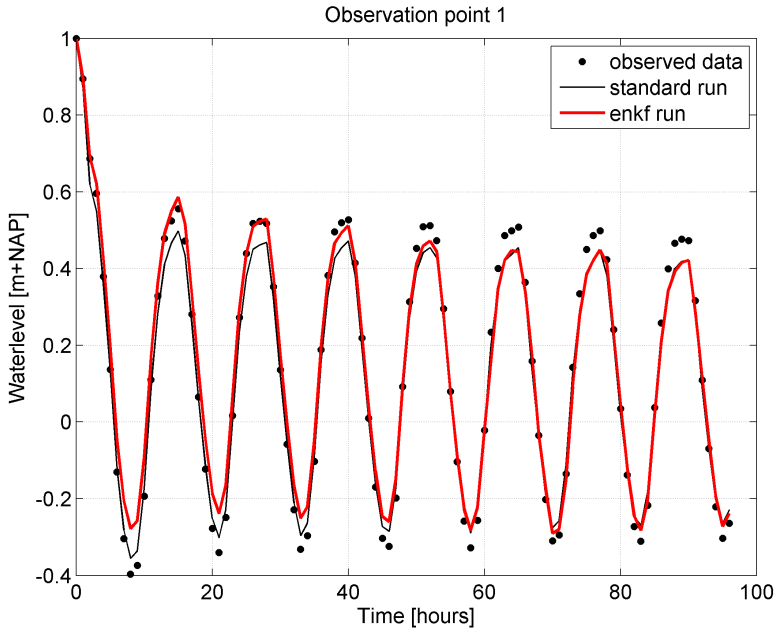


Figure 20.1: *Visualisation of the EnKF computation results from OpenDA for a certain observation point. The dots represent the observed data, the black line represents the original computation with D-Flow FM (without Kalman filtering) and the red line represents the D-Flow FM computation with Kalman filtering.*

Step 5: Evaluate the outcomes

After having run the computation, output files have been generated in Matlab-format. The relevant files are placed in the directory <estuary_kalman>. The data are stored in the Matlab file <Enkf_results.m>. Visualisation could be accomplished like shown in Figure 20.1.

20.6.3 Example 3: EnKF with uncertainty in the inflow velocity

The geometry in this example is the same as for the calibration example: a two-dimensional river model, the initial waterlevel is zero, the river bed is filled gradually due to the boundary conditions. At the inflow boundary, a constant discharge is prescribed (along the line <sw_east_dis_0001.pli>), whereas at the outflow boundary, a constant water level is prescribed (along the line <sw_west_wlev_0001.cmp>).

There are 3 observation locations along the river (Obs01, Obs02 and Obs03). The matlab script <plot_results_hisfile.m> is available to plot the water level as a function of time for these 3 stations. Simulation time span is 100 days (Start: 199208310000, End: 199212090000). The noise contribution is found in file <sw_east_dis_noise.pli>. Initially, no noise is present, so the file contains zeroes in directory <input_dflowfm>.

20.6.4 Example 4: EnKF with uncertainty in the inflow condition for salt

The geometry in this example and the boundary conditions for waterlevel and velocity are exactly the same as in `simple_waal_kalman`. The transport of salt is added to the computation by a discharge boundary condition `sw_east_dis_sal_001.pli` and a noise component added to this boundary.

20.6.5 Example 5: EnKF with uncertainty on the wind direction

This example is also converted from a Delft3D test case (`d3d_lake_2d`): a lake forced by an uniform wind field. This example is a twin experiment with spatially correlated 2D-noise added to the wind field. The noise is created on cartesian (equidistant grid), the noise realisations are written by OpenDA to the <lake2d_windx_noise.amu>. The 2D noise field is interpolated at computational grid by D-Flow FM and added to the uniform wind field. The <SequentialSimulationNoise.oda> can be used to perform a single D-Flow FM run where wind with noise is used as forcing. The resulting <lake2d_his.nc> file can be is used as syntethic observations by the <stochObserver>.

20.6.6 Example 6: EnKF with the DCSM v5 model and uncertainty on the wind direction

This example is converted from the SIMONA DCSM v5 model with spatially correlated 2D-noise added to the wind field.

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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*.

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A The master definition file

The mdu-file contains the key information of the flow model. Besides the names of the relevant user specified files, such as the grid file and the external forcings file, the values of various model parameters should be specified in the MDU-file. The most important model parameter settings are given in Table A.1 as well as the associated default setting for these parameters.

The basename of the mdu-file, without `.mdu`, is also used as the model identification string, and is often denoted as *mdu_name* throughout this User Manual. It is equivalent to Delft3D-FLOW's *runid* concept.

Table A.1: *Standard MDU-file with default settings.*

Keyword	Default setting	Description
`[model]`		
`Program`	`D-Flow FM`	Program
`Version`	`1.1.134.38754`	Version
`MDUFormatVersion`	`1.02`	File format version. Do not edit this.
`AutoStart`	`0`	Autostart simulation after loading MDU or not (0=no, 1=autostart, 2=autostartstop).
`[geometry]`		
`NetFile`		*_net.nc
`BathymetryFile`		*.xyb
`DryPointsFile`		Dry points file *.xyz, third column dummy z values, or polygon file *.pol.
`WaterLevIniFile`		Initial water levels sample file *.xyz
`LandBoundaryFile`		Only for plotting
`ThinDamFile`		*_thd.pli, Polyline(s) for tracing thin dams.
`FixedWeirFile`		*_fxw.pliz, Polyline(s) x,y,z, z = fixed weir top levels (formerly fixed weir)
`VertplizFile`		*_vlay.pliz), = pliz with x,y, Z, first Z =nr of layers, second Z = laytyp
`ProflocFile`		*_proflocation.xyz) x,y,z, z = profile refnumber
`ProfdefFile`		*_profdefinition.def) definition for all profile nrs
`ProfdefxyzFile`		*_profdefinition.def) definition for all profile nrs
`ManholeFile`		File containing manholes (e.g. *.dat)
`PartitionFile`		*_part.pol, polyline(s) x,y
`Uniformwidth1D`	`2.`	Uniform width for 1D profiles not specified bij profloc
`WaterLevIni`	`0.`	Initial water level
`Bedlevuni`	`-5.`	Uniform bed level, (only if bedlevtype>=3, used at missing z values in netfile
`Bedslope`	`0.`	bedslopeinclination, sets zk = bedlevuni + x*bedslope ans sets zbndz = xbndz*bedslope
`BedlevType`	`3`	1: at cell center (tiles xz,yz,bl,bob=max(bl)), 2: at face (tiles xu,yu,blu,bob=blu), 3: at face (using mean node values), 4: at face (using min node values), 5: at face (using max node values), 6: with bl based on node values
`Blmeanbelow`	`-999.`	if not -999d0, below this level the cell centre bedlevel is the mean of surrouding netnodes
`Blminabove`	`-999.`	if not -999d0, above this level the cell centre bedlevel is the min of surrouding netnodes
`AngLat`	`0.`	Angle of latitude S-N (deg), 0=no Coriolis
`AngLon`	`0.`	Angle of longitude E-W (deg), 0=Greenwich
`Conveyance2D`	`-1`	-1:R=HU,0:R=H, 1:R=A/P, 2:K=analytic-1D conv, 3:K=analytic-2D conv

(continued on next page)

Keyword	Default setting	Description
		(continued from previous page)
Nonlin2D	0	Non-linear 2D volumes, only icm ibedlevtype = 3 and Conveyance2D>=1
Sillheightmin	0.0	Weir treatment only if both sills larger than this value (m)
Makeorthocenters	0	1=yes, 0=no switch from circumcentres to orthocentres in geominit
Dcenterinside	1.	limit cell center; 1.0:in cell <-> 0.0:on c/g
Bamin	1.d-6	Minimum gridcell area , icm cutcells
OpenBoundaryTolerance	3.	Search tolerance factor between boundary polyline and grid cells. Unit: in cell size units (i.e., not metres).
Kmx	0	Max nr of vertical layers
Layertype	1	1= all sigma, 2 = all z, 3 = use VertplizFile
Numtopsig	0	Nr of sigmalayers in top of Zlayer model
SigmaGrowthFactor	1.	layer thickness growth factor from bed up
[numerics]		
CFLMax	0.7	Max. Courant nr.
CFLWaveFrac	0.1	Wave velocity fraction, total courant vel = u + cflw*wavevelocity
AdvecType	33	Adv type, 0=no, 1= Wenneker, qu-udzt, 2=1, q(uio-u), 3=Perot q(uio-u), 4=Perot q(ui-u), 5=Perot q(ui-u) without itself
Lincontin	0	Default 0; Set to 1 for linearizing d(Hu)/dx; link to AdvecType
TimeStepType	2	0=only transport, 1=transport + velocity update, 2=full implicit step_reduce, 3=step_jacobi, 4=explicit
Limtyphu	0	Limiter type for waterdepth in continuity eq., 0=no, 1=minmod,2=vanLeer,3=Kooren,4=Monotone Central
Limtypmom	4	Limiter type for cell center advection velocity, 0=no, 1=minmod,2=vanLeer,3=Kooren,4=Monotone Central
Limtypsa	4	Limiter type for salinity transport, 0=no, 1=minmod,2=vanLeer,3=Kooren,4=Monotone Central
Maxdegree	6	Maximum degree in Gauss elimination
Vertadvtypsal	5	Vertical advection type for salinity, 0=No, 1=UpwexpL, 2=Centralexpl, 3=UpwimpL, 4=CentraLimpL, 5=4 but 3 for neg. stratif., 6=higher order expl, no forester
Icgsolver	4	Solver type , 1 = sobekGS_OMP, 2 = sobekGS_OMPthreadsafe, 3 = sobekGS, 4 = sobekGS + Saadilud, 5 = parallel/global Saad, 6 = parallel/Petsc, 7 = parallel/GS
FixedWeirScheme	9	6 = semi-subgrid scheme, 8 = Tabellenboek, 9 = Villemonte
FixedWeirContraction	1.	flow width = flow width*FixedWeirContraction
Jbasqbnddownwindhs	0	0 : original hu on qbnd, 1 = downwind hs on qbnd
Izbndpos	0	Position of z boundary, 0=D3Dflow, 1=on net boundary, 2 = on specifiend polyline
Tlfsmo	0.	Fourier smoothing time on waterlevel boundaries (s)
Slopedrop2D	0.	Apply droplosses only if local bottom slope > Slopedrop2D, <=0 =no droplosses
Chkadvd	0.1	Check advection terms if depth < chkadvdp, => less setbacks
Teta0	0.55	Teta of time integration, 0.5 < Teta < 1d0
		(continued on next page)

Keyword	Default setting	Description
		(continued from previous page)
Qhrelax	1.d-2	Relaxation qhbnd ( )
cstbnd	0	Delft-3D type velocity treatment near boundaries for small coastal models (1) or not (0)
Maxitverticalforestersal	10	0 : no vertical filter, > 0 = Max nr of iterations
Maxitverticalforestertem	0	0 : no vertical filter for temp, > 0 = Max nr of iterations
Jaorgsethu	1	0 : setumod, sethu, setau sequence, 1 : sethu, setau, setumod sequence (standard)
ilutype	0	0: parms-default
nlevel	0	0: parms-default
dtol	0.	0d0: parms-default
Epshu	1.d-4	Input for threshold water depth for wet and dry cells
Maxwaterleveldiff	0.	upper bound (in m) on water level changes, <= 0: no bounds
Maxvelocitydiff	0.	upper bound (in m/s) on velocity changes, <= 0: no bounds
TransportMethod	1	Transport method
Turbulencemodel	3	0=no, 1 = constant, 2 = algebraic, 3 = k-eps, 4 = k-tau
Turbulenceadvection	3	0=no, 3 = hor. expl., vert. impl.
[physics]		
UnifFrictCoef	2.3d-2	Uniform friction coefficient, 0=no friction
UnifFrictType	1	0=Chezy, 1=Manning, 2=White-Colebrook, 3=idem, WAQUA style
UnifFrictCoef1D	2.3d-2	Uniform friction coefficient in 1D links, 0=no friction
UnifFrictCoefLin	0.	Uniform linear friction coefficient for ocean models (m/s), 0=no
Umodlin	0	linear friction umod , ifrctyp 4,5,6
Vicouv	1.	Uniform horizontal eddy viscosity (m2/s)
Dicouv	1.	Uniform horizontal eddy diffusivity (m2/s)
Vicoww	5.d-5	Uniform vertical eddy viscosity (m2/s)
Dicoww	5.d-5	Uniform vertical eddy diffusivity (m2/s)
Vicwminb	0.	Minimum visc in prod and buoyancy term (m2/s)
Smagorinsky	0.	Add Smagorinsky horizontal turbulence : vicu = vicu + ((Smagorinsky*dx)**2)*S, e.g. 0.1
Elder	0.	Add Elder contribution : vicu = vicu + Elder*kappa*ustar*H/6), e.g. 1.0
irov	0	0=free slip, 1 = partial slip using wall_ks
wall_ks	0.	Nikuradse roughness for side walls, wall_z0=wall_ks/30
Rhomean	1000.	Average water density (kg/m3)
Idensform	0	1=Eckart, 2=UNESCO, 3=barocin case
Ag	9.813	Gravitational acceleration
TidalForcing	0	Tidal forcing (0=no, 1=yes) (only for jsferic == 1)
Doodsonstart	55.565	TRIWAQ = 55.565D0 , D3D = 57.555D0
Doodsonstop	375.575	TRIWAQ = 375.575D0 , D3D = 275.555D0
Doodsoneps	0.0	TRIWAQ = 0.0 400 cmps , D3D = 0.03 60 cmps
Salinity	0	Include salinity, (0=no, 1=yes)
InitialSalinity	0.	Inital salinity concentration (ppt)
Sal0abovezlev	-999.	Salinity 0 above level (m)
DeltaSalinity	-999.	for testcases
Temperature	0	Include temperature, (0=no, 1=only transport, 5=heat flux model (5) of D3D), 3=excess model of D3D
InitialTemperature	6.	Inital temperature (degC)
		(continued on next page)

Keyword	Default setting	Description
		(continued from previous page)
Secchidepth	2.	Water clarity parameter (m)
Stanton	0.0013	Coefficient for convective heat flux ( ), if negative, use Cd wind
Dalton	0.0013	Coefficient for evaporative heat flux ( ), if negative, use Cd wind
SecondaryFlow	0	Secondary flow (0=no, 1=yes)
[wind]		
ICdtyp	2	( ),1=const, 2=S&B 2 breakpoints, 3= S&B 3 breakpoints, 4=Charnock constant
Cdbreakpoints	6.3d-4 7.23d-3	( ), e.g. 0.00063 0.00723
Windspeedbreakpoints	0. 100.	(m/s), e.g. 0.0 100.0
Rhoair	1.205	Air density (kg/m3)
PavBnd	0.	Average air Pressure on open boundaries, (N/m2), only applied if value > 0
[time]		
RefDate	20010101	Reference date (yyyymmdd)
Tzone	0.	Data Sources in GMT are interrogated with time in minutes since refdat-Tzone*60
Tunit	S	Time units in MDU (H, M or S)
DtUser	300.	User timestep in seconds (interval for external forcing update & his/map output)
DtMax	30.	Max timestep in seconds
DtInit	1.	Initial timestep in seconds
TStart	0.	Start time w.r.t. RefDate (in TUnit)
TStop	8640000.	Stop time w.r.t. RefDate (in TUnit)
[restart]		
RestartFile		Restart file, only from netcdf-file, hence: either *_rst.nc or *_map.nc
RestartDateTime		Restart time (YYYYMMDDHHMMSS), only relevant in case of restart from *_map.nc
[externalforcing]		
ExtForceFile		Old format for external forcings file *.ext, link with tim/cmp-format boundary conditions specification
ExtForceFileNew		New format for external forcings file *.ext, link with bc -format boundary conditions specification
[output]		
OutputDir		Output directory of map-, his-, rst-, dat- and timings-files, default: DFM_OUTPUT_<modelname>. Set to . for no dir/current dir.
ObsFile		*.xyn Coords+name of observation stations.
CrsFile		*_crs.pli Polyline(s) defininingcross section(s).
HisFile		*_his.nc History file in NetCDF format.
HisInterval	120.	History output, given as 'interval' 'start period' 'end period' (s)
XLSInterval	0.	Interval (s) between XLS history
FlowGeomFile		*_flowgeom.nc Flow geometry file in NetCDF format.
MapFile		*_map.nc Map file in NetCDF format.
MapInterval	1200.	Map file output, given as 'interval' 'start period' 'end period' (s)
		(continued on next page)

Keyword	Default setting	Description
		(continued from previous page)
MapFormat	1	Map file format, 1: netCDF, 2: Tecplot, 3: netCFD and Tecplot
Heatfluxesonoutput	0	1=yes,0=no
Richardsononoutput	0	1=yes,0=no
RstInterval	86400.	Restart file output, given as 'interval' 'start period' 'end period' (s)
S1incinterval	0.	Interval (m) in incremental file for waterlevels S1
WaqFileBase		Basename (without extension) for all Delwaq files to be written.
WaqInterval	0.	Interval (in s) between Delwaq file outputs
StatsInterval	0.	Interval (in s) between simulation statistics output.
Writebalancefile	0	Write Balancefile, 1=yes, 0=no
TimingsInterval	0.	Timings output interval
TimeSplitInterval	0X	Time splitting interval, after which a new output file is started. value+unit, e.g. '1 M', valid units: Y,M,D,h,m,s.
MapOutputTimeVector		File (.mpt) containing fixed map output times (s) w.r.t. RefDate
FullGridOutput	0	0:compact, 1:full time-varying grid data
SnapshotDir	figures	Directory where snapshots/screendumps are saved.

B Attribute files

B.1 Introduction

In the following sections we describe the attribute files used in the input file (MDU-file) of D-Flow FM. Most of these files contain the quantities that describe one specific item, such as the location of open boundaries, or time dependent data of fluxes discharged in the model area by discharge stations. Most of the attribute files can be generated by the Delta Shell GUI after defining an input scenario. Some files can almost only be generated by utility programs such as the unstructured grid generated by RGFGRID. Still, we describe both type of files as it might be useful to know how the input data is structured to be able to generate (large) files, such as astronomic boundary conditions, or time-series for wind speed and direction by client specific tools.

B.2 Polyline/polygon file

D-Flow FM uses the same format for polylines and (closed) polygons. When used as a polygon file, there is *not* the requirement that the first and last point should be identical. It is good modelling practice to name files containing polygons with the extension `.pol`, and files containing polylines with the extension `.pli`. When the polylines have a third column with z-coordinates, the extension `.pliz` is advised.

File contents	The coordinates of one or more polylines. Each polyline (piecewise linear) is written in a single block of data.
Filetype	ASCII
File format	Free formatted
Filename	<*name*.pol>
Generated	RGFGRID, QUICKIN, Delta Shell, etc

Record description:

Record	Record description
	Preceding description records, starting with an asterisk ($*$), and will be ignored.
1	A non blank character string, starting in column one.
2	Two integers N_r, N_c representing the numbers of rows and number of columns for this block of data.
	Two reals representing the x, y or λ, ϕ-coordinate, followed by remaining data values at that location (if $N_c > 2$).

Example:

```
*
* Polyline L007
*
L007
6  2
            132400.0    549045.0
            132345.0    549030.0
            132165.0    549285.0
            131940.0    549550.0
```

```
            131820.0    549670.0
            131585.0    549520.0
*
* Polyline L008
*
L008
4  2
            131595.0    549685.0
            131750.0    549865.0
            131595.0    550025.0
            131415.0    550175.0
*
* Polyline L009
*
L009
6  2
            131595.0    549655.0
            148975.0    564595.0
            150000.0    564935.0
            152105.0    565500.0
            153150.0    566375.0
            154565.0    567735.0
```

B.3 Sample file

Sample file are used for several of D-Flow FM's input files.

File contents	The location and value of samples.
Filetype	ASCII
File format	Free formatted
Filename	<*name*.xyz>
Generated	Manually or Offline with QUICKIN or Delta Shell and data from digitised charts or GIS-database.

Record description:

Filetype	Record description
Free formatted	Location and sample value per row Two reals representing the x, y or λ, ϕ-coordinate and one real representing the sample value

Example:

Sample file with 12 sample values with their location (free formatted file).

```
   213813.2       603732.1      -4.053000
   214686.0       607226.1      -4.522000
   214891.7       610751.2      -5.000000
   210330.8       601424.1      -2.169000
   211798.0       604444.8      -2.499000
   212460.0       607475.7      -2.760000
   212436.9       610362.5      -2.865000
   185535.4       606607.9       1.360000
   186353.0       603789.4       1.122000
   187959.2       601197.6      0.9050000
   190193.0       599101.5      0.7050000
   208578.7       602513.7     -0.7990000
```

B.4 Time series file (ASCII)

Time series files are used for several of D-Flow FM's input files. There is no header, except for optional comment lines. There should be two or more columns: the first column contains time in minutes since the model's reference date, all remaining columns contain the data values. Each line contains a single time with its (space-uniform) values.

B.5 The external forcings file

Two definition files for the external forcings are supported, each with their own format.

B.5.1 Old style external forcings

The name of the file is specified in the MDU-file as `"ExtForceFile"`. External forcings are specified in in blocks key-value pairs, e.g.

```
* comments
* comments

QUANTITY =waterlevelbnd
FILENAME =tfl_01.pli
FILETYPE =9
METHOD   =3
OPERAND  =O

QUANTITY = ...
FILENAME = ...
...
```

The format is not case-sensitive, but key-value pairs are expected in the *particular order* shown below. Accepted keywords are:

quantity	character	Name of the quantity, see the list below
filename	character	File associated with this forcing
sourcemask*	character	File containing a mask
filetype	integer	Indication of the filetype: 1. Time series (D.2.1) 2. Time series magnitude and direction 3. Spatially varying weather 4. ArcInfo 5. Spiderweb data (cyclones) (B.12.3) 6. Curvilinear data (B.12.2) 7. Samples (B.3) 8. Triangulation magnitude and direction 9. Polyline (<∗.pli>-file, B.2) 11. NetCDF grid data (e.g. meteo fields) 14. NetCDF wave data
method	integer	Method of interpolation: 1. Pass through (no interpolation) 2. Interpolate time and space 3. Interpolate time and space, save weights 4. Interpolate space 5. Interpolate time 7. Interpolate/Extrapolate time
operand	integer	
value*	float	custom coefficients for transformation
factor*	float	
ifrctyp*	float	
averagingtype*	float	
relativesearchcellsize*	float	
extrapoltol*	float	
area*	float	Area for source/sink

Note: Keywords marked with ∗ are optional

B.5.2 New style external forcing (boundary conditions only)

The name of the file is specified in the MDU-file as "ExtForceFileNew". External forcings are specified in the ini-file format in blocks headed by [boundary], followed by a list of key-value pairs in random order, e.g.

```
* comments
[boundary]
quantity=waterlevelbnd
locationfile=tfl_01.pli
forcingfile=tfl_01.bc

[boundary]
quantity= ...
...
```

Accepted keywords are:

quantity	character	Name of the quantity, see the list below (boundaries only)
locationfile	character	Boundary polyline <∗.pli>
forcingfile	character	BC-file with boundary data <∗.bc>
	character	NetCDF-file with boundary time series <∗.nc>
return_time*	float	Thatcher-Harleman (section 8.4.4) return time (default=0, meaning Thatcher-Harleman disabled).

Note: Keywords marked with ∗ are optional

B.5.3 Accepted quantity names

Most members on the list of accepted quantity names can be sorted in either of five categories:

- ◇ Boundary conditions
- ◇ Meteorological fields
- ◇ Structure parameters
- ◇ Initial fields
- ◇ Spatial physical properties

Table B.1: *List of accepted external forcing quantity names.*

Quantity	pg.	Description
Boundary conditions:		
waterlevelbnd	123	Water level
neumannbnd	125	Water level gradient
riemannbnd	126	Riemann invariant
outflowbnd		
velocitybnd	124	Velocity
dischargebnd	124	Discharge
riemann_velocitybnd		Riemann invariant velocity
salinitybnd	155	Salinity
temperaturebnd	155	Temperature
sedimentbnd	227	Suspended sediment
uxuyadvectionvelocitybnd		
normalvelocitybnd, tangentialvelocitybnd	131	Normal and tangential velocity
qhbnd	127	Discharge-water level dependency
tracerbnd<*tracername*>	155	User-defined tracer
Meteorological fields:		
windx, windy, windxy	180	Wind components, wind vector
airpressure_windx_windy	180	Atmospheric pressure and wind components
atmosphericpressure	180	Atmospheric pressure
rainfall		Precipitation
humidity_airtemperature... ..._cloudiness		
humidity_airtemperature... ..._cloudiness_solarradiation		
discharge_salinity... ..._temperature_sorsin	154	Discharge, salinity and heat sources
Structure parameters:		
pump	45	Pump capacity
damlevel		
gateloweredgelevel		
generalstructure		
Initial fields:		

Quantity	pg.	Description
initialwaterlevel	357	
initialsalinity	357	
initialsalinitytop	357	
initialtemperature	357	
initialverticaltemperatureprofile	357	
initialverticalsalinityprofile	357	
initialtracer<*tracername*>	357	
Spatial physical properties:	358	
frictioncoefficient		
horizontaleddyviscositycoefficient		
horizontaleddydiffusivitycoefficient		
advectiontype		
ibotlevtype		
Miscelaneous:		
shiptxy		
movingstationxy	368	Moving observation point for output (time,x,y)

B.6 Trachytopes

The trachytope functionality allows for the usage of different types of roughness formulations at different locations within the computational domain. Multiple formulation may be active in the same grid cell. Several keywords in the MDU file influence the functioning. All keywords below should be placed underneath the [trachytopes] section in the MDU file.

Keyword	**Value**	**Description**	**Default**
TrtRou	Y or N	Trachytope option activated	N
TrtDef	<name.ttd>	Definition file trachytopes	
Trtl	<name.arl>	Area Roughness on Link file trachytopes	
DtTrt	pos. real	Time step in seconds for updating roughness and resistance coefficients based on trachytopes. Must be a multiple of DtUser.	1 DtUser
TrtMnH	pos. real	Minimum water depth in roughness computation	.2 Epshu
TrtMth	1 or 2	Area averaging method	1
TrtAsr	real $\in [0, 1]$	Serial factor in averaging of area roughnesses	0.6
TrtMxR	integer	Maximum recursion depth for mixed trachytope definitions	8

B.6.1 Area Roughness on Links (ARL-file)

File contents	The Area Roughness on Links file (ARL-file) is the input file for the spatial distribution of the alluvial and vegetation roughness which are handled by the trachytopes module.
Filetype	ASCII
File format	Space separated file format
Filename	<*name*.arl>
Generated	At present: Conversion possible from structured Delft3D-FLOW input files with matlab conversion tool from Open Earth Tools (`http://www.openearth.info/`), see example below (section B.6.1.2).

The ARL file has the following properties:

- A single line comment, starts with a hash tag "`#`" or an asterisk "`*`".
- Each line has the format
  "`xu yu zu TrachytopesNr Fraction`",
  - where `xu`, `yu`, `zu` is the coordinate of the midpoint of the netlink,
  - `TrachytopeNr` is an integer corresponding to the number as described in the TrachyTopes Definition File (cf. section B.6.2),
  - and `Fraction` is a Fraction between `0.0` and `1.0`
- A line with a midpoint-netlink-coordinate which is the same as the preceding line (comments not considered) allows multiple types of trachytopes roughness definitions, provided the sum of the `Fraction` keywords does not add to a value greater than `1.0`.
- If the sum is less than `1.0` the background roughness prescribed in the `[physics]` chapter in the MDU file is prescribed for the remaining `Fraction`, cf. Appendix A. Only a single roughness type is allowed in combination with the Trachytopes module.
- If a midpoint-netlink-coordinate is repeated in the .arl file with the midpoint-netlink-coordinate `xu`, `yu`, `zu` in the preceding line being different, all previous instances of the specific `xu`, `yu`, `zu` are ignored.

B.6.1.1 Example

An example of the <arl> file is given below based on the <ttd> file given in section B.6.2. In this case the netlink with u point located at x_u = 10.542 and y_u = 11.6, which is covered for 30 %, 30 % 20 % and 20 % for `TrachytopeNr` = 1, 2, 4 and 3 respectively.

```
(continued)
...
10.542    11.6    0    1      0.3
10.542    11.6    0    2      0.3
10.542    11.6    0    4      0.2
10.542    11.6    0    3      0.2
...
(continued)
```

B.6.1.2 Conversion from Delft3D input files

Open Earth Tools has different matlab tools available for the conversion of Delft3D models to D-Flow FM models (e.g. dflowfmConverter.m and d3d2dflowfm.m).

An extra Matlab conversion script has been added to convert Delft3D's <∗.aru> and <∗.arv> files to <∗.arl> files for D-Flow FM:
d3d2dflowfm_friction_trachytopes.m.

It can be called as follows:

```
oetsettings
d3d2dflowfm_friction_trachytopes(filgrd,filaru,filarv,filnet,filarl)
```

where the variables are defined as follows:

filgrd	delft3d grid filename (*.grd)
filaru	delft3d area definition file in u-direction (*.aru)
filarv	delft3d area definition file in v-direction (*.arv)
filnet	name of the dflowfm network file (*_net.nc)
filarl	name of the dflowfm trachytope file (*.arl))

B.6.2 Trachytope Definition file (TTD-file)

The trachytope definition file contains lines of the following format defining the different types of trachytopes. The types which are supported are general, discharge dependent and water-level dependent formats.

B.6.2.1 General format

The general format is formatted as follows:

```
TrachytopeNr    FormulaNr     ...Parameters...
```

where `...Parameters...` indicates a space separated list of formula specific parameters; the parameters required and their order are specified in section B.6.2.5. The user must specify for each trachytope (combination of formula number and parameters) a unique positive trachytope number. This trachytope number is used in the area files (see section B.6.1) to indicate the roughness types on a net link.

B.6.2.2 Example

An example of such a file where the first three codes 1–3 with a Nikuradse roughness height are defined, and the fourth (code 4) is Chézy roughness height.

```
1       51      0.1
2       51      0.2
3       51      0.3
4       52      35
```

B.6.2.3 Discharge dependent format

The discharge dependent format is formatted as follows:

```
TrachytopeNr    DISCHARGE    "Cross-section name"
TrachytopeNr    Q1      FormulaNr     ...Parameters...
TrachytopeNr    Q2      FormulaNr     ...Parameters...
TrachytopeNr    Q3      FormulaNr     ...Parameters...
TrachytopeNr    Q4      FormulaNr     ...Parameters...
...
```

which again expects a user defined `TrachytopeNr`. The first row contains the keyword “DISCHARGE” and subsequently a cross-section name occuring in CrsFile in the mdu-file.

The cross-section name can be enclosed by quotation marks, for instance when the cross-section name is made up of more than one word. The subsequent rows all have the same `TrachytopeNr` as the first row and furthermore every `FormulaNr` should be the same. The list of discharges Q1, Q2, Q3, Q4 should be monotonically increasing.

The `...Parameters...` for each formula type are specified in section B.6.2.5.

B.6.2.4 Water level dependent format

The water-level dependent format is similar to the discharge dependent format and is formatted as follows:

```
TrachytopeNr    WATERLEVEL    "Observation-station name"
TrachytopeNr    ZS1      FormulaNr     ...Parameters...
TrachytopeNr    ZS2      FormulaNr     ...Parameters...
TrachytopeNr    ZS3      FormulaNr     ...Parameters...
TrachytopeNr    ZS4      FormulaNr     ...Parameters...
...
```

which again expects a user defined `TrachytopeNr`. The first row contains the keyword "WATERLEVEL" and subsequently an observation-station name occuring in ObsFile in the mdu-file. The observation-statopm name can be enclosed by quotation marks, for instance when the observation-station name is made up of more than one word. The subsequent rows all have the same `TrachytopeNr` as the first row and furthermore every `FormulaNr` should be the same. The list of waterlevels ZS1, ZS2, ZS3, ZS4 should be monotonically increasing.

The `...Parameters...` for each formula type are specified in section B.6.2.5.

B.6.2.5 Supported roughness formulations

The roughness formulations specified in the table below are supported by D-Flow FM. These formulations are specified in the .ttd by `FormulaNr` and `...Parameters...` in the order in which they appear in the table below. The related formulae are presented in the Technical Reference Manual

FormulaNr	Description	Parameters
Special classes (1–50)		
1	flood protected area, reduces the effective area of the grid cell. It has no influence on the continuity equation (i.e. it does not decrease the surface area of the grid cell).	–
2	composite trachytope: fraction α of type T_1 and fraction β (generally $\beta = 1 - \alpha$) of type T_2	T_1, T_2, α, β
Area trachytope classes: simple type (51–100)		
51 52 53 54	constant White-Colebrook/Nikuradse value constant Chézy value constant Manning value constant z_0 value	k [m] C [m$^{1/2}$/s] n [s/m$^{1/3}$] z_0 [m]
61 62 63 64	constant White-Colebrook/Nikuradse values for ebb and flood constant Chézy values for ebb and flood constant Manning values for ebb and flood constant z_0 values for ebb and flood	k_{ebb} [m], k_{flood} [m] C_{ebb} [m$^{1/2}$/s], C_{flood} [m$^{1/2}$/s] n_{ebb} [s/m$^{1/3}$], n_{flood} [s/m$^{1/3}$] $z_{0,ebb}$ [m], $z_{0,flood}$ [m]
Area trachytope classes: alluvial type (101–150)		
101 102 103[1] 104[1] 105[1] 106[1]	simplified Van Rijn power relation Van Rijn predictor Struiksma predictor bedforms quadratic bedforms linear	A [m$^{0.3}$], B [m$^{0.3}$] A [m$^{1/2}$/s], B [-] - A_1 [m$^{1/2}$/s], A_2 [-], θ_c [-], θ_m [-], $C_{\min}$ [m$^{1/2}$/s] - -
Area trachytope classes: vegetation type (151–200)		
151 152 153 154	Barneveld 1 Barneveld 2 Baptist 1 Baptist 2	h_v [m], n [1/m] h_v [m], n [1/m], C_D [-], k_b [m] h_v [m], n [1/m], C_D [-], C_b [m$^{1/2}$/s] h_v [m], n [1/m], C_D [-], C_b [m$^{1/2}$/s]
Linear trachytope classes: various (201–250)		
201 202	hedges 1 hedges 2	h_v [m], n [1/m] h_v [m], n [1/m]
Linear trachytope classes: various (251–300)		
251	trees	h_v [-], C_D [-]

[1] The alluvial roughness predictors 103, 104, 105 and 106 are not yet supported, because the coupling with the morphology module is not yet available.

B.7 Weirs

A fixed weir has many quantitites. On a polyline several quantitites has to be specified. In the table below an overview is given of all these quantities.

Keyword	Description	Default value
`X-coordinate`	X-coordinate of polyline point	-
`y-coordinate`	Y-coordinate of polyline point	-
`Crest level`	crest height	- [m]
`Sill up`	Sill height at left/bottom side	0.0 [m]
`Sill down`	Sill height at right/top	0.0 [m]
`Crest length`	length of weir in perpendicular direction	3.0 [m]
`Talud up`	Slope of weir at left/bottom side	4.0 [-]
`Talud down`	Slope of weir at right/top	4.0 [-]
`Vegetation coefficient`	Friction due to vegetation on weir	0.0 [-]
`Weir type`	(v)illemonte or (t)abellenboek	v [-]

The last column with the weir type (Villemonte or Tabellenboek) is optional. In this way, individual polyline can be given another weir type. For example, if FixedweirType=9 (Villemonte) has been specified in the MDU-file, then individual polylines can be set to Tabellenboek by adding a "t" to all points in the polyline; see the example below.

B.7.0.1 Example

An example of a polyline with fixed weir input is given below. It consists of a polyline with two points

```
(continued)
...
weir
     2     10
     399.999420   99.997688    2.0   0.2   0.8   3.0   4.0   4.0   0   t
     399.999420  100.999542    2.1   0.3   0.9   3.0   4.0   4.0   0   t

...
(continued)
```

In general, fixed weir polylines do not coincide with the computational grid. The polylines are snapped to flow links, which is illustrated in Figure 4.15. This is computed by the computational kernel of D-Flow FM.

In practice, it is possible that a certain flow link contains multiple snapped fixed weirs. This is for example the case when polylines with fixed weirs cross each other. Then, the fixed weir with the highest crest level is taken, because the crest level is used in the drying-flooding algorithm. In this way, overtopping of a weir the water level only occurs if the water level is above the weir with the highest crest level.

B.8 Calibration Factors

The calibration factor functionality is a multiplier for the rouhgness at different locations within the computational domain. Multiple formulation may be active in the same grid cell. Several keywords in the MDU file influence the functioning. All keywords below should be placed under the `[calibration]` section in the MDU file.

Keyword	Value	Description	Default
`UseCalibration`	1 or 0	Calibration factor option activated	N
`DefinitionFile`	<name.cld>	Calibration factor definition file	
`AreaFile`	<name.cll>	Calibration factor area file	

B.8.1 Calibration factor definition file (CLD-file)

The calibration class definition file contains lines of the following format defining the different calibration classes. It supports constant values and values that depend on the discharge at a named cross section or the water level at a named location.

B.8.1.1 Header of the CLD-file

The file starts with the following header

```
# [FileInformation]
#   FileType     = CalibrationFactorsDefinitionFile
#   FileVersion  = 1.0
# [CalibrationFactors]
```

B.8.1.2 Constant values

The format for constant values is as follows:

```
CalibrationClassNr  ConstantValue
```

where `ConstantValue` indicates the calibration value to be used (use 1.0 to use the uncalibrated roughness). The user must specify for each calibration class (line in this file) a unique calibration class number `CalibrationClassNr`. This calibration class number is used in the calibration area <.cll> file to indicate the area of influence of this class.

B.8.1.3 Discharge dependent format

The discharge dependent line is formatted as follows:

```
CalibrationClassNr DISCHARGE "Cross-section name"
CalibrationClassNr Q1 ConstantValueAtQ1
CalibrationClassNr Q2 ConstantValueAtQ2
CalibrationClassNr Q3 ConstantValueAtQ3
CalibrationClassNr Q4 ConstantValueAtQ4
...
```

which again expects a user defined calibration class number `CalibrationClassNr`. The first line contains the keyword `DISCHARGE` and subsequently a cross-section name occurring in the CrsFile in the mdu-file. The cross-section name can be enclosed by quotation marks, for instance when the name

contains spaces. The subsequent lines all start with the same calibration class number as the first line. The list of discharges `Q1`, `Q2`, `Q3`, and `Q4` should be monotonically increasing. For each discharge value a calibration value should be specified. Between the discharges specified, the calibration values are linearly interpolated. Below the minimum and above the maximum discharge the first and last values are used respectively.

B.8.1.4 Water level dependent format

The water-level dependent format is similar to the discharge dependent format and is formatted as follows:

```
CalibrationClassNr WATERLEVEL "Observation-station name"
CalibrationClassNr ZS1 ConstantValueAtZS1
CalibrationClassNr ZS2 ConstantValueAtZS2
CalibrationClassNr ZS3 ConstantValueAtZS3
CalibrationClassNr ZS4 ConstantValueAtZS4
...
```

which again expects a user defined calibration class number `CalibrationClassNr`. The first line contains the keyword `WATERLEVEL` and subsequently an observation-station name occurring in ObsFile in the mdu-file. The observation-station name can be enclosed by quotation marks, for instance when the name contains spaces. The subsequent lines all start with the same calibration class number as the first line. The list of water levels `ZS1`, `ZS2`, `ZS3`, and `ZS4` should be monotonically increasing. For each water level value a calibration value should be specified. Between the water levels specified, the calibration values are linearly interpolated. Below the minimum and above the maximum water level the first and last values are used respectively.

B.8.1.5 Example

The example file given below defines three calibration classes. In the area associated with the first class, the roughness values are used without any adjustment. In the area associated with the second class, the roughness value is decreased by 20%. In the area associated with the third and final class, the increase in the roughness value varies between 0% and 30% depending on the discharge at a specific location.

```
# [FileInformation]
#   FileType     = CalibrationFactorsDefinitionFile
#   FileVersion  = 1.0
# [CalibrationFactors]

# areas without any calibration adjustment
1 1.0

# areas with 20% decreased roughness value
2 0.8

# area with calibration depending on discharge at crsX
10 DISCHARGE 'crsX'
10 500  1.0
10 1000 1.1
10 3000 1.3
```

B.8.2 Calibration Class Area on Links (CLL-file)

B.8.2.1 Header of the CLL-file

The file starts with the following header

```
# [FileInformation]
#   FileType     = CalibrationAreasFile
#   FileVersion  = 1.0
# [CalibrationAreas]
```

B.8.2.2 Body of the CLL-file

The body of the CLL-file consists of comment lines (any line starting with # or *) or data lines of the following format:

```
xu yu zu CalibrationClassNr AreaFraction
```

where `xu`, `yu`, `zu` is the coordinate of the midpoint of the netlink, `CalibrationClassNr` is an integer corresponding to the number as described in the Calibration Class Definition File (cf. section B.8.1), and `AreaFraction` is an area fraction between 0.0 and 1.0.

All lines that list the same `xu`, `yu`, `zu` coordinates are combined to a weighted average of multiple calibration classes, provided the sum of the fractions does not add to a value greater than 1.0.

If the sum of the areas specified for a certain netlink is less than 1.0, then the a constant calibration factor of 1.0 is assumed for the remaining area (i.e. no calibration effect). The result is that if for a specific netlink no line is specified at all, then the roughness of this netlink will be unaffected by the calibration process.

B.8.2.3 Example

The example of the <CLL>-file is given below based on the <CLD>-file given in section B.8.1. In this case the roughness at netlink with midpoint located at `xu` = 10.542 and `yu` = 11.6 is completely affected by calibration class 1, the netlink with midpoint at `xu` = 11.120 and `yu` = 12.1 is affected for 60% by calibration class 1 and 40% by calibration class 10, and the final location listed uses only the value resulting from calibration class 10.

```
...
10.542 11.6 0 1 1.0
11.120 12.1 0 1 0.6
11.120 12.1 0 10 0.4
12.635 12.6 0 10 1.0
...
```

B.9 Sources and sinks

Sources and sinks (section 7.8) are defined as part of the <*.ext> file, as follows:

```
QUANTITY=discharge_salinity_temperature_sorsin
FILENAME=chan1_westeast.pli  # A file 'chan1_westeast.tim', with same basename
                             # as the polyline should be present
FILETYPE=9
METHOD  =1
OPERAND =O
AREA    =1.5
```

The <∗.pli> file is a polyline file (section B.2) with two or three columns (for 2D or 3D models, respectively). Along with the <∗.pli>-file, there has to be a time series file (section D.2.1) with the same basename as the <∗.pli>-file, and extension <.tim>. The columns in the <∗.tim> are as follows: time in minutes, discharge Q in [m^3/s], and *all* constituents in the model. The order of consituents is: salinity in [ppt], temperature T in [°C], sediment concentrations, spiral flow intensity and tracers. For example, if we only have temperature and two tracers we get 5 columns: time, discharge, temperature, tracer 1, tracer 2.

B.10 Dry points and areas

Dry points can either be defined by a basic sample file (see section B.3), or a polygon file (see section B.2).

Special attention must be given to the optional third column of a polygon file: when the first point has a z-value of -1, the polygon mask is inverted, i.e., all points outside the polygon are set as dry points.

More details can be found in section 4.4.2.7.

B.11 Structure INI file

Hydraulic structures are defined in a <structures.ini> file. Each structures is defined in its own `[structure]` section, followed by a set of key-value parameters that depend on the type of structure:

```
[structure]
type                  = weir                # Type of structure
id                    = weir01              # Name of the structure
polylinefile          = weir01.pli          # *.pli; Polyline location for structure
crest_level           = weir01_crest.tim    # Crest level in [m]

[structure]
type                  = gate                # Type of structure
id                    = gate01              # Name of the structure
polylinefile          = gate01.pli          # *.pli; Polyline location for structure
sill_level            = gate01_crest.tim    # Sill (crest) level in [m]
sill_width            = 39.5                # (Optional) sill width in [m], between
                                          # the fixed side walls.
door_height           = 8.54                # Gate door height in [m], used for
                                          # detecting flow across door.
lower_edge_level      = gate01_ledge.tim    # Position of gate's lower edge in [m],
                                          # used for flow underneath door.
opening_width         = gate01_opening.tim  # (Optional) opening width between two
                                          # sideways closing gate doors.
horizontal_opening_direction = from_left/from_right/symmetric # (Optional) Opening
                                          # direction of the gate door(s).

[structure]
type                  = pump                # Type of structure
id                    = pump01              # Name of the structure
polylinefile          = pump01.pli          # *.pli; Polyline location for structure
capacity              = pump01_cap.tim      # Pumping capacity in [m3/s]
```

B.12 Space varying wind and pressure

In many cases the space varying wind data is provided by a meteorological station. This data is often defined on a different grid than the computational grid used in D-Flow FM. Translating these files into files defined on the grid of the computational engine is often a lengthy process and can result in huge files. This feature facilitates the reading of the meteorological data on its own grid and interpolates the data internally to the grid of D-Flow FM. D-Flow FM can handle three types of meteorological input:

1 Time- and space-varying wind on an equistant grid
2 Time- and space-varying wind on a curvilinear grid
3 Time- and space-varying wind on a Spiderweb grid

B.12.1 Meteo on equidistant grids

File contents	Time-series of a space varying wind and atmospheric pressure defined on an equidistant (Cartesian or spherical) grid.
File format	Free formatted or unformatted, keyword based.
Generated	Some offline program.

Remark:
- ◇ The keywords are case insensitive.

Header description for the wind velocity files:

Keywords	Value	Description
`FileVersion`	1.03	version of file format
`Filetype`	meteo_on_equidistant_grid	meteo input on equidistant grid
`NODATA_value`	*free*	value used for input that is to be neglected
`n_cols`	*free*	number of columns used for wind datafield
`n_rows`	*free*	number of rows used for wind datafield
`grid_unit`	m *or* degree	unit of distances on the grid in both x- and y-direction
`x_llcorner`	*free*	x-coordinate of lower left corner of lower left grid cell (in units specified in `grid_unit`
`y_llcorner`	*free*	y-coordinate of lower left corner of lower left grid cell (in units specified in `grid_unit`
`x_llcenter`	*free*	x-coordinate of centre of lower left grid cell (in units specified in `grid_unit`
`y_llcenter`	*free*	y-coordinate of centre of lower left grid cell (in units specified in `grid_unit`
`dx`	*free*	gridsize in x-direction in units specified in `grid_unit`
`dy`	*free*	gridsize in y-direction in units specified in `grid_unit`
`n_quantity`	1	number of quantities specified in the file
`quantity1`	x_wind *or* y_wind	the velocity component given in unit `unit1`

Keywords	Value	Description
unit1	m s-1	unit of quantity1: metre/second

The user must specify the location of the equidistant grid on which the meteorological data is specified. If one has the location of the lower left corner of the lower left grid cell, one can specify the starting point of the grid using keywords x_llcorner and y_llcorner. If one has the location of the cell centre of the lower left grid cell, one should use the keywords x_llcenter and y_llcenter. Using the first option, the first data value is placed at (x_llcorner$+\frac{1}{2}dx$, y_llcorner$+\frac{1}{2}dy$), which is the cell centre of cell (1,1). Using the latter option, the first data value is placed at (x_llcenter, y_llcenter), which is again the cell centre of cell (1,1), i.e. the data values are always placed at the cell centres of the meteorological grid. Note that the lower left grid cell is defined to be the grid cell with index (1,1). When using the option of meteorological data on a separate curvilinear grid, the origin and orientation of the data set can be chosen freely with respect to the grid on which it is specified, see section B.12.2 for details.

Time definition and data block description for the wind velocity files

Keywords	Value	Description
Time	*fixed format described below*	time definition string

The time definition string has a fixed format, used to completely determine the time at which a dataset is valid. The time definition string has the following format:

TIME *minutes/hours since* YYYY-MM-DD HH:MM:SS TIME ZONE, e.g.

```
360 minutes since 2008-07-28 10:55:00 +01:00
```

The format of the string is completely fixed. No extra spaces or tabs can be added between the different parts of the definition. The time definition is followed by the datablock of input values corresponding to the specified time. The data block contains values for the wind velocity in x- or y-direction for *n_cols* by *n_rows* points, starting at the top left point. The time definition and the data block are repeated for each time instance of the time-series.

The atmospheric pressure file

The header for the atmospheric pressure is similar to that of the wind velocity files, except for the following differences.

Keywords	Value	Description
quantity1	air_pressure	air pressure
unit1	Pa *or* mbar	unit of quantity1: Pascal or millibar

The specification of the time definition and the data block is fully conform the wind velocity files.

File version and conversion

The current description holds for FileVersion 1.03. The table below shows the latest modifications in the file format (and version number).

FileVersion	Modifications
1.03	Use of keyword Value_pos to indicate the position of the lower left corner of the grid replaced by use of the combination of keywords: x_llcorner and y_llcorner or x_llcenter and y_llcenter
1.02	No changes for this meteo input type, but for the meteo type *meteo_on_spiderweb_grid*
1.01	Changed keyword MeteoType to FileType Changed fixed value of input type (Keyword Filetype) from *ArcInfo* to *meteo_on_equidistant_grid*

Restrictions:

- ◇ The contents of the file will not be checked on its domain.
- ◇ Keywords are followed by an equal sign '=' and the value of the keyword.
- ◇ When a keyword has value *free*, the value of this keyword is free to choose by the user. When only one value is given for a keyword, this keyword has a fixed value and when 2 or more options are shown, the user can choose between those values.
- ◇ Times must be specified exactly according to the time definition. See the examples shown in this section.
- ◇ The atmospheric pressure file must use the same grid definition and time frame as the files for the wind velocity components.
- ◇ The unit of the meteo grid must be the same as the computational grid, i.e. both with grid_unit = [m] or both with grid_unit = [degree].
- ◇ Input items in a data block are separated by one or more blanks.
- ◇ The wind components are specified at the cell centres (water level points) of the numerical grid.
- ◇ The wind components are specified in the west-east (x_wind) and south-north directions (y_wind).

Remarks:

- ◇ The time definition in the meteo files contains the number of minutes or hours since a reference date and time in a certain time zone. The reference time and time zone may differ from those of the simulation. During a simulation the computational engine will search in the meteo file for the current simulation time and interpolate between neighbouring times if necessary. Possible differences in time zone will be accounted for by shifting the meteo input data. The reference times within the time definition string may vary in a meteo file, i.e. it is possible to attach new input with a different reference time, behind the last data block. Consecutive times must always be increasing in the input file.
- ◇ Comments can be added after pound signs (#). These are not read.

Example of a file containing wind in x-direction (west-east)

The data blocks in this example are the result of the following FORTRAN statements:

```
do j = nrows,1,-1
   write(out,*) (xwind(i,j),i=1,ncols)
enddo
```

The x-wind velocity file for a 3 (n_cols) by 4 (n_rows) grid has the following layout:

```
FileVersion      =    1.03
filetype         =    meteo_on_equidistant_grid
NODATA_value     =    -999.000
n_cols           =    3
n_rows           =    4
grid_unit        =    degree
x_llcenter       =    -12.000
```

```
y_llcenter       =     48.000
dx               =    0.12500
dy               =    0.083333333
n_quantity       =    1
quantity1        =    x_wind
unit1            =    m s-1
TIME =      0.0 hours since 2008-01-15 04:35:00 +00:00
2   3.0  3.6
3   4.5  2
2.2 1    2.3
1.2 0.7 -0.4
TIME =      6.0 hours since 2008-01-15 04:35:00 +00:00
-1.1 -2.3 -3.6
-3.2  0.8  1.1
 2.2 -1   -1.6
 1.2 -0.7 -0.4
```

This results in an x-component of wind velocity given - in [m/s] - on a spherical, 3 by 4, equidistant grid, with grid sizes given by *dx* and *dy* (in degrees) and where the centre point of the lower left cell of the grid lies in (longitude, latitude) (-12.0, 48.0) on the globe. Data is given at two times: 0 and 6 hours since January 15th, 2008, 4:35 AM, in UTC+0.

Remark:

- ◇ The layout of the data blocks is from north to south (whereas most of the other files in Delft3D-FLOW, such as the curvilinear grid file, are ordered from south to north).
  Usually the signal corresponds to Mean Sea Level. One actually wants to prescribe an input signal corresponding to the local pressure prescribed by the space varying meteo input. To this end, it is possible to specify an average pressure - which should correspond to your input signal on the open boundaries - which is then used to determine local pressure gradients that need to be applied along the open boundaries to obtain an input signal that is consistent with the local atmospheric pressure. Using this keyword one can specify an average pressure that is used on all open boundaries, independent of the type of wind input. The pressure must be specified in N/m^2. An example:

B.12.2 Curvilinear data

File contents	Time-series of a space varying wind and atmospheric pressure defined on a curvilinear (Cartesian or spherical) grid.
File format	Free formatted or unformatted, keyword based.
Generated	Some offline program.

Remark:

- ◇ The keywords are case insensitive.

Header description for the wind velocity files:

Keywords	Value	Description
`FileVersion`	1.03	version of file format
`Filetype`	meteo_on_curvilinear_grid	meteo input on curvilinear grid
`NODATA_value`	*free*	value used for input that is to be neglected
`grid_file`	*free*.grd	name of the curvilinear grid file on which the data is specified
`first_data_value`	grid_llcorner *or* grid_ulcorner *or* grid_lrcorner *or*	*see example below*

Keywords	Value	Description
	grid_urcorner	
data_row	grid_row *or* grid_column	*see example below*
n_quantity	1	number of quantities specified in the file
quantity1	x_wind *or* y_wind	the velocity component given in unit unit1
unit1	m s-1	unit of quantity1: metres/second

Time definition and data block description for the wind velocity files

For a description of the time definition and data block see section B.12.1.

The atmospheric pressure file

For a description of the atmospheric file see section B.12.1.

File version and conversion

The current description holds for FileVersion 1.03. The table below shows the latest modifications in the file format (and version number).

FileVersion	Modifications
1.03	Fixed bug in interpolation of data from meteo grid to computational grid: Conversion script mirrored data set erroneously. This was treated correctly by meteo module. Fixed both the conversion script and the meteo module together: Required modification in meteo input file: Change first_data_value = grid_llcorner into grid_ulcorner or vice versa or Change first_data_value = grid_lrcorner into grid_urcorner or vice versa
1.02	No changes for this meteo input type, but for the meteo type *meteo_on_spiderweb_grid*
1.01	Changed keyword MeteoType to FileType Changed keyword Curvi_grid_file to Grid_file Changed fixed value of input type (Keyword Filetype) from *Curvi* to *meteo_on_curvilinear_grid*

Restrictions:

- The restrictions for space varying wind and pressure on a separate curvilinear grid are the same as for space varying wind and pressure on an equidistant grid, described in section B.12.1. A differerence is that the data values on the curvilinear grid are not specified in the cell centres, but in the grid points (cell corners).
- The unit of the meteo grid must be the same as the computational grid, i.e. both with grid_unit = [m] or both with grid_unit = [degree].

Remark:

◇ The remarks for space varying wind and pressure on a separate curvilinear grid are the same as for space varying wind and pressure on an equidistant grid, described in section B.12.1.

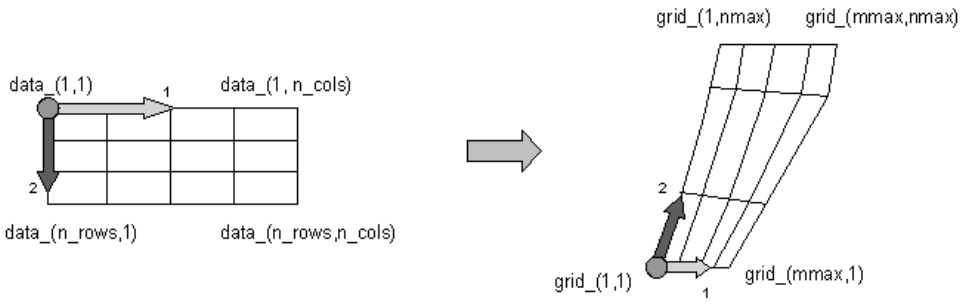


Figure B.1: *Illustration of the data to grid conversion for meteo input on a separate curvilinear grid*

Example:

A file for input of x-velocity (in west-east direction) on a 4 (n_rows) by 5 (n_cols) curvilinear grid, where the meteorogical data is mirrored vertically with respect to the grid, has the following layout:

```
FileVersion      =    1.03
filetype         =    meteo_on_curvilinear_grid
NODATA_value     =    -999.000
grid_file        =    curviwind.grd
first_data_value =    grid_llcorner
data_row         =    grid_row
n_quantity       =    1
quantity1        =    x_wind
unit1            =    m s-1
TIME =      0.0 minutes since 1993-06-28 14:50:00 -02:00
 1   2   3   4   5
 6   7   8   9  10
11  12  13  14  15
16  17  18  19  20
TIME =      600.0 minutes since 1993-06-28 14:50:00 -02:00
 1   2   3   4   5
 6   7   8   9  10
11  12  13  14  15
16  17  18  19  20
```

This results in an x-component of velocity given - in [m/s] - on the curvilinear grid specified in file <curviwind.grd>. The data set will be mirrored such that the first value of the data (upper left corner, in the example '1') corresponds to the lower left corner of the grid (point (1,1)) and a row of data corresponds to a row on the grid, see Figure B.1. Data is given at two times: 0 and 600 minutes since June 28th, 1993, 14:50 PM, in UTC-2.

B.12.3 Spiderweb data

Remarks:

- ◇ The spiderweb file format used in D-Flow FM forms a subset of the the format described below. The extensive format is accepted by D-Flow FM, but not all keywords are required and/or meaningful.
- ◇ The keywords `grid_unit` and `air_pressure_reference` are ignored.
- ◇ The keyword `n_quantity` is ignored; the number of quantities is always 3.
- ◇ The keywords `quantity1`, `quantity1` and `quantity1` are ignored, the order of the variables in the file is assumed to be wind speed, wind direction and pressure drop.
- ◇ The keywords `unit1` and `unit2` are ignored.
- ◇ The keyword `unit3` is optional; if omitted or different from '`mbar`', Pa is silently assumed

Cyclone winds are governed by a circular motion, combined with a cyclone track. This type of wind is generally very difficult to implement on a curvilinear grid. This feature facilitates the reading of the so-called Spiderweb files and interpolates the wind and pressure data internally to the computational grid. A special feature of the space varying wind and pressure on the Spiderweb grid is that it can be combined with one of the other meteorological input options described in this manual, i.e. to either uniform wind and pressure, or to one of the space varying wind and pressure options, see section B.12.

File contents	Time-series of a space varying wind and atmospheric pressure defined on a Spiderweb grid. This grid may be specified in Cartesian or spherical coordinates.
File format	Free formatted or unformatted, keyword based.
Generated	Some offline program.

Remarks:

- ◇ The keywords are case insensitive.
- ◇ Space varying wind and pressure on a Spiderweb grid is added to other wind input and the wind fields are interpolated and combined in and around the cyclone.

Header description of the Spiderweb wind and pressure file:

Keywords	Value	Description
`FileVersion`	1.03	version of file format
`Filetype`	meteo_on_spiderweb_grid	meteo input on Spiderweb grid
`NODATA_value`	*free*	value used for input that is to be neglected
`n_cols`	*free*	number of gridpoints in angular direction
`n_rows`	*free*	number of gridpoints in radial direction
`grid_unit`	m *or* degree	unit of the Spiderweb grid
`spw_radius`	*free*	radius of the spiderweb given in units given by `spw_rad_unit`
`spw_rad_unit`	m	unit of the Spiderweb radius
`spw_merge_frac`	[0.0,1.0]	fraction of the Spiderweb radius where merging starts of the background wind with the Spiderweb wind. Default is 0.5
`air_pressure`	air_pressure_default_from	Both keyword and value are too

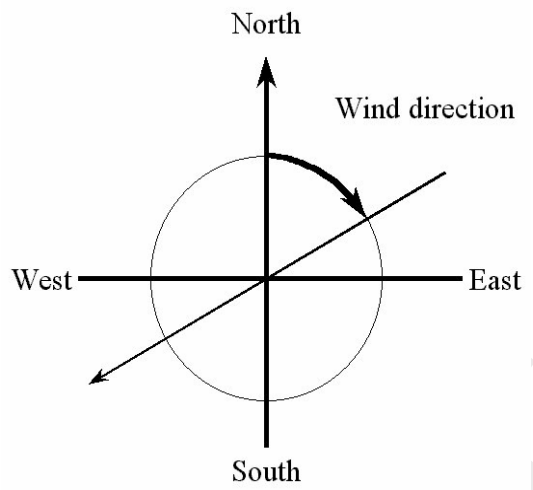


Figure B.2: *Wind definition according to Nautical convention*

Keywords	Value	Description
`_reference`	_computational_engine *or free*	long to fit on one line. Reference value related to p_drop is the default air pressure of the computional engine *or* the value specified. If missing, p_drop is extracted from the actual atmospheric pressure.
`n_quantity`	3	number of quantities specified in the file
`quantity1`	wind_speed	wind speed given in unit `unit1`
`quantity2`	wind_from_direction	direction where the wind is coming from given in unit `unit2`
`quantity3`	p_drop	drop in atmospheric pressure given in unit `unit3`
`unit1`	m s-1	unit of `quantity1`: metres/second
`unit2`	degree	unit of `quantity2`: degrees
`unit3`	Pa *or* mbar	unit of `quantity3`: Pascal or millibar

Time definition and data block description

For a description of the time definition see section B.12.1.

Cyclone track information:

For each time in the time series of space varying wind and pressure on a Spiderweb grid, the position of the cyclone eye (and thus also the spiderweb grid) must be given, as well as the drop of atmospheric pressure in the cyclone eye.

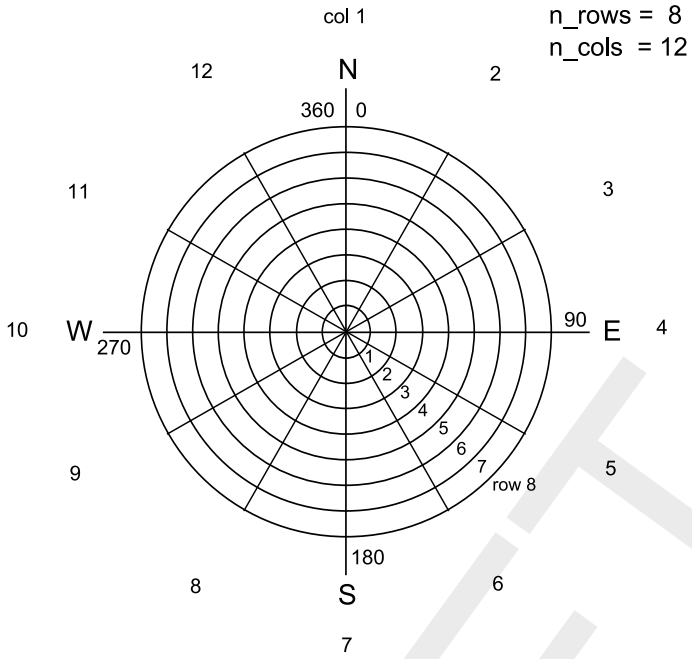


Figure B.3: *Spiderweb grid definition*

File version and conversion

The current description holds for `FileVersion` 1.03. The table below shows the latest modifications in the file format (and version number).

FileVersion	Modifications
`1.03`	No changes for this meteo input type
`1.02`	Changed the use of keyword `n_rows` and `n_cols`. The radius of the cyclone is divided in *n_rows* rings of width: spw_radius/n_rows [m] and the circle is divided in *n_cols* parts of $2\pi/n\_cols$ [rad].
`1.01`	Changed keyword `MeteoType` to `FileType` Changed fixed value of input type (Keyword `Filetype`) from *Spiderweb* to *meteo_on_spiderweb_grid*

Restriction:

- ◇ The restrictions for space varying wind and pressure on a Spiderweb grid are the same as for space varying wind and pressure on an equidistant grid, described in section B.12.1.

Remarks:

- ◇ The remarks for space varying wind and pressure on a separate curvilinear grid are the same as for space varying wind and pressure on an equidistant grid, described in section B.12.1.
- ◇ The Spiderweb grid is circular and the definitions of the number of rows `n_rows` and the number of columns `n_cols` is therefore different then for the other meteo input formats. For the Spiderweb grid, the number of rows determines the grid size in radial direction. The number of columns defines the grid size in angular direction. See Figure B.3.
- ◇ The wind is specified according to the nautical convention, i.e. wind from the true North has direction zero and the wind turns clockwise with an increasing angle. See Figure B.2.

Example:

A file for input of space varying wind and pressure on a 5x3 Spiderweb grid, has the following layout:

```
FileVersion            = 1.03
filetype               = meteo_on_spiderweb_grid
NODATA_value           = -999.000
n_cols                 = 3
n_rows                 = 5
grid_unit              = degree
spw_radius             = 600000.0
spw_rad_unit           = m
air_pressure_reference = air_pressure_default_from_computational_engine
n_quantity             = 3
quantity1              = wind_speed
quantity2              = wind_from_direction
quantity3              = p_drop
unit1                  = m s-1
unit2                  = degree
unit3                  = Pa
TIME          =    0.0 hours since 1997-07-14 03:00:00 -06:00
x_spw_eye     = 115.1
y_spw_eye     = 18.9
p_drop_spw_eye = 5300.0
1.38999       1.38261       1.38315
1.28251       1.34931       1.22571
1.27215       1.31214       1.32451
1.38999       1.86592       2.87732
1.43899       1.24912       2.21519
60.0000       180.0000      270.0000
28.7500       20.0000       31.2500
42.5000       53.7500       65.0000
49.3400       60.2400       81.5200
51.4100       62.0000       43.1200
5301.280      5294.490      5156.240
5043.460      5112.040      5264.020
5140.020      5202.520      5411.210
5294.730      5285.760      5235.250
5242.530      5156.190      5124.240
TIME          =     1.0 hours since 1997-07-14 03:00:00 -06:00
x_spw_eye     = 114.8
y_spw_eye     = 18.8
p_drop_spw_eye = 5250.0
1.35763       1.35763       1.35763
1.35763       1.87273       2.24784
1.92214       2.47836       2.17266
1.87662       2.72116       2.82375
1.26585       2.24146       2.38722
159.0000      346.5200      290.6400
342.3200      282.1400      20.2400
10.7500       25.5300       36.4500
61.8400       81.6200       45.5100
49.5250       56.7500       75.1300
5314.520      5104.490      5287.240
5124.240      5285.760      5252.420
5152.460      5247.040      5222.020
5242.020      5223.520      5475.210
5244.270      5211.210      4998.110
```

This results in the following set of meteo data. Velocities given in [m/s] and pressure drops in [Pa] on a Spiderweb grid which is given in spherical coordinates (`grid_unit` = degree). The cyclone and spiderweb grid have a radius of 600 km. The grid is 5x3, which means the radius is divided in five parts of 120 km and the 360 degrees are divided in 3 parts of 120 degrees each. Wind speeds, wind directions and pressure drops are given at two times: 0 and 1.0 hour since July 14th, 1997, 03:00 AM, in UTC-6. Between these two times the cyclone eye moves from (longitude, latitude) (115.1, 18.9) to

(114.8, 18.8) on the globe and the pressure drop in the cylcone eye decreases from 5300.0 [Pa] to 5250.0 [Pa].

B.12.4 Fourier analysis

File contents	All parameters required to execute an online Fourier analysis for specified quantities, a specified period and for specified frequencies (Data Group *Output - Storage*).
Filetype	ASCII
File format	Fix formatted for text variables, free formatted for real and integer values.
Filename	<*name*.fou>
Generated	Manually offline

Record description:

Record	Record description
each record	Variable on which the Fourier analysis is to be performed (2 characters): wl water levels uv velocities qf mass fluxes of water ct temperature cs salinity cn n-th constituent in the MDF-file bs bed stress Analysis start time in minutes after 00:00:00 on the Reference Date, Analysis stop time in minutes after 00:00:00 on the Reference Date, Number of cycles within the analysis time frame, Nodal amplification factor, Astronomical argument, Layer number for the Fourier analysis, Flag for the computation of elliptic parameters: y/n (default no) if number of cycles $>$ 0, min/max if number of cycles = 0.

Remarks:

- ◇ If the number of cycles is set equal to 0, the mean level of the variable over the interval specified by the start and stop time is determined.
- ◇ If, in addition, the flag for the computation of elliptic parameters is set to “max” or “min” the maximal or minimal value is determined of the selected variable as it occured during the simulation.
- ◇ Computed Fourier amplitudes slightly differ from the amplitude of the corresponding tidal component. When comparisons with co-tidal maps have to be made, this factor can be determined using the subsystem ASCON of Delft3D-TIDE, the tidal analysis package of Deltares.
- ◇ Computed Fourier phases are related to the reference date of the FLOW computation. For comparisons with co-tidal maps a phase shift equal to the astronomical argument has to be applied.
- ◇ The layer number is not relevant for water levels.
- ◇ For computational cells which are dry during all Fourier cycles, no values are associated, and hence they contain missing value.

Restrictions:

- ◇ Times specified must be a multiple of the computational time step.
- ◇ Times specified must be a valid time, i.e. must fit in the simulation time frame of the FLOW computation.
- ◇ Items in a record must be separated by one or more blanks.
- ◇ The variable’s name must start in position one.

Example:

A Fourier analysis is requested for:

- ◇ Water level: mean value and the first two harmonics.
- ◇ U- and V-velocity: first harmonic, in the top layer (1).
- ◇ Mass fluxes of water: first harmonic, in the top layer (1).
- ◇ Temperature: first harmonic, in the third layer.
- ◇ Salinity: mean value of the third layer.
- ◇ Four constituents: mean value for a slightly shifted time period in the top layer for 3 constituents; and the maximum for the fourth constituent.

```
wl      720.    1440.     2    1.000   0.000
wl      720.    1440.     1    1.000   0.000
wl      720     1440.     0    1.000   0.000
uv      720.    1440.     1    1.000   0.000      1
qf      720.    1440.     1    1.000   0.000      1
ct      720.    1440.     1    1.000   0.000      3
cs      720.    1440.     0    1.000   0.000      3
c1      710.    1430.     0    1.000   0.000      1
c2      710.    1430.     0    1.000   0.000      1
c3      710.    1430.     0    1.000   0.000      1
c4      710.    1430.     0    1.000   0.000      1    max
```

Remark:

- ◇ A layer value of 0 in a 3D model is not allowed; i.e. this will NOT result in a depth-averaged value.

C Initial conditions and spatially varying input

C.1 Introduction

Spatially varying input is input data that varies in space, not in time, such as initial conditions (water levels, etc.), or spatially varying model parameters (friction coefficients, etc.). D-Flow FM uses input data in *model-independent coordinates*, that is, the input files should contain their own spatial coordinates, and do not correspond with the D-Flow FM grid cell numbering. As a result, the model grid can always be changed, without the need to change all other spatial input. The spatial input will be interpolated onto the active model grid. Spatial input has to be specified in the ext-file (section B.5). All supported quantities are listed in Table B.1 under "Initial fields" and "Spatial physical properties".

Initial conditions can also be set using a restart-file, which assigns the exact values in the file to the current model grid. No interpolation is performed, and the restart file should correspond exactly with the current model.

C.2 Supported quantities

C.2.1 Water levels

Water levels can come from both all file types listed below. The restart file sets the water level both at the old and new time step. Non-restart files should be specified using `QUANTITY=initialwaterlevel`.

C.2.2 Initial velocities

Initial velocities should come from restart files, such that they exactly correspond with the model's waterdepths. They can also come from non-restart files using `QUANTITY=initialvelocityx/y`, but this is not advised.

C.2.3 Salinity

Salinity concentrations from non-restart files are possible as spatially varying, depth-averaged values, or (for 3D models) as linearly interpolated values between a top layer concentration and a bottom layer concentration. The latter is achieved by specifying two `QUANTITY` blocks: `initialsalinity` and `initialsalinitytop`. For 3D models, alternatively, spatially constant, but depth-varying salinities can be set using the `QUANTITY=initialverticalsalinityprofile`, and a vertical profile file (see section C.3.3).

C.2.4 Temperature

Temperature values from non-restart files are possible as depth-averaged values, using `QUANTITY=initialtemperature`.

For 3D models, alternatively, spatially constant, but depth-varying temperatures can be set using the `QUANTITY=initialverticaltemperatureprofile`, and a vertical profile file (see section C.3.3).

C.2.5 Tracers

Initial tracer concentrations from non-restart files are similar to temperature values, now specified using `QUANTITY=initialtracer`<*tracername*>. The set of tracer name(s) is not listed in the MDU-file explicitly, they are inferred from all supplied initial tracer definitions *and* the tracer boundary conditions (see also section D.1.6). The <*tracername*> postfix can uniquely associate an `initialtracer` quantity with a `tracerbnd` quantity.

C.2.6 Sediment

Initial sediment concentrations for the Delft3D-SED-based sediment transport module (see section 8.2 for an explanation) is via the <∗.sed> file. See the Delft3D-SED User Manual for further details.

C.2.7 Physical coefficients

A second group of spatially varying input are the physical and numerical coefficients listed below. They allow changing model parameters in space or in certain sub-regions of the domain, and as such these values override the uniform values from the MDU file. The input data can come from the in-polygon file type (section C.3.1 or the sample file type (section C.3.2).

quantity name	MDU uniform equivalent	description
`frictioncoefficient`	`UnifFrictCoef`	Friction coefficient (use `IFRCTYP` and `UnifFrictType`, resp. to set the friction type.
`horizontaleddy... ...viscositycoefficient`	`Vicouv`	Horizontal eddy viscosity coefficient (m^2/s).
`horizontaleddy... ...diffusivitycoefficient`	`Dicouv`	Horizontal eddy diffusivity coefficient (m^2/s).
`advectiontype`	`AdvecType`	Type of advection scheme.
`ibotlevtype`	`BedlevType`	Type of bed-level handling.

C.3 Supported file formats

All file formats below, except for restart files, are in *model-independent coordinates* and will be cropped and/or interpolated onto the model grid.

C.3.1 Inside-polygon option

A spatially constant value in a restricted part of the domain can be set by specifying a polygon file (section B.2) in the ext-file as follows:

```
QUANTITY=frictioncoefficient
FILENAME=winterbed.pol
FILETYPE=10
METHOD  =4
VALUE   =55
IFRCTYP =1  # Optional, override uniform [physics] UnifFrictType=..
```

The interpolation option `METHOD=4` simply specifies the no-interpolation is to be performed, only inside-polygon cropping. For `QUANTITY=frictioncoefficient` the default friction type may be overridden with the keyword `IFRCTYP`.

C.3.2 Sample file

Spatial data from sample files (<∗.xyz>, see section B.3) is interpolated by triangle interpolation or sample averaging. The following options control the type of interpolation:

interpolation method	options	description
METHOD=5		Triangle interpolation
	EXTRAPOLTOL=20	Allow extrapolation from convex hull of samples up to . . . meters (default: 0).
METHOD=6		Sample averaging inside control volumes:
	AVERAGINGTYPE=1	Normal (unweighted) averaging
	AVERAGINGTYPE=2	Nearest neighbour
	AVERAGINGTYPE=3	Maximal value
	AVERAGINGTYPE=4	Minimal value
	AVERAGINGTYPE=5	Inverse weighted distance averaging
	AVERAGINGTYPE=6	Minimal absolute value
	RELATIVESEARCHCELLSIZE =. . .	Control size of search volume: 1=actual cell, 1.5=50 % larger in all directions.

C.3.3 Vertical profile file

Initial values that are constant in 2D space, but vary in depth can be specified using vertical profile files, which are basic polyline files (section B.2). For example for a linearly varying salinity from 30 to 20 ppt from -10 to 0 m :

```
L1
2 2
-10 30
 0 20
```

The METHOD keyword must be specified, but is further ignored: linear interpolation is always used.

C.3.4 Map file

Initial field data from a map file may be used as non-restart input. Values are read in from the map files as if they were samples, and further treated and interpolated as such. All interpolation options from section C.3.2 can be used here. This option may be used as a non-exact restart state when the model grid has been changed (e.g., locally refined or cropped to a subdomain).

C.3.5 Restart file

Restart files are discussed in section E.3.3. They should be included in your model in the mdu-file as follows:

```
[restart]
RestartFile     = mdu_name_yyyymmdd_HHMMSS_rst.nc
RestartDateTime = # Restart time (YYYYMMDDHHMMSS), only relevant
                  # in case of restart from *_map.nc
```

Concerning parallel runs, each subdomain can generate its own restart/map file. To restart a parallel run, one can use any of the following approaches:

- ◇ On each subdomain use its own restart/map file, provided that the partition does not change. (This means that in each partition MDU file specify its own restart/map file.)
- ◇ Merge the subdomain restart/map files to one global file (see 5.2.5.2). This file enables to restart a parallel run with a different or the same partition. (This means that specify the merged file for all the partition MDU files.) One can also run a sequential simulation with this merged restart/map file.

D Boundary conditions specification

Boundary conditions are part of the external forcing of a model and and as such declared in the external-forcings file (section B.5).

D.1 Supported boundary types

D.1.1 Astronomic boundary conditions

Boundary values can be specified for any location in terms of astronomical components in attribute files with extension <cmp> (the BC-format, discussed furtheron, is supported as an alternative). Tidal motion are described as a series of simple harmonic constituent motions, each with its own characteristic period:

$$H(t) = A_0 + \sum_{i=1}^{k} A_i F(c_i) \cos\left(\frac{2\pi}{T(c_i)} t + (V_0 + u)\,(c_i) - G_i\right) \tag{D.1}$$

in which:

c_i	i-th component, specified by label (name)
A_i	amplitude of the i-th component
G_i	phase of the i-th component
$T(c_i)$	period
$H(t)$	boundary value at time t
A_0	constant offset value
k	number of relevant components
$F(c_i)$	nodal amplitude factor
$(V_0 + u)(c_i)$	astronomical argument

The component (by label) c_i, amplitude A_i and phase G_i for each component i are required in the <cmp>-file In addition to the primary constituents, compound and higher harmonic constituents may have to be used. This is the case in shallow water areas for example, where advection, large amplitude to depth ratio, and bottom friction give rise to non-linear interactions.

F, V_0 and u are also *time-dependent*. For a given period, their values are easily calculated or obtained various tidal year books. V_0 is a frequency dependent phase correction factor relating the local time frame of the observations to an internationally agreed celestial time frame. F_i and u_i are slowly varying amplitude and phase corrections, The variations depend on the frequency, often with a cyclic period of 18.6 years. By default, the nodal amplitude factors and astronomical arguments are re-calculated every 6 hours.

D.1.2 Astronomic correction factors

For individual astronomic components, correcting factor α_i for amplitude and offset δ_i may be specified by the user so that the effective amplitude for that component becomes $\alpha_i\, A_i$ and the effective phase becomes $G_i + \delta_i$.

D.1.3 Harmonic flow boundary conditions

Harmonic boundary conditions are specifies in a manner similar their astronomical counterpart, except that the periods (first column of a .cmp file) are declared explicitly, rather than using component names. Equation ((D.1)) applies with $T(c_i) = T_i$ and furthermore $F = 1$ and $(V_0 + u) = 0$.

D.1.4 QH-relation flow boundary conditions

In this type of boundary condition, a waterlevel is prescribed as a function of the integrated discharge through a crossection defined by the polyline of the boundary.

The relation between waterlevel and discharge is specified in a lookup-table.

Within this table linear interpolation is applied.

Note that only one waterlevel is set for the entire QH-boundary, and that its behaviour is specified by a *single* QH-table for the entire boundary.

D.1.5 Time-series flow boundary conditions

Time-series in the general time-series file format (section D.2.1) can be used to specify values on boundaries.

Boundary values are provided at discrete points in time, which are then used for interpolation at times in between.

Extrapolation beyond the range of specified times is not supported, Time-series are also supported at multiple vertical levels for quantities that are defined on layers (tracers, salinity, temperature, velocity). These need to be specified in the BC-format (section D.2.3).

D.1.6 Time-series transport boundary conditions

The boundary conditions of tracers, salinity and temperature are specified similar to any other quantity already mentioned. The quantity name should be in the form `tracerbnd`<name>, where name is the user-defined tracer name.

D.1.7 Time-series for the heat model parameters

In order to conduct a heat flux simulation (if in the MDU-file "`Temperature`" under `[physics]` was set to 5), then four time-varying meteorological fields become relevant:

- humidity
- airtemperature
- cloudiness
- solar radiation

These are read as a three- or four-column vector (the first three variables of this list, either with or without solar radiation). The corresponding quantity names in the <ext>-file are:

- `humidity_airtemperature_cloudiness`
- `humidity_airtemperature_cloudiness_solarradiation`

As for filetype, currently only the curvilinear format (B.12.2) and the multicolumn time series (D.2.1) are supported.

D.2 Boundary signal file formats

D.2.1 The <cmp> format

```
* comments
* ...
c[0]      amplitude[0]    phase[0]
c[1]      amplitude[1]    phase[1]
...
```

where `c` represents a period in minutes or the name of a valid astronomic component. Amplitudes are assumed to be in the unit of the quantity.

D.2.2 The <qh> format

```
* comments
* ...
discharge[0]      waterlevel[0]
discharge[1]      waterlevel[1]
...
```

D.2.3 The <bc> format

The BC-format for boundary signal data was introduced to combine multiple quantities for multiple locations in a single (ASCII) file. Each location will be defined in a separate 'BC block', which consists of a column-wise table, (the data), and a header specifiying how this table should be interpreted.

The BC-format is pseudo-formally defined below, using EBNF[1]-notation. Though all BC keywords in this description are uppercase, nothing in the BC-format is case-sensitive, not even user-defined names. Whitespace is optional, except for the new lines as in the definitions below.

```
BC-file = { BC-block }

BC-block = "[FORCING]" ,
           "FUNCTION = " , function ,
           "NAME = ",location ,
          ["OFFSET = " , offset ] ,
          ["FACTOR = " , factor ] ,
          ["VERTICAL POSITION SPECIFICATION = " , {vertical-position} ,
           "VERTICAL INTERPOLATION = " , vertical-interpolation  ,
           "VERTICAL POSITION TYPE = " , vertical-position-type] ,
           "MISSING VALUE DEFINITION = " , float ,
           "TIME INTERPOLATION = " , time-interpolation,
          { quantity-block | vector-block },
          { data-block }
```

```
function = "TIMESERIES" | "HARMONIC" | "ASTRONOMIC" | "HARMONIC-CORRECTION" |
           "ASTRONOMIC-CORRECTION" | "T3D" | "QHTABLE"
```

The `FUNCTION` attribute specifies how the BC-block should be interpreted. The options are:

`"TIMESERIES"`	Value(s) as a function of time
`"HARMONIC"`	Period, amplitude, phase
`"ASTRONOMIC"`	Component-name, amplitude, phase
`"HARMONIC-CORRECTION"`	Period, amplitude-factor, phase-offset
`"ASTRONOMIC-CORRECTION"`	Component-name, amplitude-factor, phase-offset
`"T3D"`	Values on multiple vertical positions versus time
`"QHTABLE"`	Discharge as a function of waterlevel

A single BC-block is uniquely tied to a single boundary location by the `location` value:

```
location = pli-name , ["_" , pointnumber]
```

The pli-name pointnumber combination identifies the BC-block (when searched). The pointnumber should be omitted for blocks providing valies for an entire polyline. Currently this is *only* the case for blocks with the function `"QHTABLE"`, which apply to *all* points on a polyline,

[1] https://en.wikipedia.org/wiki/Extended_Backus%E2%80%93Naur_Form

```
vertical-interpolation = "LINEAR" | "LOG" | "BLOCK"
time-interpolation = "LINEAR" | "BLOCK-TO" | "BLOCK-FROM"
```

"LINEAR"	linear interpolation between times or vertical positions.
"LOG"	logarithmic interpolation between vertical positions (e.g. vertical velocity profiles).
"BLOCK"	equal to the value at the directly lower specified vertical position.
"BLOCK-FROM"	equal to that at the start of the time interval (latest specified time value).
"BLOCK-TO"	equal to that at the end of the time interval (upcoming specified time value) .

```
vertical-position-type = "PERCBED" | "ZBED"
```

"PERCBED"	Percentage wrt. waterdepth from the bed upward (sigma layers).
"ZBED"	Absolute distance from the bed upward (z-layers).

vertical-position

The vertical position is specified as a space- or comma-separated list of floats, the interpretation of which varies according to the vertical position type. The order of the positions in the list becomes relevant when referring to them from the quantity blocks. However, no specific ordering of these positions (ascending or descending) is assumed.

```
quantity-block = "QUANTITY = ",quantity-name
                 {quantity-property}

quantity-property = |"VERTICAL POSITION = ", vertical-position-index |
                     "UNIT = " unit |

vector block = vectorname,":",[{quantity-name}","],quantity-name
data-block = {column-data}
```

quantity-name (character string)

The quantity name, in conjunction with the BC-block name (representing location) serves as a searching key in the BC-file to find the BC-block and column within that block. These names can be chosen freely, except that some names and combinations have a special meaning.

1. a quantity *bndname* in a block with function "HARMONIC" or "HARMONIC-CORRECTION" should have the quantities
   - HARMONIC COMPONENT
   - *bndname* AMPLITUDE
   - *bndname* PHASE
2. a quantity *bndname* in a block with function "ASTRONOMIC" or "ASTRONOMIC-CORRECTION" should have the quantities
   - ASTRONOMIC COMPONENT
   - *bndname* AMPLITUDE
   - *bndname* PHASE
3. Blocks with function "TIMESERIES" or "T3D" require a quantity
   - TIME

This also implies that the component-quantity in harmonic and astronomic BC-blocks applies to any quantity in that block. The same holds for the time-quantity in timeseries and T3D blocks.

vertical-position-index (integer)

This is a (one-based) index into the vertical-position-specification, assigning a vertical position to the quantity (`T3D`-blocks only)

offset, factor (floating points)

These are set for the complete BC-block. In the case of timeseries (function is `"TIMESERIES"` or `"T3D"`), all values in the table are multiplied with the factor and increased by the offset. In the case of astronomic or harmonic components (function is `"HARMONIC"` or `"ASTRONOMIC"`), only the amplitude column is multiplied by the given factor.

datablock

This block holds the actual data in columns. The interpretation of the columns is fully determined by the order of the quantity-blocks in the header, i.e. the n-th quantity-block in the header refers to the n-th column. Therefore, The columns should contain valid floating point numbers (scientific notation is also allowed).

The only exception is the column associated with astronomic component names, which is expected to contain strings.

D.2.4 The NetCDF-format for boundary condition time-series

Time series data for 2D boundaries can also be ingested from NetCDF files.

These files should meet the following structure:

- To look up boundary signal locations with a certain label, a character variable should be defined with attribute `cf_role = 'timeseries_id'`. This variable should have two dimensions. The first dimension corresponds with the different boundary signal locations in the file.
  The contents are interpreted as location identifiers of support points of the boundaries.
- The variables containing the timeseries for the support points should have the attribute `standard_name = <quantity-name>`, so as to associate the variable with a requested quantity. The first dimension corresponds with the different boundary signal locations in the file.
  The second dimension corresponds with time and is the only dimension that can be 'UNLIMITED'.

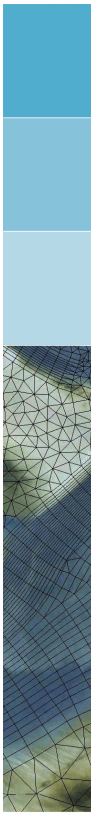
So, similar to the (ASCII) BC-format, location name and quantity name together determine the time-series to be read, only now

- the quantity name is sought among the variables standard-name attributes.
- the location name is sought in a separate list of timeseries IDs, of which
  - the first dimension matches the first dimension of the 'data'-variables.
  - the role as 'timeseries_id' is signified through the cf_role attribute.

E Output files

D-Flow FM can produce several types of output into several different files. This chapter summarizes the types of output and how to configure them in them model definition. We distinguish five types of output here:

1 The diagnostics file, a log file with live details of a single model run.
2 NetCDF output files for history, map and restart data.
3 Tecplot.
4 Timings file with performance statistics.
5 Shapefiles.



E.1 Diagnostics file

The diagnostics (dia) file is the log file of a single model simulation run. It is an important file to check for warning or error messages, when suspecting a faulty model run. The filename is automatically chosen as <*mdu_name*.dia>. For parallel model runs, each process writes its own file <*mdu_name*_000X.dia>. The dia file has the following global structure:

Various INFO/DEBUG messages:
```
** INFO   : Opened file : unstruc.hlp
```
[..]
The version of D-Flow FM used for this calculation:
```
* Deltares, D-Flow FM Version 1.1.145.41271M, Aug 11 2015, 18:05:31
```
Date and time of model run start:
```
File creation date: 18:27:44, 06-09-2015
```
[..]

Check for possible model initialization errors:
```
** WARNING: readMDUFile: [numerics] cflwavefrac=0.1 was in file, but not used.
```
[..]

Upon successful initialization, a full printout of the effective model settings is given:
```
** INFO   : ** Model initialization was successful **
** INFO   : * Active Model definition:
# Generated on 18:27:45, 06-09-2015
# Deltares, D-Flow FM Version 1.1.145.41271M, Aug 11 2015, 18:05:31
[model]
```
[..]

Next, the time loop is started:
```
** INFO   : **
** INFO   : Writing initial output to file(s)...
** DEBUG  : Opened NetCDF file 'DFM_OUTPUT_035hammen/035hammen_his.nc' as #3.
** DEBUG  : Opened NetCDF file 'DFM_OUTPUT_035hammen/035hammen_map.nc' as #4.
** INFO   : Done writing initial output to file(s).
```
[..]

Finishing summary of model run:
```
** INFO   : simulation period     (s)  :          6400.0000000000
** INFO   : nr of timesteps       ( )  :           771.0000000000
** INFO   : average timestep      (s)  :             8.3009079118
```
[..]
Some basic run time statistics
```
** INFO   : time steps            (s)  :            76.2840000003
** INFO   : Computation started  at: 18:27:45, 06-09-2015
** INFO   : Computation finished at: 18:29:04, 06-09-2015
** INFO   :
```
Which parallellization options have been active in this run:
```
** INFO   : MPI    : no.
** INFO   : OpenMP : yes.
```

```
          #threads max : 8
```

E.2 Demanding output

The configuration of what output should be produced during a model run is via the MDU file, and several attribute files for history files.

E.2.1 The MDU-file

The MDU-file has an aptly named `[output]`-section, with a range of key-value-pair options. See Table A.1 on page 326 for all available output options.

E.2.2 Observation points

Observation points in a single observation point file <∗.xyn> define the locations for time series output for single grid cells. The observation point file is basically like a sample file (section B.3), but now with station id strings in the third column:

```
-2.06250000e+00 5.71583333e+01 ABDN
-2.73750000e+00 5.15083334e+01 AVMH
-2.11250000e+00 4.91750000e+01 'St Helier Jersey'
```

Remarks:

- The observation points are stationary by default.
- The x,y-locations are snapped to the grid cell in which they lie. When an observation point lies on a grid cell edge, snapping results are unpredictable.
- Time series are reported for the cell-centered solution data, that is: *no* interpolation to the exact x,y-location takes place.
- Observation points may have non-unique names (also together with moving observation points), but the results can only be distinguished by the column number in the output file, and this practice is not advised.
- The station id/name may contain spaces, in which case it should be surrounded by single quotes.

E.2.3 Moving observation points

Moving observation points are specified via the <∗.ext>-file:

```
QUANTITY=movingstationtxy
FILENAME=movingstation1.tim
FILETYPE=1
METHOD=1
OPERAND=O
```

The <∗.tim> file (one for each moving observation point) is a standard time series file (section D.2.1) with three columns, containing the time in minutes since the reference data, the x- and y-position of the moving station at that time.

Remarks:

- Stationary and moving observation points form one large set of observation points in the output his file.

◇ No space, nor time interpolation is done: the reported values are instantaneous values for the grid cell in which the moving observation point lies at that each output time.

E.2.4 Cross-sections

Cross-sections are polylines in a single <_crs.pli> polyline file (section B.2). Cross section polylines are snapped to the grid cell edges, and cumulative, space-integrated discharges and constituent transport are reported as time series.

Remarks:

◇ The first header line of each polyline block contains the name of each cross section.
◇ The cross section polyline is snapped to all grid cell edges (i.e., velocity points), whose flow link is intersected by the polyline.
◇ The flow data on velocity points is integrated along the polyline and across all vertical layers, resulting in a single time series per cross section and flow quantity.

E.3 NetCDF output files

All flow data output produced by D-Flow FM is written in the NetCDF format. This cross-platform storage format is widely used in the world. The contents of a file can be documented using variable attributes and standardized meta data. For this purpose the D-Flow FM output files aim to satisfy the CF-conventions.

E.3.1 Timeseries as NetCDF his-file

The history file <*mdu_name*_his.nc> contains the dimensions and variable definitions in its header, followed by the actual data. For parallel runs, all data is gathered by domain #0 into <*mdu_name*_0000_his.nc> (section 5.2.5).

Dimensions

The following dimensions are defined in a his file header:

```
netcdf weirfree_his {
dimensions:
       time = UNLIMITED ; // (64 currently)
       name_len = 64 ;
       stations = 18 ;
       cross_section = 4 ;
       cross_section_name_len = 64 ;
       cross_section_pts = 3 ;
       npumps = 2 ;
       // and possibly nweirgens, nweirs, ngategens, ngates, nsources/sinks
```

Location variables

The original location and IDs for stations, cross sections and sources/sinks are also included in the his file:

```
variables:
 double station_x_coordinate(stations) ;
   station_x_coordinate:units = "m" ;
   station_x_coordinate:standard_name = "projection_x_coordinate" ;
   station_x_coordinate:long_name = "x-coordinate" ;
 double station_y_coordinate(stations) ;
   station_y_coordinate:units = "m" ;
```

```
    station_y_coordinate:standard_name = "projection_y_coordinate" ;
    station_y_coordinate:long_name = "x-coordinate" ;
  char station_name(stations, name_len) ;
    station_name:cf_role = "timeseries_id" ;
    station_name:long_name = "Observation station name" ;

  double cross_section_x_coordinate(cross_section, cross_section_pts) ;
    cross_section_x_coordinate:units = "m" ;
    cross_section_x_coordinate:standard_name = "projection_x_coordinate" ;
    cross_section_x_coordinate:long_name = "x-coordinate" ;
  double cross_section_y_coordinate(cross_section, cross_section_pts) ;
    cross_section_y_coordinate:units = "m" ;
    cross_section_y_coordinate:standard_name = "projection_y_coordinate" ;
    cross_section_y_coordinate:long_name = "y-coordinate" ;
  char cross_section_name(cross_section, cross_section_name_len) ;

  double source_sink_x_coordinate(source_sink, source_sink_pts) ;
    source_sink_x_coordinate:units = "m" ;
    source_sink_x_coordinate:standard_name = "projection_x_coordinate" ;
    source_sink_x_coordinate:long_name = "x-coordinate" ;
  double source_sink_y_coordinate(source_sink, source_sink_pts) ;
    source_sink_y_coordinate:units = "m" ;
    source_sink_y_coordinate:standard_name = "projection_y_coordinate" ;
    source_sink_y_coordinate:long_name = "y-coordinate" ;
  char source_sink_name(source_sink, source_sink_name_len) ;
```

Variables on stations

Variables on observations station are typically defiend as follows:

```
  double waterlevel(time, stations) ;
    waterlevel:standard_name = "sea_surface_level" ;
    waterlevel:long_name = "Water level" ;
    waterlevel:units = "m" ;
    waterlevel:coordinates = "station_x_coordinate station_y_coordinate station_name" ;
    waterlevel:_FillValue = -999.
;
```

Other quantities that can be written are:

- ◇ Water depth
- ◇ Flow velocity (x and y)
- ◇ Salinity, temperature and other transported quantities, such as tracers

Variables on cross sections

Variables on cross sections are typically defined as follows:

```
  double cross_section_discharge(time, cross_section) ;
    cross_section_discharge:units = "m^3/s" ;
    cross_section_discharge:coordinates = "cross_section_name" ;
```

Other quantities that can be written are:

- ◇ Cross section flow area at current time;

◇ Cross section average velocity at current time;

Mass balance output

The history file may also contain model-global, time-integrated mass balance output, for example:

```
double WaterBalance_total_volume(time) ;
  WaterBalance_total_volume:units = "m3" ;
```

Other quantities that can be written are:

◇ Net storage since Tstart;
◇ Volume error since Tstart;
◇ Cumulative inflow through boundaries since Tstart;
◇ Cumulative outflow through boundaries since Tstart;
◇ Net inflow through boundaries since Tstart;
◇ Cumulative inflow via SOBEK–D-Flow FM 1D–2D boundaries since Tstart;
◇ Cumulative outflow via SOBEK–D-Flow FM 1D–2D boundaries since Tstart;
◇ Net inflow via SOBEK–D-Flow FM 1D–2D boundaries since Tstart;
◇ Total precipitation volume since Tstart;
◇ Net inflow via source–sink elements since Tstart;

Variables on sources/sinks

Variables on sources/sinks are typically defined as follows:

```
double source_sink_prescribed_discharge(time, source_sink) ;
source_sink_prescribed_discharge:units = "m^3/s" ;
source_sink_prescribed_discharge:coordinates = "source_sink_name" ;
```

Other quantities that can be written are:

◇ source sink prescribed salinity increment;
◇ source sink prescribed temperature increment;
◇ source sink current discharge;
◇ source sink cumulative volume;
◇ source sink discharge average.

These variables are automatically written to his-file if any source/sink exists. One can switch it off by setting in MDU-file that `[output] Wrihis_sourcesink = 0`.

Hydraulic structure output

A history file can also contain automatic output for hydraulic structures, without the need to add an explicit cross section at the same location. An example variable is:

```
double weirgen_discharge(time, weirgens) ;
  weirgen_discharge:long_name = "Weir accumulated discharge (via general structure)" ;
```

Other quantities that can be written are:

- ◇ weir crest level at current time;
- ◇ Total discharge through gate at current time;
- ◇ gate sill level at current time;
- ◇ gate sill width at current time;
- ◇ gate door lower edge level at current time;
- ◇ gate door opening width at current time;
- ◇ Total pump discharge at current time;
- ◇ Max. pump capacity at current time;

E.3.2 Spatial fields as NetCDF map-file

The map file <*mdu_name*_map.nc> contains data on the entire model grid in 1D, 2D and 3D. Three formats are currently supported, selected by the `MapFormat` keyword in the MDU:

```
[output]
MapFormat = 1  # Map file format, 1: NetCDF, 2: Tecplot, 3: NetCFD and Tecplot, 4: NetCDF-UGR
```

D-Flow FM is using the more standardized UGRID[1] format. This is the default option. Delta Shell and Delft3D-QUICKPLOT also support this format. In this section only the conventional NetCDF format (1) is further discussed.

For parallel runs, each process writes a separate file for each partition as <*mdu_name*_000X_map.nc>.

The map file contains the dimensions and variable definitions in its header, followed by the actual data.

Dimensions

The following dimensions are defined in a map file header:

```
netcdf weirfree_map {
dimensions:
       nNetNode = 310 ;
       nNetLink = 486 ;
       nNetLinkPts = 2 ;
       nBndLink = 252 ;
       nNetElem = 180 ;
       nNetElemMaxNode = 4 ;
       nNetLinkContourPts = 4 ;
       nFlowElem = 180 ;        // Nr.
of grid cells
       nFlowElemMaxNode = 4 ;
       nFlowElemContourPts = 4 ;
       nFlowLink = 246 ;        // Nr.
of flow links (open cell edges)
       nFlowLinkPts = 2 ;
       time = UNLIMITED ; // (64 currently)
```

For plotting solution data, the grid cells (flow nodes) are important, and the flow links (open cell edges). All `Net*` dimensions relate the flow grid tot the original unstructured network. More explanation of these topological naming conventions can be found in section 7.3.1.

[1] https://github.com/ugrid-conventions/ugrid-conventions

Location variables

The location and shape of grid cells is stored in several x,y variables:

```
 double FlowElem_xcc(nFlowElem) ;
   FlowElem_xcc:units = "m" ;
   FlowElem_xcc:standard_name = "projection_x_coordinate" ;
   FlowElem_xcc:long_name = "Flow element circumcenter x" ;
   FlowElem_xcc:bounds = "FlowElemContour_x" ;
 double FlowElem_ycc(nFlowElem) ;
   FlowElem_ycc:units = "m" ;
   FlowElem_ycc:standard_name = "projection_y_coordinate" ;
   FlowElem_ycc:long_name = "Flow element circumcenter y" ;
   FlowElem_ycc:bounds = "FlowElemContour_y" ;
// [..]
 double FlowElemContour_x(nFlowElem, nFlowElemContourPts) ;
   FlowElemContour_x:units = "m" ;
   FlowElemContour_x:standard_name = "projection_x_coordinate" ;
   FlowElemContour_x:long_name = "List of x-points forming flow element" ;
   FlowElemContour_x:_FillValue = -999.
;
// [..]
 double FlowElem_bl(nFlowElem) ;
   FlowElem_bl:units = "m" ;
   FlowElem_bl:positive = "up" ;
   FlowElem_bl:standard_name = "sea_floor_depth" ;
   FlowElem_bl:long_name = "Bottom level at flow element\'s circumcenter." ;
```

Variables on grid cells/pressure points

Variables on grid cells (represented by the pressure point/cell circumcenter) are typically defined as follows:

```
 double s1(time, nFlowElem) ;
   s1:coordinates = "FlowElem_xcc FlowElem_ycc" ;
   s1:standard_name = "sea_surface_level" ;
   s1:long_name = "waterlevel" ;
   s1:units = "m" ;
   s1:grid_mapping = "projected_coordinate_system" ;
```

Other quantities that can be written are:

- ◇ Water level at beginning of time step;
- ◇ Water depth;
- ◇ Numlimdt: number of times each cell was limiting the time step;
- ◇ Bed shear stress;
- ◇ Cell-centered velocity components;
- ◇ Effective Chézy roughness;
- ◇ Salinity;
- ◇ Temperature;
- ◇ Tracers and other constituents;
- ◇ Heat flux quantities, air temperature, relative humidity, cloudiness, and more detailed fluxes (chapter 10);
- ◇ Streamline curvature and spiral flow intensity (section 7.6);
- ◇ Suspended sediment concentrations and erodable layer thicknesses (chapter 18);
- ◇ Cell-centered wind speed components and atmospheric pressure;

Variables on flow links/velocity points

Variables on grid cell edges (represented by the velocity point) are typically defined as follows:

```
double q1(time, nFlowLink) ;
  q1:coordinates = "FlowLink_xu FlowLink_yu" ;
  q1:long_name = "Flow flux" ;
  q1:units = "m3/s" ;
```

Other quantities that can be written are:

- ◇ Normal velocities at the old and new time level;
- ◇ Horizontal viscosity and diffusivity;
- ◇ Edge-centered wind speed components;
- ◇ Effective roughness values from trachytopes/vegetation (section 13.2)

E.3.3 Restart files as NetCDF rst-file

Restart files <*mdu_name*_yyyymmdd_HHMMSS_rst.nc> are almost identical to map files, except that they contain all data for just a single time. The grid and flow geometry information is not present, except for the flow cell/link coordinates. Moreover, restart files resulted from a parallel run contains parallelization information. For this reason, restart files are less suitable for plotting, but efficient for restarting a computation.

E.4 Shapefiles

Shapefiles[2] are widely used for visualization in geographic information system (GIS) software. A shapefile stores geometric locations and corresponding attributes information for the spatial features. D-Flow FM can generate shapefiles by setting keyword in the MDU file. Table E.1 shows what features can be written to a shapefile by D-Flow FM, and the corresponding MDU settings. (By default these keywords are zero, which disables writing the shapefile.) Moreover, this function is also valid in parallel simulation.

Table E.1: *Features and MDU settings for generating shapefiles*

Features for shapefiles	MDU setting
Cross sections	`[output] Wrishp_crs = 1`
Weirs	`[output] Wrishp_weir= 1`
Gates	`[output] Wrishp_gate= 1`
Fixed weirs	`[output] Wrishp_fxw = 1`
Thin dams	`[output] Wrishp_thd = 1`
Embankments	`[output] Wrishp_ebm = 1`
Observation stations	`[output] Wrishp_obs = 1`
Source-sinks	`[output] Wrishp_src = 1`

[2] https://www.esri.com/library/whitepapers/pdfs/shapefile.pdf

F Spatial editor

F.1 Introduction

The spatial editor is a generic feature of the Delta Shell framework for editing spatial data (e.g. bed level, roughness, viscosity, initial conditions, sediment availability). The spatial editor supports both point clouds and coverages (e.g. data on a grid or network). Therefore, you can use the spatial editor both to edit spatial data in general and to prepare model input. This Chapter describes the general features of the spatial editor (section F.2), (spatial) quantity selection (section F.3), geometry operations (section F.4), spatial operations (section F.5) and the operation stack (section F.6). The examples given below are typically focusing on use of the spatial editor in the D-Flow FM plugin, but are in principal applicable to any Delta Shell plugin.

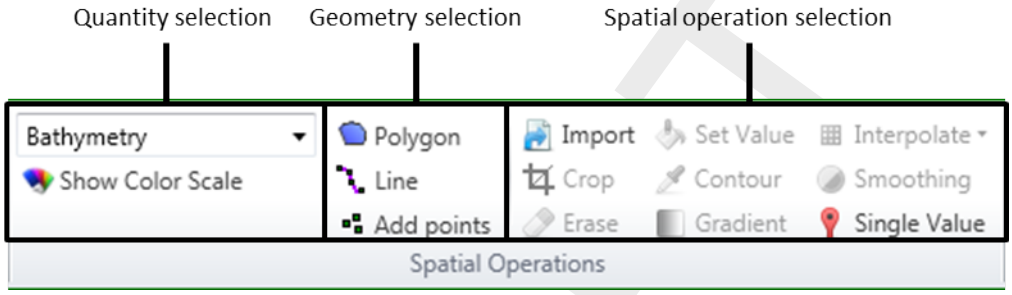


Figure F.1: *Overview of spatial editor functionality in Map ribbon*

F.2 General

F.2.1 Overview of spatial editor

The spatial editor functionality can be accessed from the “Spatial Operations” section of the “Map Ribbon” (Figure F.1). Typically, you first select which dataset or quantity (either a point cloud or a coverage) to work on (e.g. bed level, roughness, viscosity, initial conditions, sediment availability), then a geometry (e.g. point, line, polygon) and finally which spatial operation to perform (e.g. crop, erase, set value, contour, interpolate, smoothing). Typical workflows are as follows:

Working on a point cloud dataset:

1 Import the dataset as point cloud (section F.2.2)
2 Activate/select the dataset (quantity) in the spatial editor (section F.3)
3 Select a geometry to perform an operation on (section F.4)
4 Select the spatial operation for this geometry (section F.5)
5 Repeat steps 3 and 4 until you are satisfied with the data
6 Export the dataset (section F.6.7)

Working on a coverage (e.g. model input):

1 Activate/select the spatial quantity to work on in the spatial editor (section F.3)
2 Optional: import a dataset as point cloud (section F.5.1)
3 Select a geometry to perform an operation on (section F.4)
4 Select the spatial operation for this geometry (section F.5)
5 Repeat steps 3 and 4 until you are satisfied with the data
6 Interpolate the point cloud to the grid or network ((section F.5.10))
7 Optional: export the dataset (section F.6.7)

Upon performing a spatial operation, the ‘Operations’ panel will open (see Figure F.51) with the operations stack. This stack keeps track of the workflow of spatial operations that you performed. This helps you to make transparent how you arrived at your ‘final’ dataset without having to save all the intermediate datasets (steps) separately. Moreover, the stack is reproducible and easily editable without

having to start all over again. When working on a coverage (e.g. the second workflow), point clouds can be used to construct the coverage. In this case the coverage (for example 'Bed level') is the 'trunk' of the workflow and the point clouds (appearing as sets in the stack) are 'branches' or subsets of this trunk (see Figure F.51). By selecting the set or coverage in the 'Operations' panel you determine on which dataset you are working. The interpolate operation (section F.5.10) allows you to bring data from the point cloud (branch) to the coverage (trunk). For more information on the stack you are referred to section section F.6.

F.2.2 Import/export dataset

To import a (point cloud) dataset use the context menu on "project" in the "Project Tree", select "import" from the context menu and select the point cloud importer (Figure F.2). After the import the point cloud will be added to the project tree. To activate the point cloud in the spatial editor either double click the dataset in the project tree (Figure F.3) or select it from the drop down box in the spatial editor ribbon (Figure F.4).

Note: Exporter still to be implemented

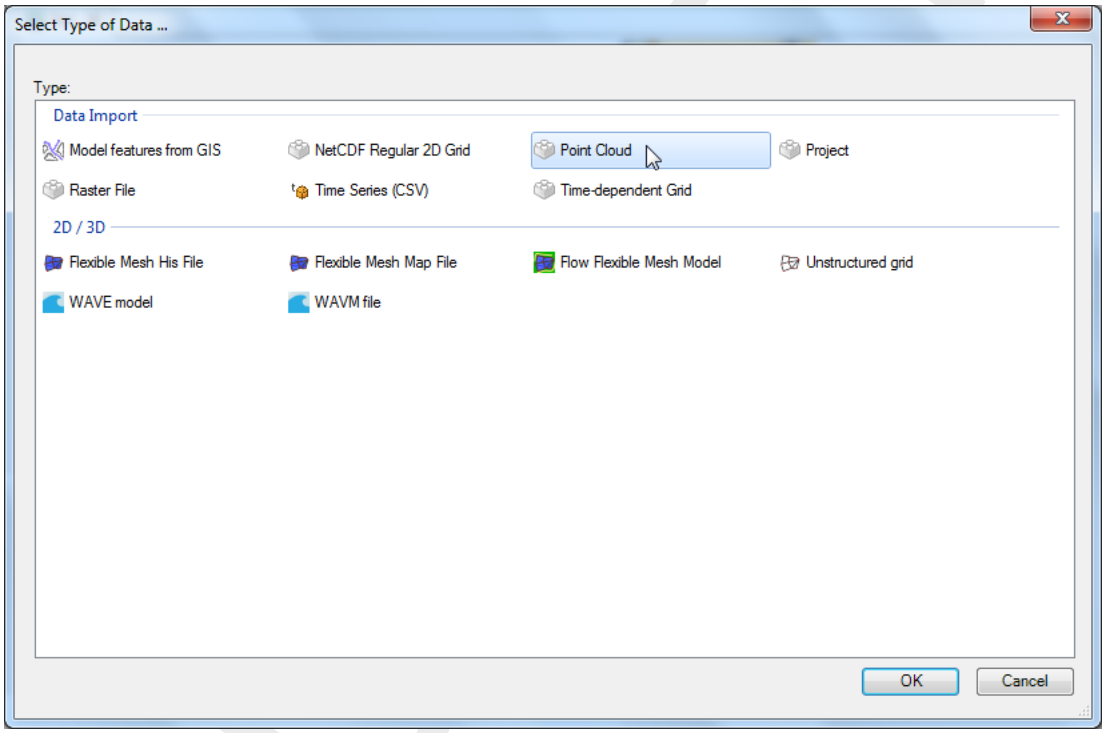


Figure F.2: *Importing a point cloud into the project using the context menu on "project" in the project tree*

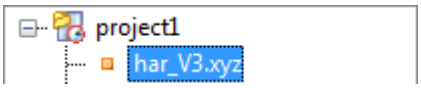


Figure F.3: *Activate the imported point cloud in the spatial editor by double clicking it in the project tree*

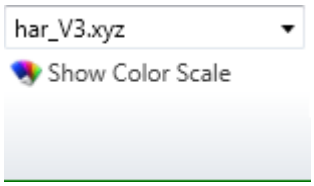


Figure F.4: *Activate the imported point cloud in the spatial editor by selecting it from the dropdown box in the Map ribbon*

F.2.3 Activate (spatial) model quantity

Similar to activating an imported dataset in the spatial editor, you can also activate a (spatial) model quantity (e.g. bed level, initial conditions, roughness, viscosity) in the spatial editor by double clicking the quantity in the project tree or selecting it from the dropdown box in the “Map” ribbon.

F.2.4 Colorscale

Upon activating a spatial quantity in the spatial editor it becomes visible in the map window with a corresponding colorscale (Figure F.5 top). You can (de-)activate the colorscale by clicking on the “Show Color Scale” button in the “Map” ribbon (Figure F.5 left panel). By default the colorscale is ranging from the minimum value of the active dataset. You can adjust/decrease this range using the sliders at the top and bottom sliders of the colorbar (Figure F.5 right panel).

You can also adjust the colormap and classes of the colorscale using the context menu on the spatial quantity in the “Map tree” and selecting “Properties” (Figure F.6 left panel). A layer properties editor will open in which you can set the colormap to your own preferences (Figure F.6 right panel). **Note:** Please note that currently you can only edit the properties of the colorscale before you perform spatial operations. Once you have performed a spatial operation this functionality will be disabled.

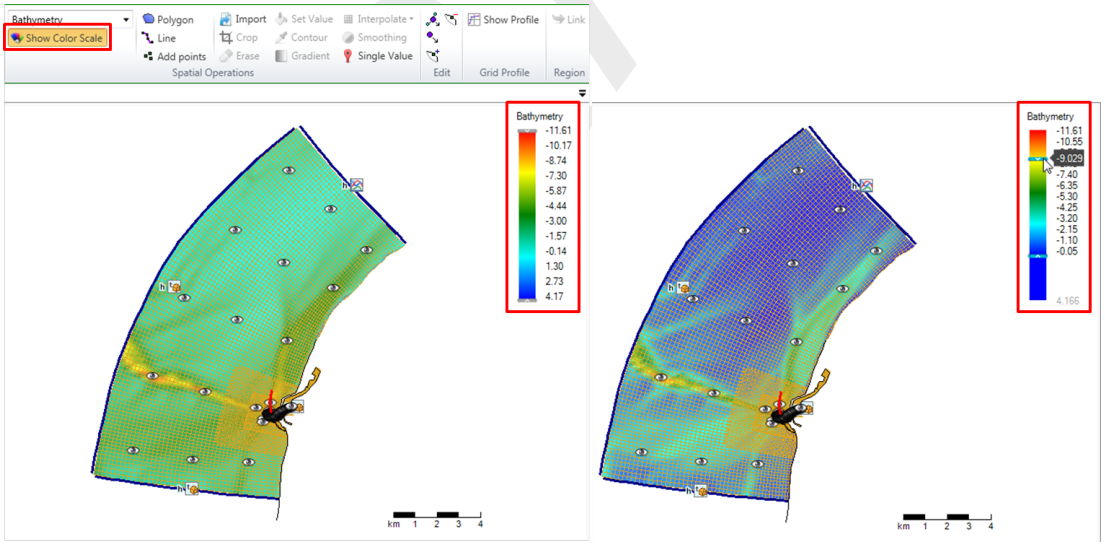


Figure F.5: *Activate the colorscale using the button in the map ribbon (top) and the colorscale will become visible in the map window (left). You can adjust/decrease the range of the colorscale using the sliders at the top and bottom of the colorbar (right).*

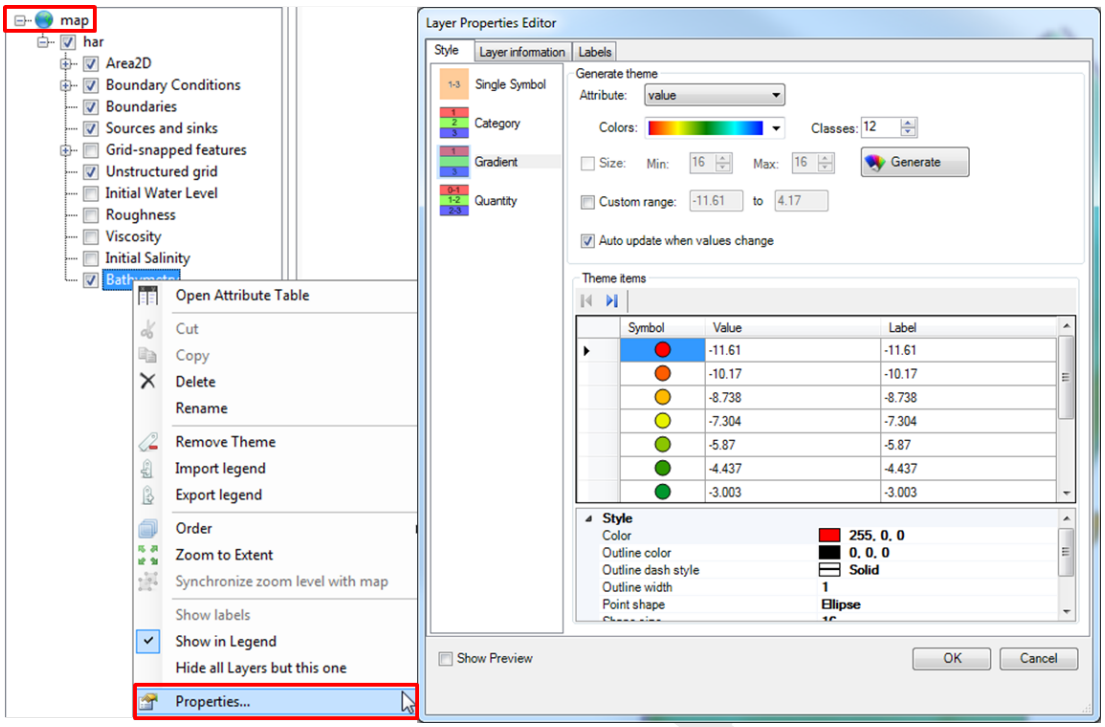


Figure F.6: *Edit the colorscale properties using the context menu on the active layer in the Map Tree*

F.2.5 Render mode

By default point clouds are rendered as (colored) points and coverages as shades (e.g. 'FillSmooth'). The render mode can be edited using the properties of the active layer Figure F.7. Delta Shell offers the following render modes:

- ◇ Points
- ◇ Lines (only for coverages)
- ◇ Shades or 'FillSmooth' (only for coverages)
- ◇ Colored numbers
- ◇ Mono colored numbers

An example of a coverage rendered as colored numbers is given in Figure F.8.

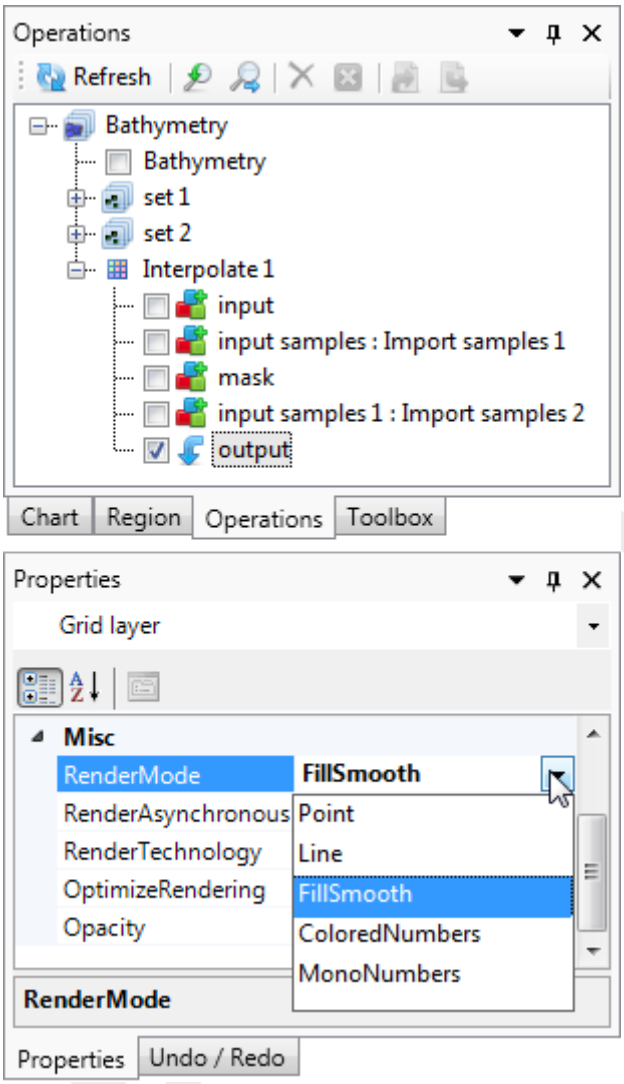


Figure F.7: *Select the rendermode for the active layer in the property grid.*

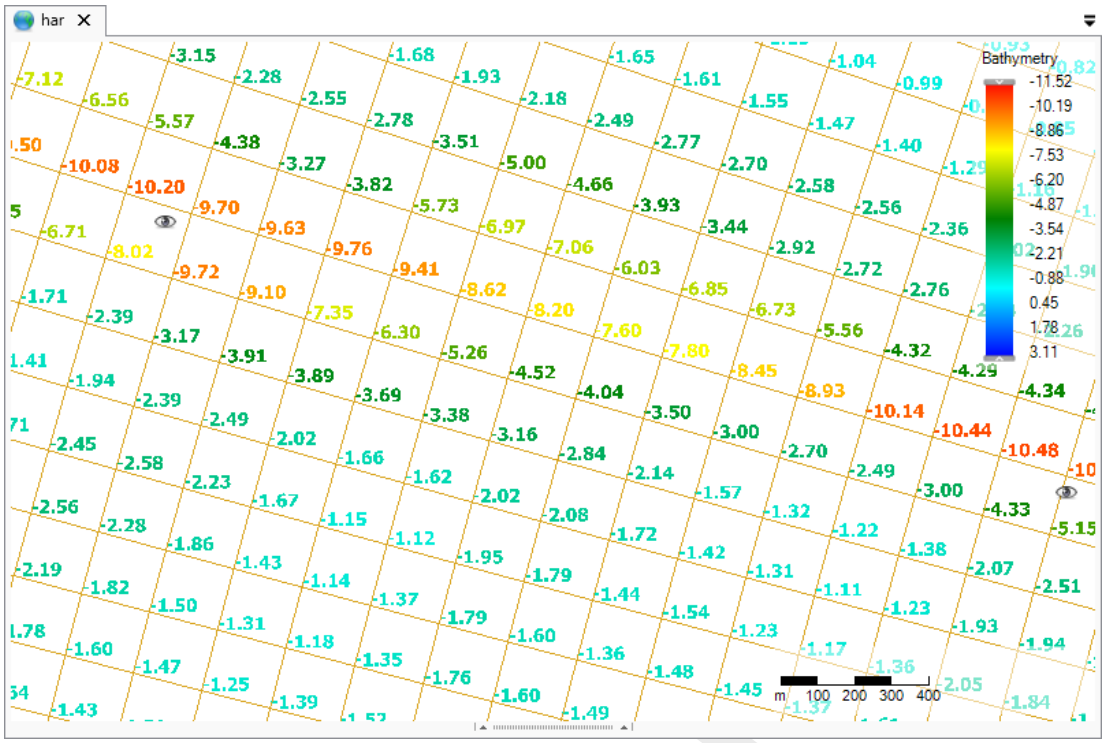


Figure F.8: *Example of a coverage rendered as colored numbers.*

F.2.6 Context menu

In addition to the selection of spatial operation from the 'Map' ribbon (see section F.5), you can also select spatial operations using the context menu (e.g. context menu). After drawing a geometry and clicking the context menu all spatial operation available for the geometry will pop-up (see Figure F.9). The spatial operation will become active upon selecting it from the context menu.

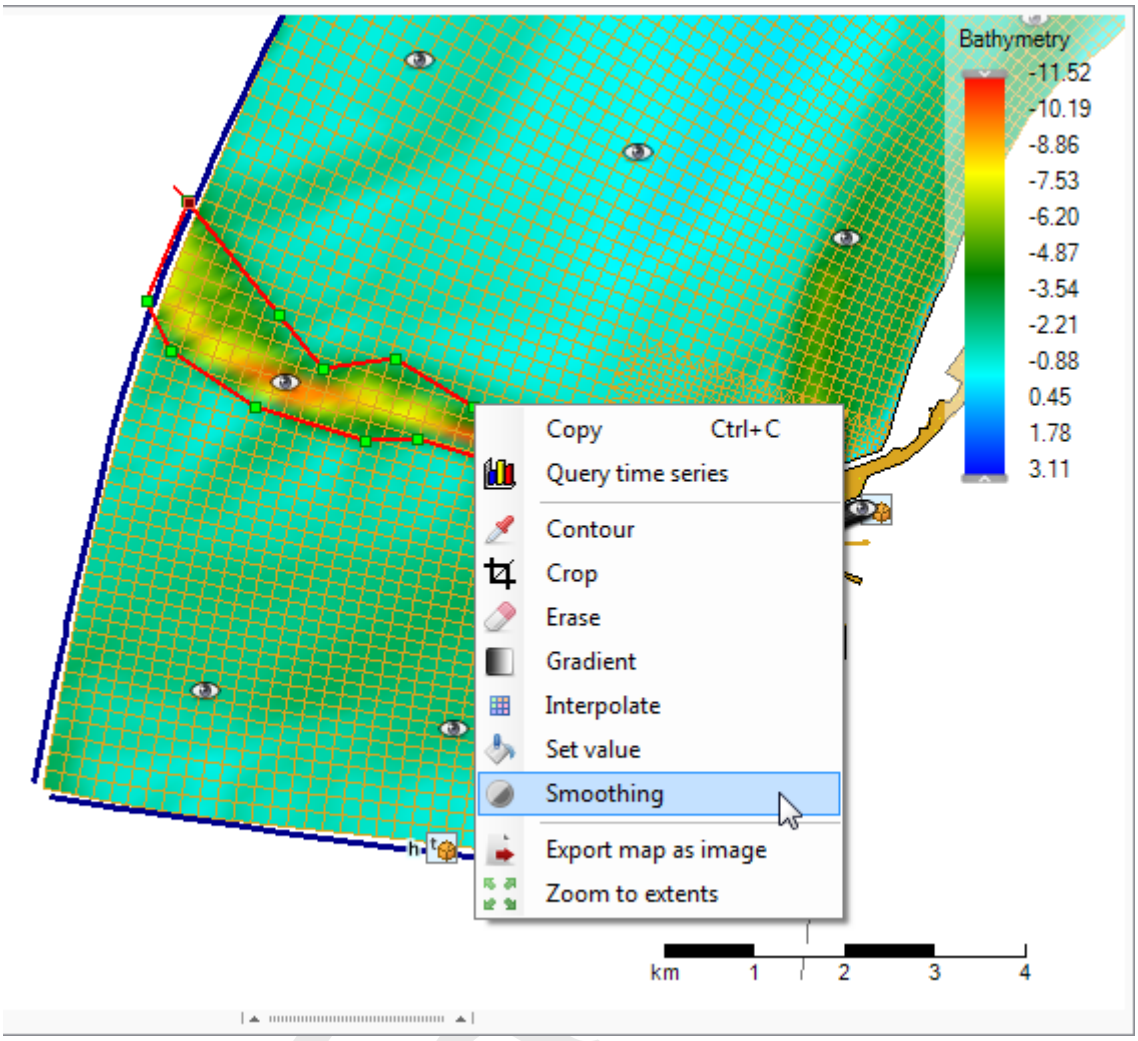


Figure F.9: *Selecting a smoothing operation for a polygon geometry from the context menu (using context menu)*

F.3 Quantity selection

A spatial quantity can be activated/selected either by double clicking it in the project tree (Figure F.10) or by selecting it from the dropdown box in the “Map” ribbon (Figure F.11). Upon selecting the spatial quantity it will be shown as a point cloud (for a dataset) or coverage (for model input) on the central map. Typically, you start from a point cloud (either obtained from import or by generating samples yourself) which will eventually be interpolated to a grid or network (e.g. coverage). The spatial editor will keep track of both the changes made to the point cloud(s) and coverage of the selected spatial quantity. The information will be saved in the Delta Shell project and available the next time you open the project. **Note:** The operations are not yet saved in a human-readable/editable file

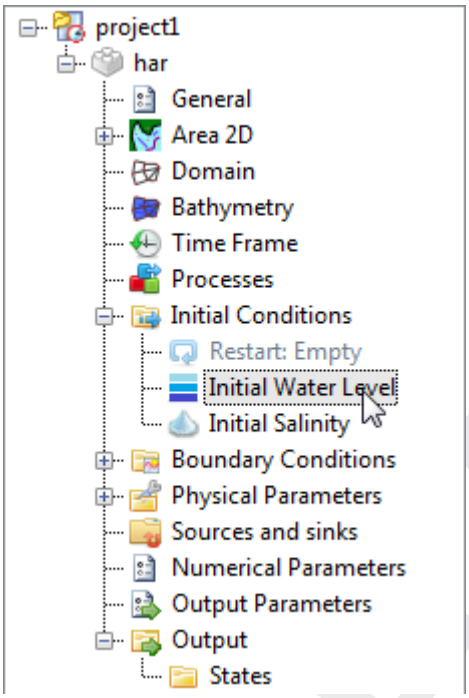


Figure F.10: *Activating a spatial quantity by double clicking it in the project tree (in this example 'Initial Water Level')*

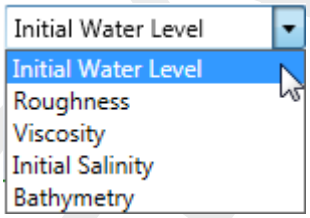


Figure F.11: *Activating a spatial quantity by selecting it from the dropdown box in the 'Map' ribbon*

F.4 Geometry operations

The spatial editor supports three types of geometry operations: (1) polygons, (2) lines and (3) points (see also Figure F.12). The following sub-sections subsequently describe how these geometries can be selected and edited. If you do not select any of these three geometry operations, the spatial operation automatically applies to all the data.

Note: Please note that the drawn geometries are not yet persistent, implying that the geometries once drawn cannot be edited yet. Upon pressing the "Esc" button while in editing mode all drawn geometries will dissapear.

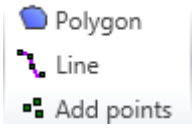


Figure F.12: *Overview of the available geometry operations in the 'Map' ribbon*

F.4.1 Polygons

Upon selecting “Polygon” from the “Map” ribbon you can draw one or multiple polygons (Figure F.13). Each polygon point is defined by a single click with the LMB. The polygon is closed by double clicking the LMB. After drawing the (first) polygon, the available spatial operations for polygons are enabled in the “Map” ribbon. The following spatial operations are available for polygons:

- Crop (section F.5.2)
- Erase (section F.5.3)
- Set Value (section F.5.4)
- Contour (section F.5.5)
- Gradient (section F.5.9)
- Smoothing (section F.5.11)
- Interpolate - only in case samples and a grid/network are available (section F.5.10)
- Copy to samples (section F.5.6)

The selected spatial operation applies to all the drawn polygons.

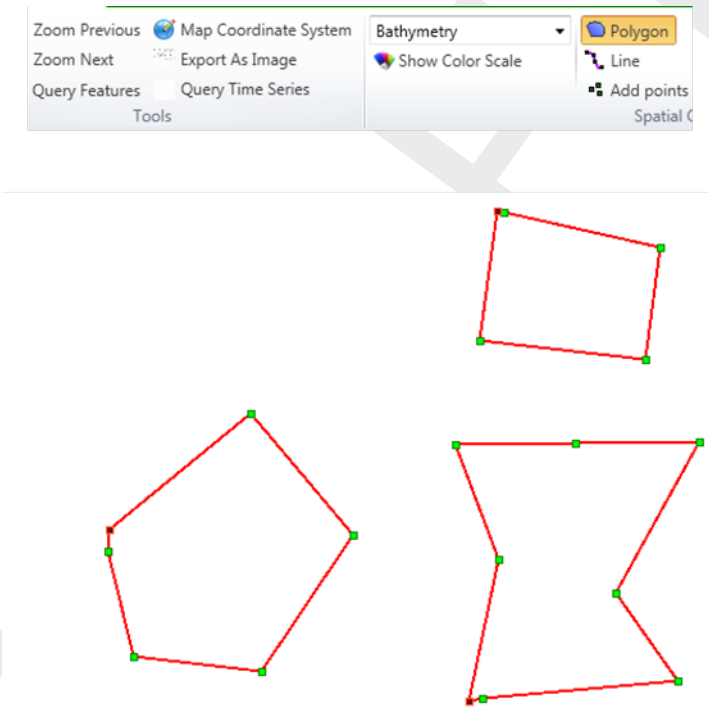


Figure F.13: *Activating the polygon operation and drawing polygons in the central map.*

F.4.2 Lines

Upon selecting “Line” from the “Map” ribbon you can draw one or multiple lines (Figure F.14). Each line point is defined by a single click with the LMB. The line is completed by double clicking the LMB. After drawing the (first) line, the available spatial operations for lines are enabled in the “Map” ribbon. The following spatial operations are available for lines:

- Contour (section F.5.5)

The selected spatial operation applies to all the drawn lines.

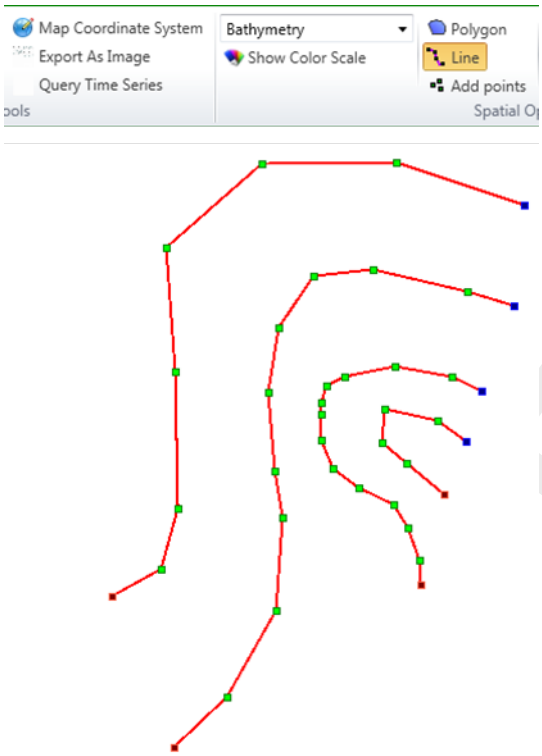


Figure F.14: *Activating the line operation and drawing lines in the central map.*

F.4.3 Points

Upon selecting “Add points” from the “Map” ribbon you can draw one or multiple points and assign a uniform value to them (Figure F.15). Each point is defined by a single click with the LMB. The group of points is completed by double clicking the LMB. Upon double clicking a popup appears in which you can assign a value to the points.

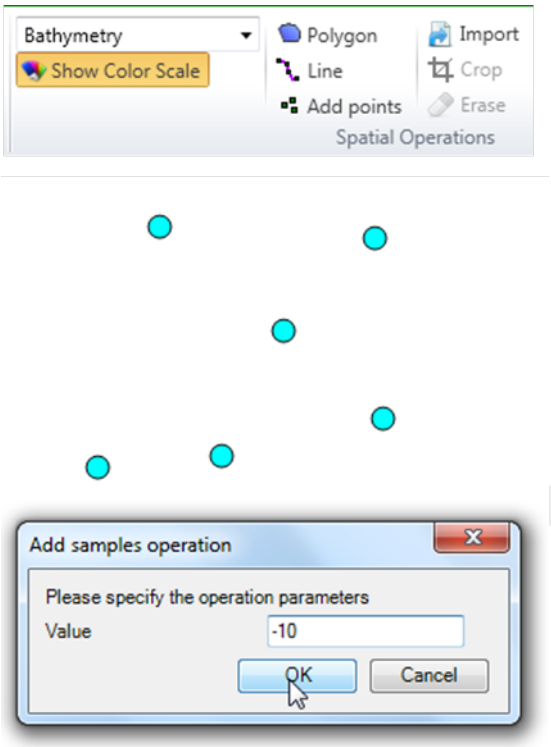


Figure F.15: *Activating the 'Add points' operation, drawing them in the central map and assigning a value to them.*

F.5 Spatial operations

The spatial editor supports the following spatial operations (see also Figure F.16):

- Import (section F.5.1) - only for point clouds
- Crop (section F.5.2)
- Erase (section F.5.3)
- Set Value (section F.5.4)
- Contour (section F.5.5) - only for point clouds
- Gradient (section F.5.9)
- Interpolate (section F.5.10) - only for point clouds
- Smoothing (section F.5.11)
- Change single value (section F.5.12) - only for grid coverages
- Merge spatial data (section F.5.8) - only for grid coverages
- Copy to samples (section F.5.6) - only for grid coverages
- Copy to spatial data (section F.5.7) - only for grid coverages

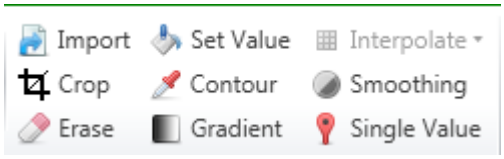


Figure F.16: *Overview of the available spatial operations in the 'Map' ribbon*

The sections below provide a description of each operation.

F.5.1 Import point cloud

With the import operation you can import a point cloud for the selected spatial quantity (**Note:** To import a coverage select 'Import' from the context menu of the spatial quantity in the project tree). For this operation no geometry is required. The import operation is activated from the 'Map' ribbon (Figure F.17). Upon importing a point cloud you are asked whether a coordinate transformation should be applied to the imported dataset (Figure F.18). By default it will be assumed that the imported data is in the same coordinate system as the model. If not, you can indicate from which to which coordinate system the data should be transformed. After import the point cloud is added to the operations stack (Figure F.19). The difference between this importer and importing a point cloud on the project or model level in the project tree (section F.2.2) is that for this importer the point cloud is directly assigned to the selected spatial quantity (e.g. model input) instead of being treated as a separate dataset.

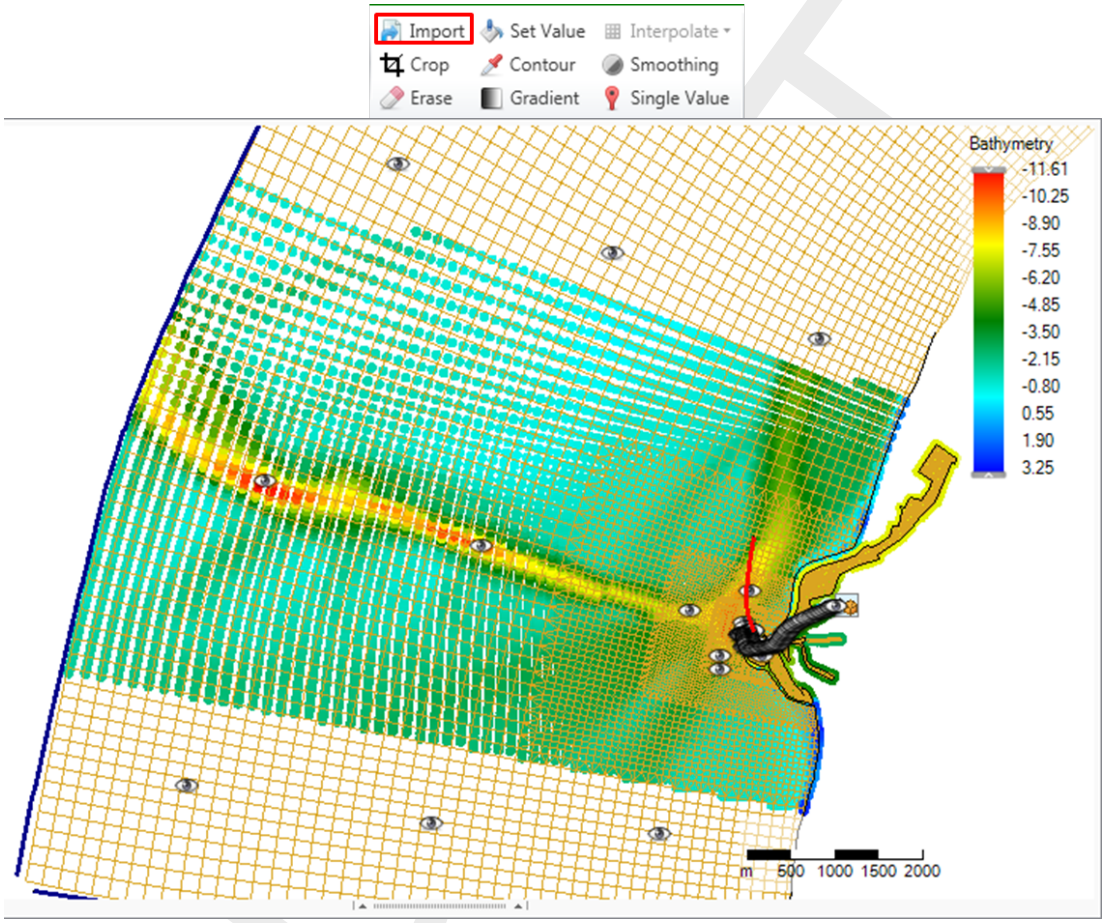


Figure F.17: *Importing a point cloud using the 'Import' operation from the 'Map' ribbon*

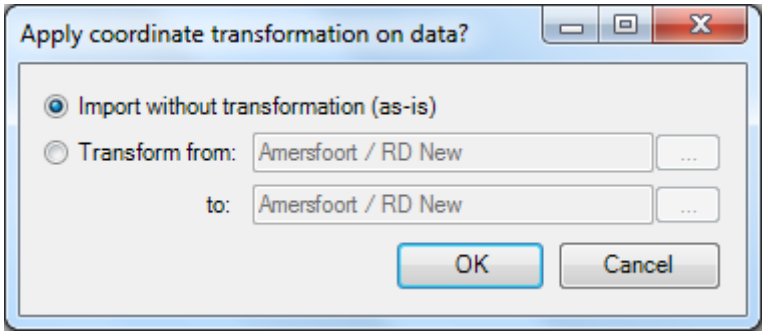


Figure F.18: *Option to perform a coordinate transformation on the imported point cloud*

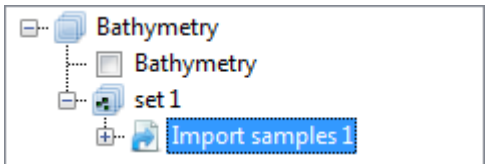


Figure F.19: *Appearance of import point cloud operation in the operations stack*

F.5.2 Crop

The crop operation crops a point cloud or coverage (depending on which one is active). The crop operation is activated from the 'Map' ribbon. and only available for polygon geometries. You can control which part of the data should be erased by using polygons. If you provide a polygon outside the point cloud or coverage, all data will be erased. For an example see Figure F.20. After cropping (part of) the point cloud of coverage the operation is added to the operations stack (Figure F.21).

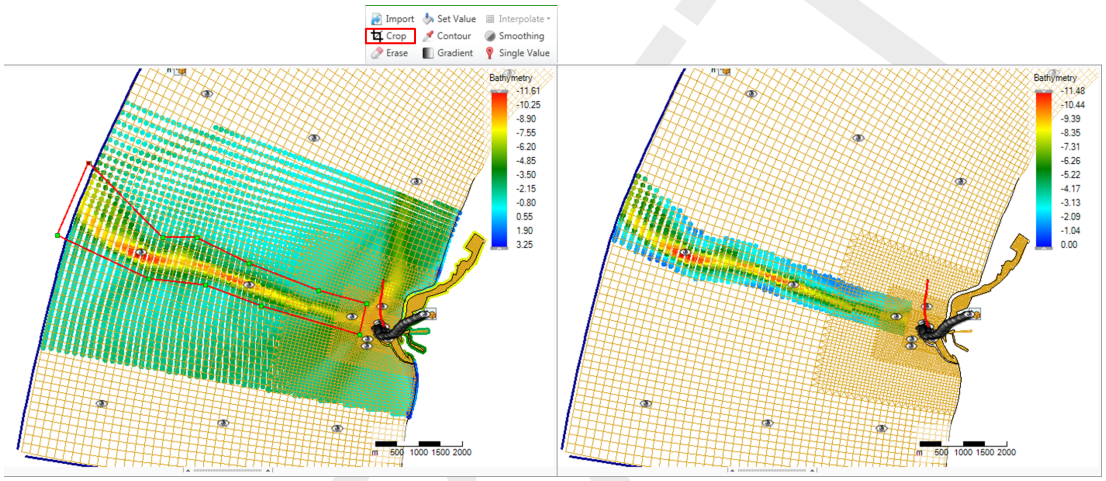


Figure F.20: *Performing a crop operation on a point cloud with a polygon using 'Crop' from the 'Map' ribbon*

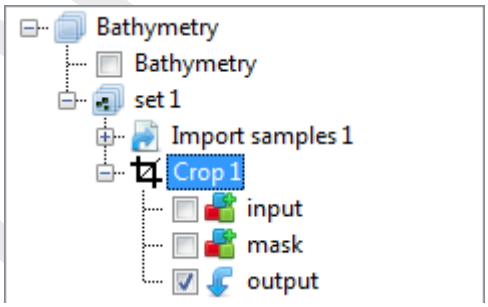


Figure F.21: *Appearance of crop operation in the operations stack*

F.5.3 Erase

The erase operation erases (part of) a point cloud or coverage (depending on which one is active). The erase operation is activated from the 'Map' ribbon. You can control which part of the data should be erased by using polygons. If no polygons are provided, the total dataset will be erased. For an example see Figure F.22. After erasing (part of) the point cloud or coverage the operation is added to the operations stack (Figure F.23).

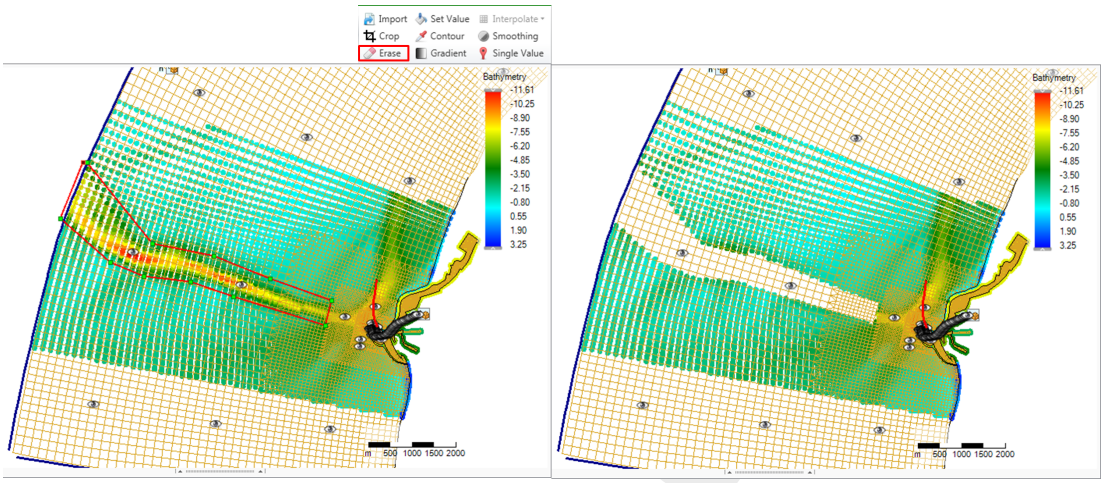


Figure F.22: *Performing an erase operation on a point cloud with a polygon using 'Erase' from the 'Map' ribbon*

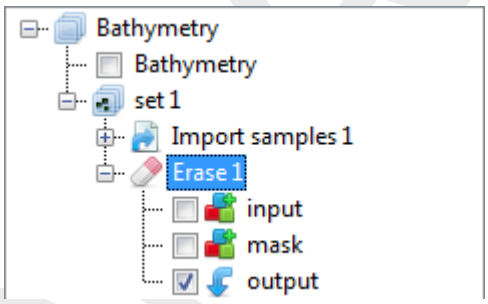


Figure F.23: *Appearance of erase operation in the operations stack*

F.5.4 Set value

The set value operation assigns a value to a point cloud or coverage (depending on which one is active). The set value operation is activated from the 'Map' ribbon and only available for polygon geometries or for the total data set if no polygon is provided. By assigning a value can choose from the following operations:

- **Overwrite** : overwrites all existing points within the polygon (excluding no data values) with the uniform value
- **Overwrite where missing (only for coverages)** : overwrites all missing values within the polygon with the uniform value
- **Add** : Adds the uniform value to all existing points within the polygon (excluding no data values)
- **Subtract** : Subtracts the uniform value from all existing points within the polygon (excluding no data values)
- **Multiply** : Multiplies all existing points within the polygon (excluding no data values) with the uniform value
- **Divide** : Divides all existing points within the polygon (excluding no data values) by the uniform value
- **Maximum** : Sets all existing points within the polygon (excluding no data values) to the maximum of its current value and the uniform value

◇ **Minimum** : Sets all existing points within the polygon (excluding no data values) to the minimum of its current value and the uniform value

For an example see Figure F.24. After performing a set value operation to (part of) the point cloud or coverage the operation is added to the operations stack (Figure F.25).

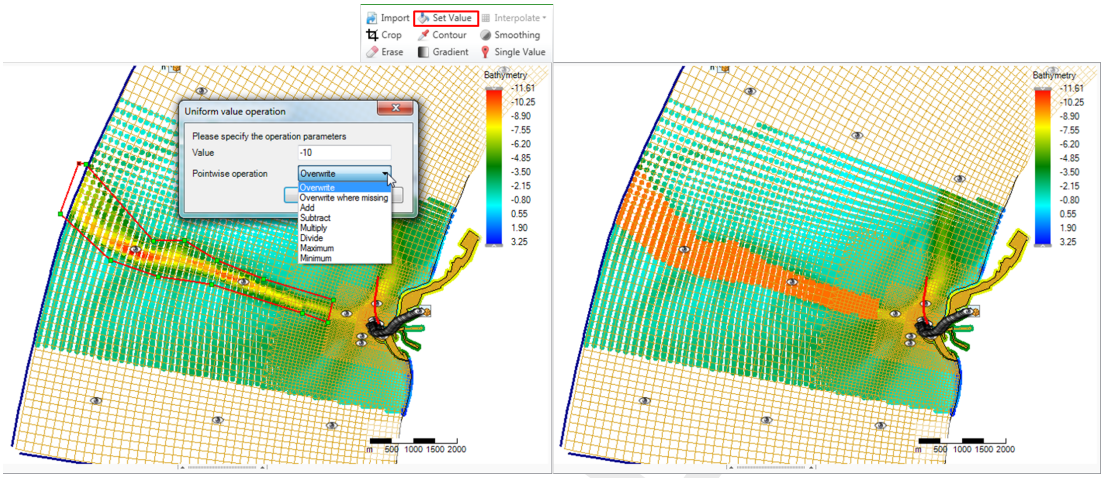


Figure F.24: *Performing a set value operation (e.g. overwrite) on a point cloud with a polygon using 'Set Value' from the 'Map' ribbon*

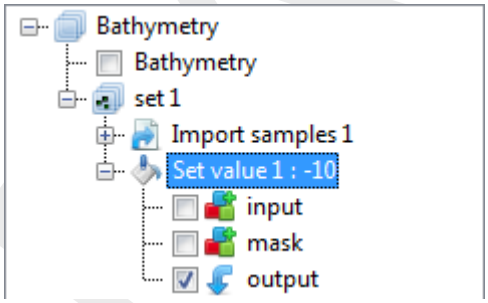


Figure F.25: *Appearance of set value operation in the operations stack*

F.5.5 Contour

The contour operation creates a point cloud with a uniform value along a line or polygon (depending on which one is active). The contour operation is activated from the 'Map' ribbon. After drawing the lines or polygons you have to assign the uniform value (argument) and the sampling interval in m. This spatial operation can be useful to digitalize information from nautical charts for example. In this case you first have to import the nautical chart as a geotiff (Figure F.26), set the right map coordinate system (Figure F.27) and then use the contour operation Figure F.28. Sometimes the samples are created behind the geotiff. Then you can use the context menu on the samples layer in the Map tree to bring the samples to the front (Figure F.29). After applying the contour operation it is added to the stack (Figure F.30).

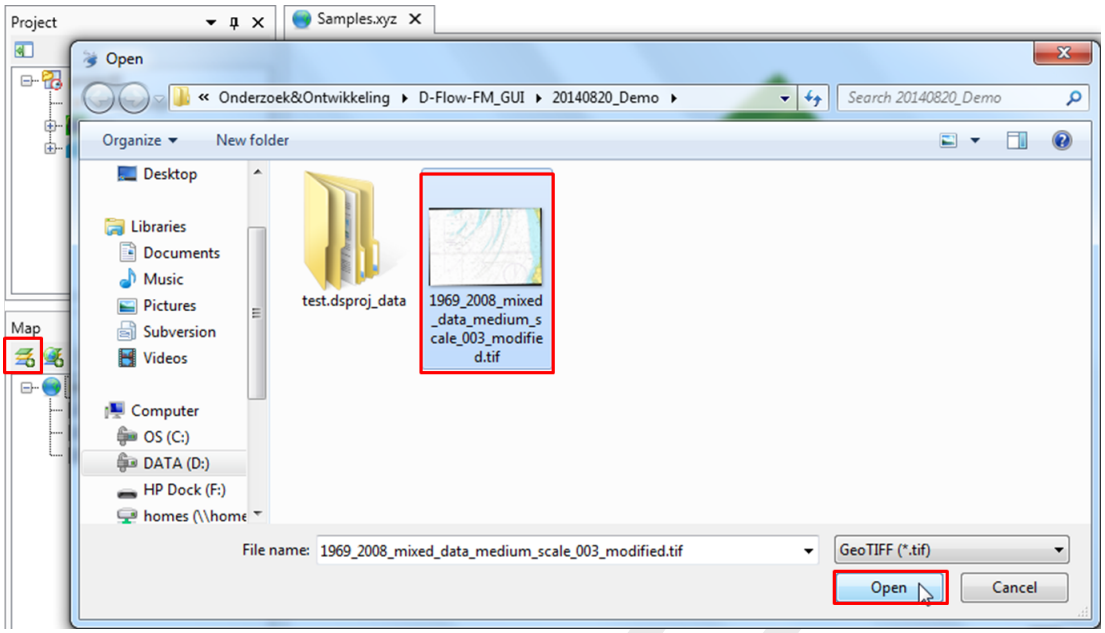


Figure F.26: *Import a nautical chart as a georeferenced tiff file*

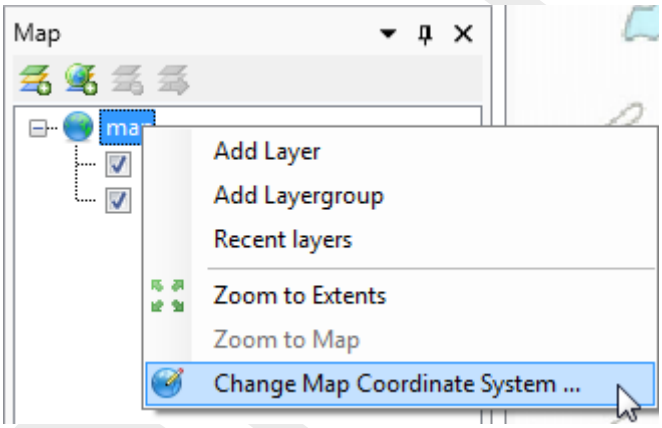


Figure F.27: *Set the right map coordinate system for the geotiff*

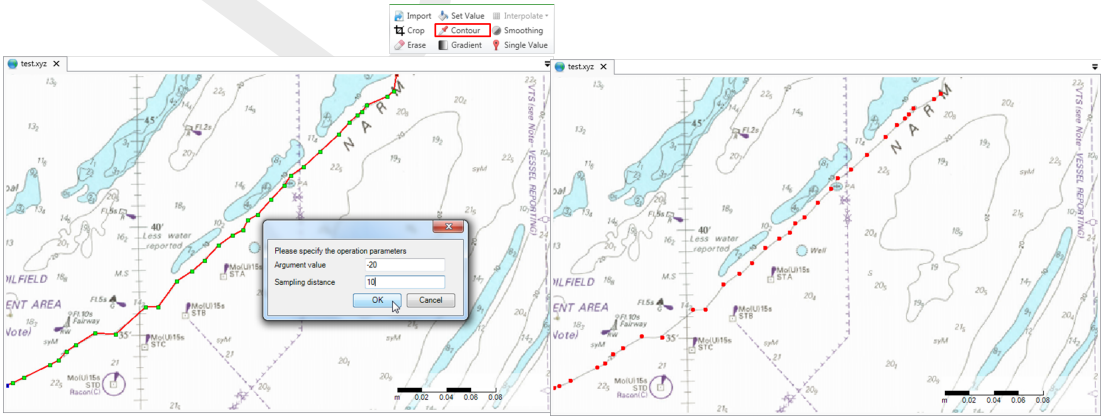


Figure F.28: *Performing a contour operation on a nautical chart using lines to define the contours and 'Contour' from the 'Map' ribbon*

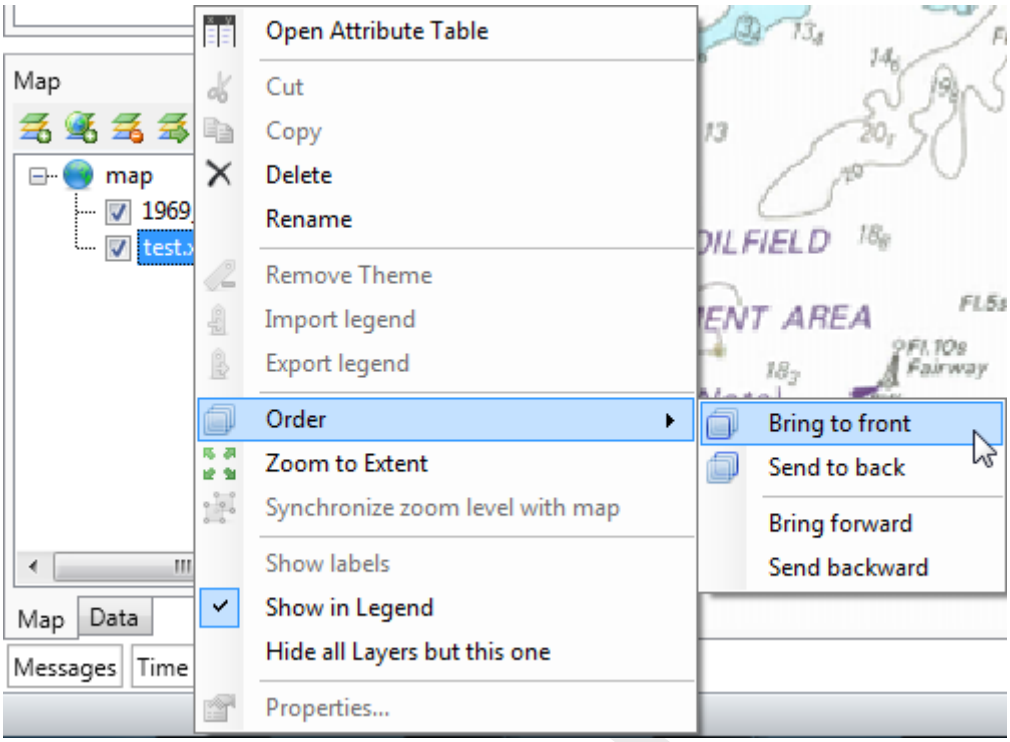


Figure F.29: *Bring the sample set to the front if it appears behind the nautical chart*

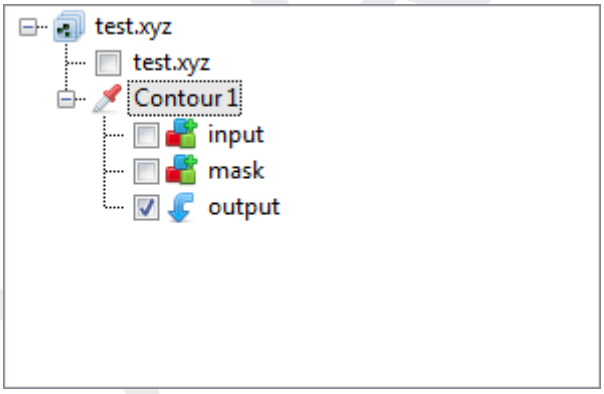


Figure F.30: *Appearance of contour operation in the operations stack*

F.5.6 Copy to samples

This operation converts the currently selected grid coverage to a sample set, which becomes that starting point of a new subset. If polygons have been drawn, the operation will confine the copy to the interiors. The operation will not convert missing values to samples. Note that the operation does keep a reference to the original copied grid coverage; if it is changes by a re-evaluation of the stack, the changes will affect the output point cloud.

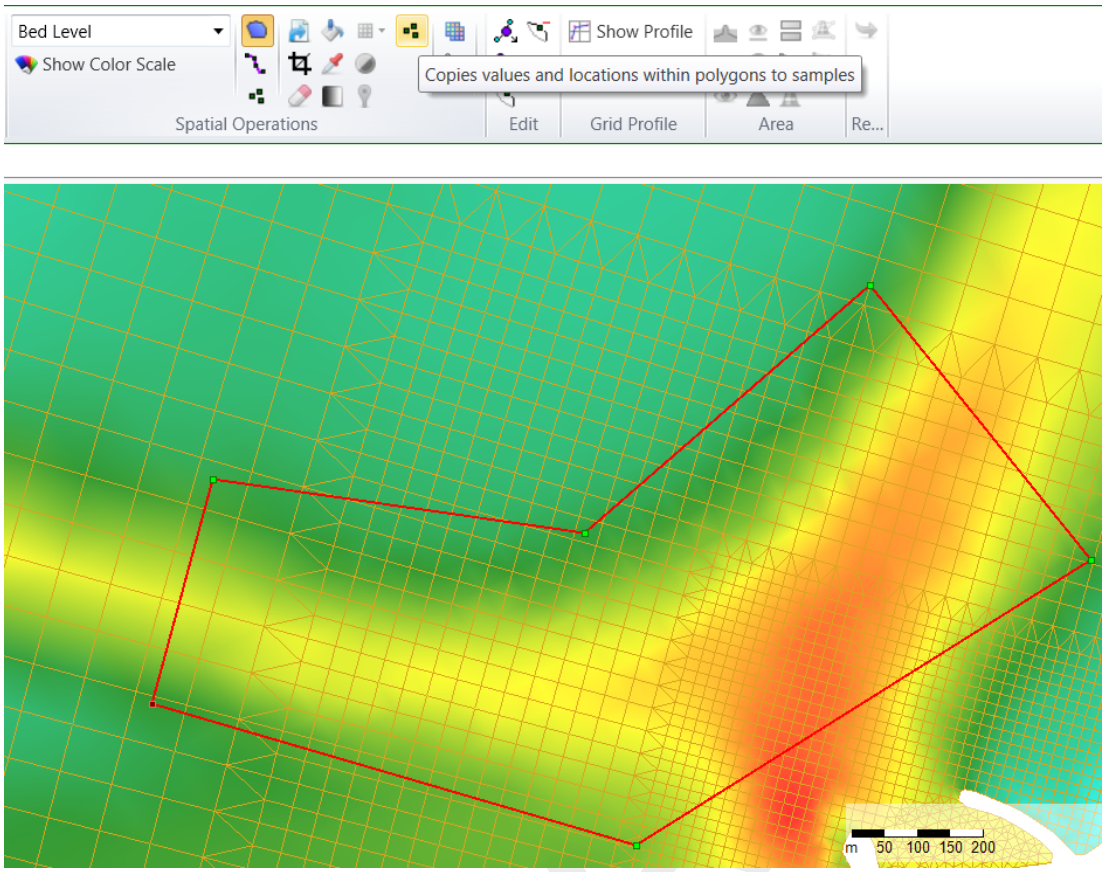


Figure F.31: *Applying the copy to samples operation*

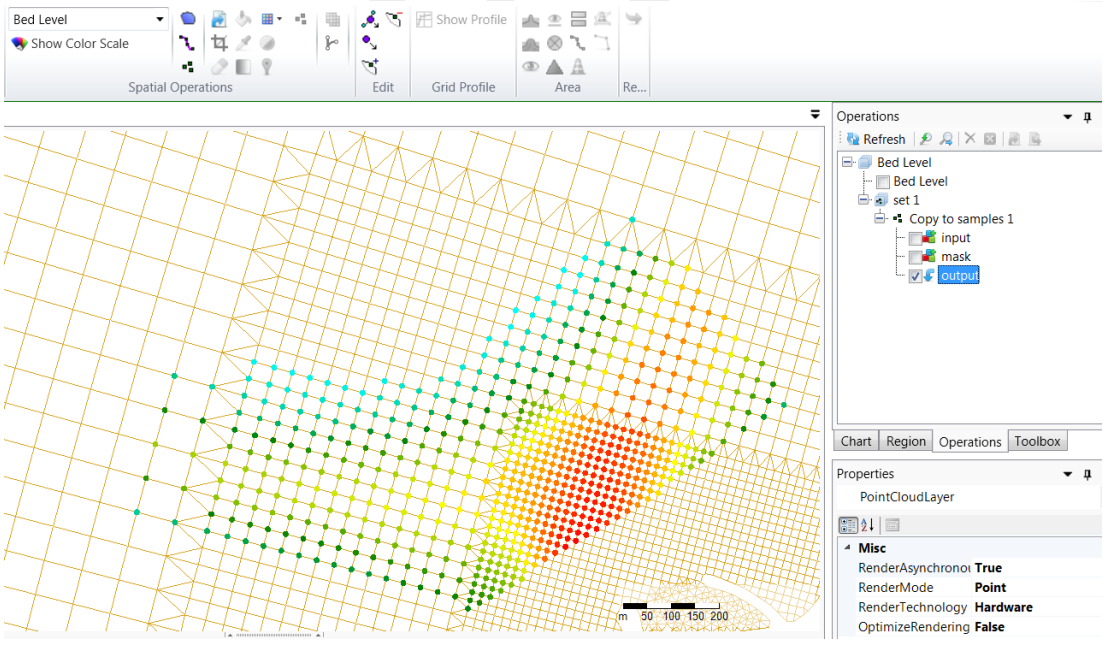


Figure F.32: *Copy to samples operation result*

F.5.7 Copy to spatial data

This operation simply clones the grid coverage, starting a new subset with a snapshot of the currently selected operation output. Similarly to F.5.6, it keeps a reference to the input data and will perform the clone again upon re-evaluation.

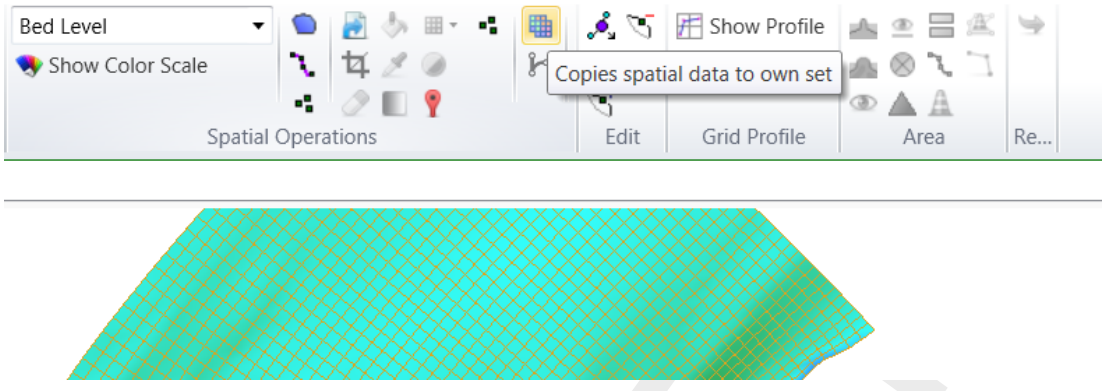


Figure F.33: *Applying the copy spatial data operation*

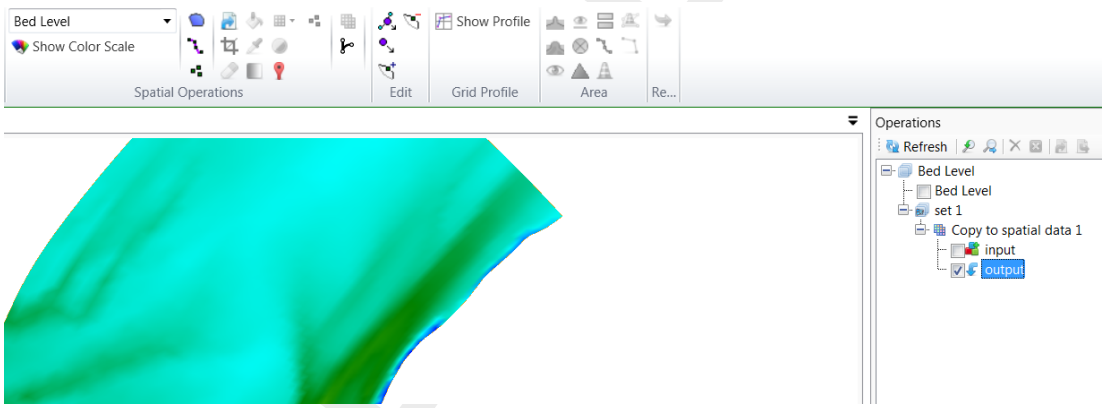


Figure F.34: *Copy spatial data operation result*

F.5.8 Merge spatial data

Whenever a subset contains a grid coverage as its editing data (after applying e.g. F.5.7) on the same grid as the main operation set, its result can be combined with the main set by applying this operation, similarly to the interpolation operation for sample sets, discussed below. Combing the grid coverages can be achieved with the usual pointwise methods.

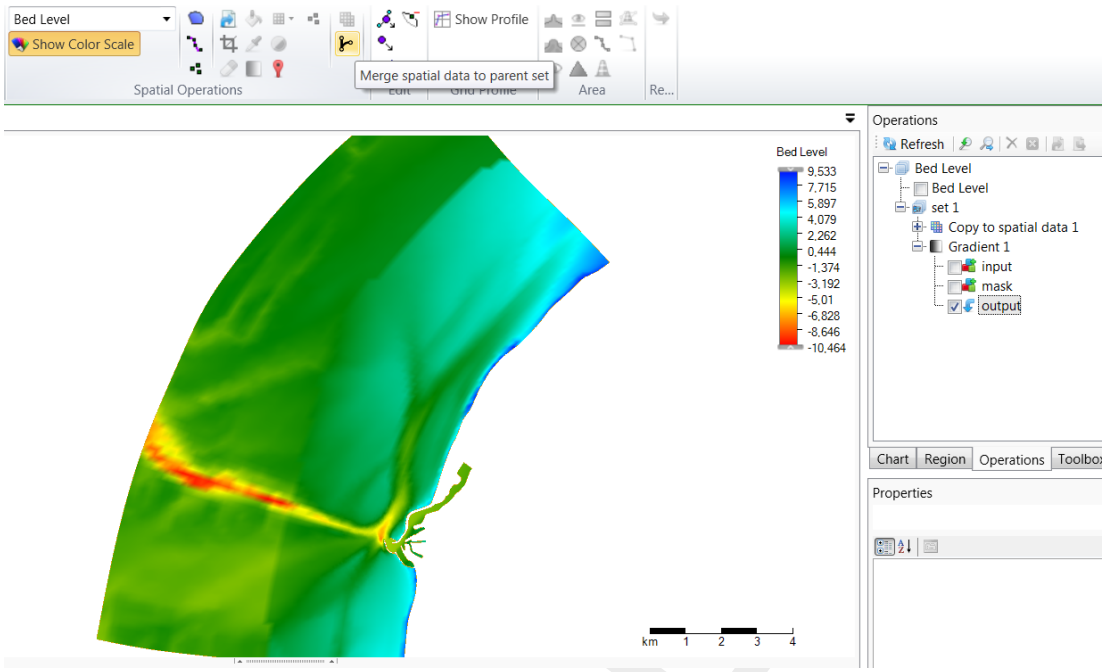


Figure F.35: *Activating the merge spatial data tool from the ribbon*

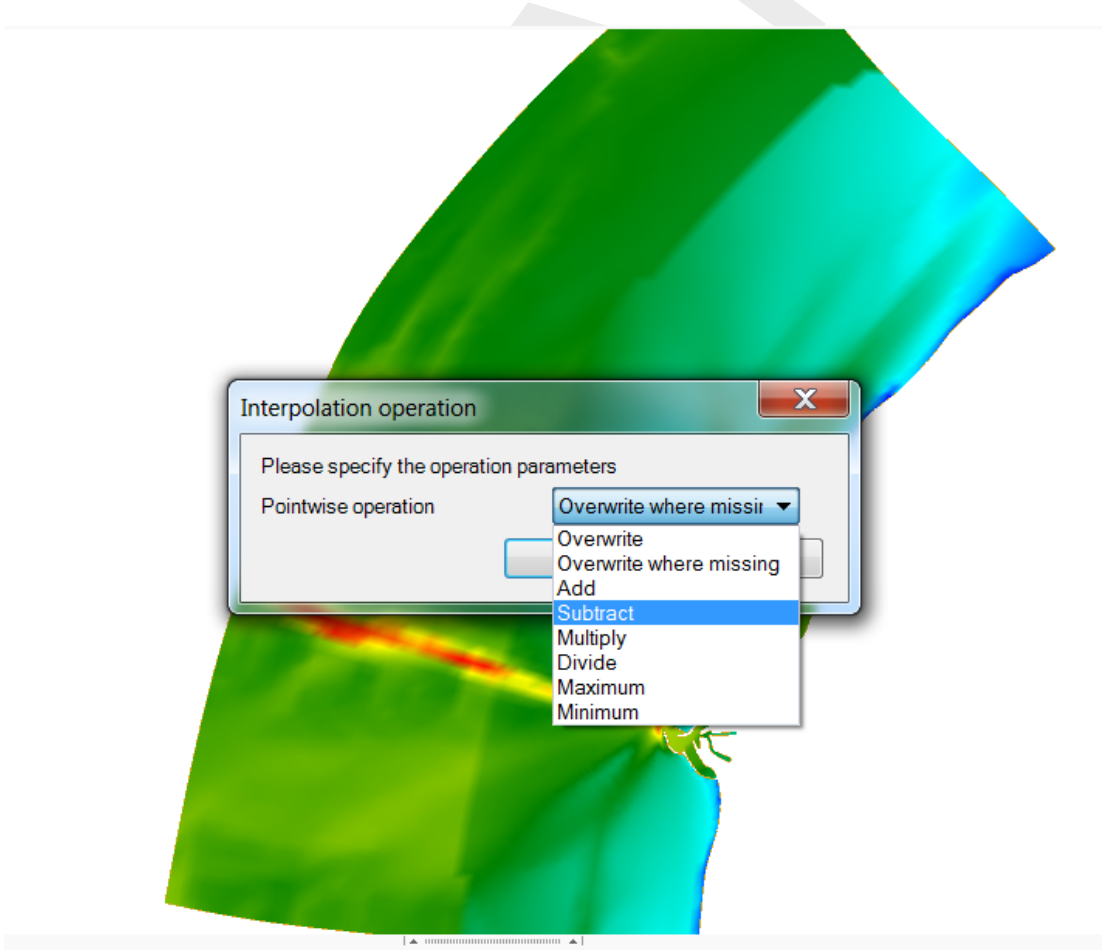


Figure F.36: *The merge operation requests a pointwise combination method*

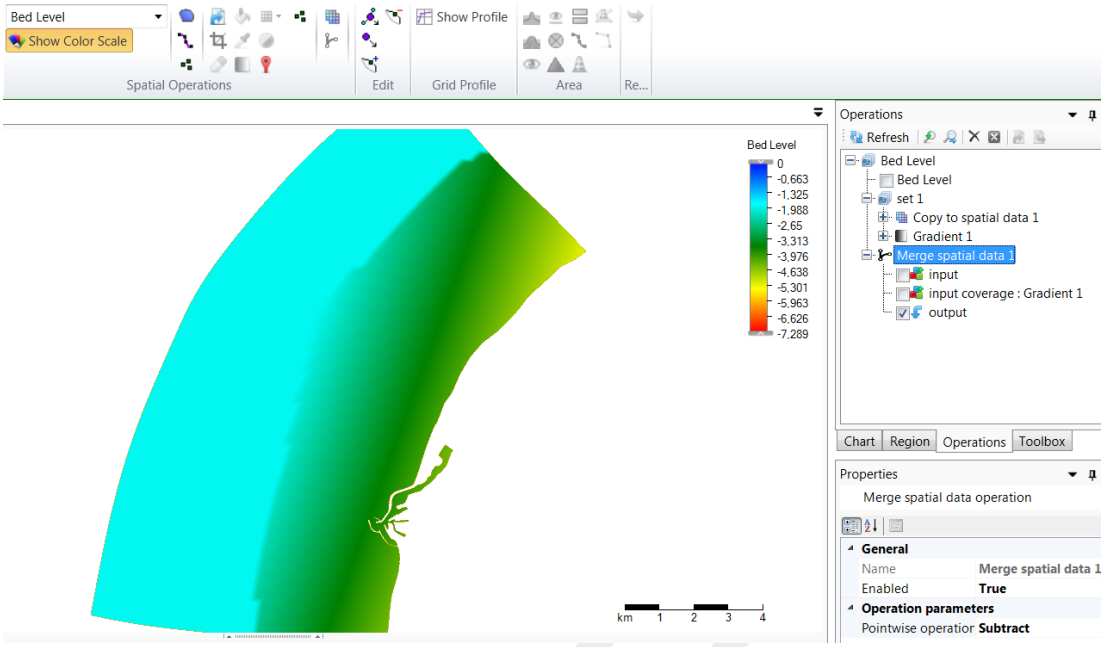


Figure F.37: *Resulting grid coverage*

F.5.9 Gradient

The gradient operation applies a gradient to a point cloud or grid coverage (depending on which one is active). The gradient operation is activated from the 'Map' ribbon and only available for polygon geometries or for the total data set if no polygon is provided. You have to assign the initial (start) value, the final (end) value and the going to angle (according to the Cartesian convention with 0 degrees is East, 90 degrees is North, etc **Note:** This is not working properly yet). For an example see Figure F.38. After applying a gradient to (part of) the point cloud or coverage the operation is added to the operations stack (Figure F.39).

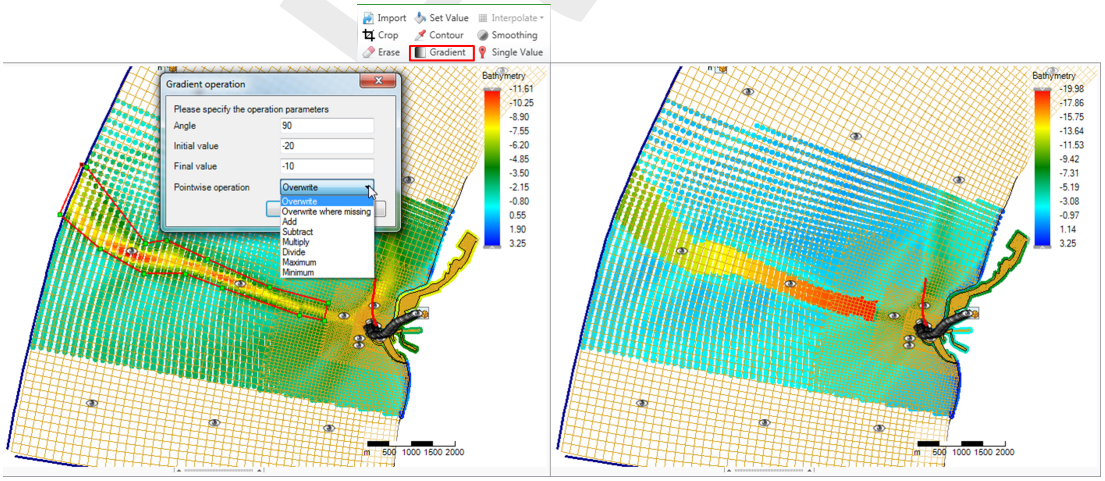


Figure F.38: *Performing a gradient operation on a point cloud with a polygon using 'Gradient' from the 'Map' ribbon*

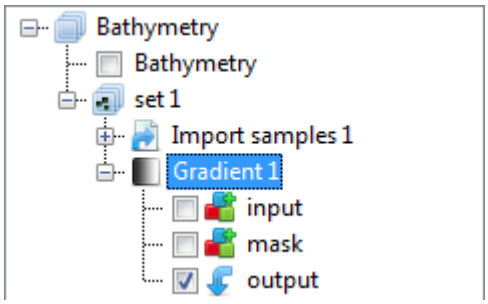


Figure F.39: *Appearance of gradient operation in the operations stack*

F.5.10 Interpolate

The interpolate operation is the way to get sample set(s) to a grid or network (e.g. coverage). In the operation stack this means that we are actively switching from working on a point cloud (helping to construct the coverage) to working on the selected coverage (or spatial quantity). The interpolation is performed on the data within a polygon or polygons (if provided) or all the data (if no polygons are provided). The interpolate operation can be performed on a single (selected) sample set or on multiple sample sets. Both methods are discussed below. The methods for interpolation are either

- ◇ Triangulation: performs a Delauney triangulation on the sample point set before projecting onto the grid.
- ◇ Averaging: combines sample points within a possible enlarged cell according an algorithm of choice. The user can set the search cell expansion factor (rel. search cell size) and a threshold for the number of sample points within a cell (minimum sample points), see Figure F.40.

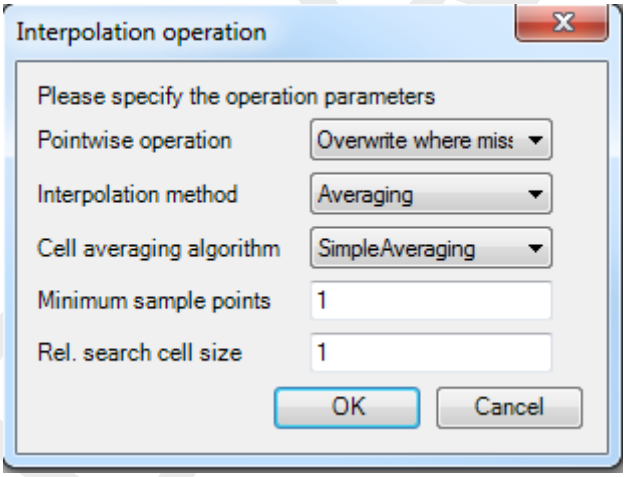


Figure F.40: *Interpolation Operation options*

Seven Cell averaging algorithms can be chosen by the user; see Figure F.41. These algorithms are explained below:

- ◇ SimpleAveraging: bilinear interpolation is applied, which uses a distanceweighted average of the surrounding samples. The closer the sample point the larger the weighted value.
- ◇ ClosestPoint: the value of the closest sample inside the search area is taken.
- ◇ MaximumValue: the maximum value of the samples inside the search area is taken.
- ◇ MinimumValue: the minimum value of the samples inside the search area is taken.
- ◇ InverseWeightedDistance: Instead of a distanceweighted average (w) in case of the inverse of SimpleAveraging, the distanceweighted average (1/w) is taken. The closer the sample point the smaller the weighted value.
- ◇ MinAbs: the minimum of the absolute values of the samples inside the search area is taken.
- ◇ KdTree: This is an obsolete option, which will be removed in a future release.

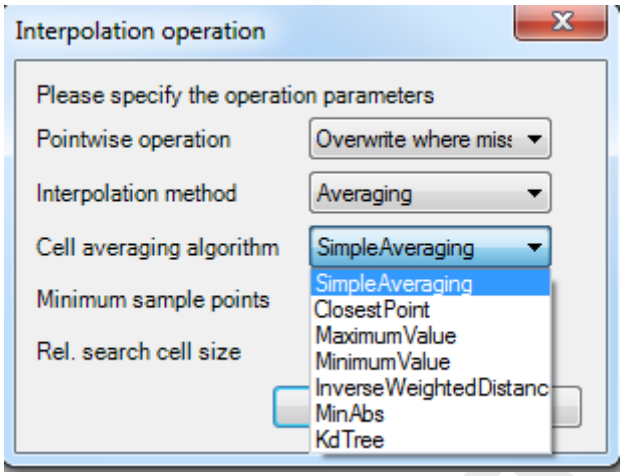


Figure F.41: *Averaging options*

By default, the interpolation will only overwrite missing values in the gridded data set. However, if the grid coverage already contains values, the user may choose to overwrite or combine the data by a pointwise arithmetic operation.

Interpolate single (selected) set

To perform interpolation on a single sample set, select the sample set (i.e. 'set1') in the operation stack and press 'Interpolate' in the 'Map' ribbon (Figure F.42). Since no polygon is provided in this example, all the samples will be interpolated to the grid. Use polygons if you would like to have more control over the interpolation. After the interpolation the operation is added to the operations stack (Figure F.43). Please note that after performing the interpolation the workflow in the stack is shifting from the sample set (i.e. 'set1' - which was a side step to construct the coverage) to the coverage (i.e. 'bed level').

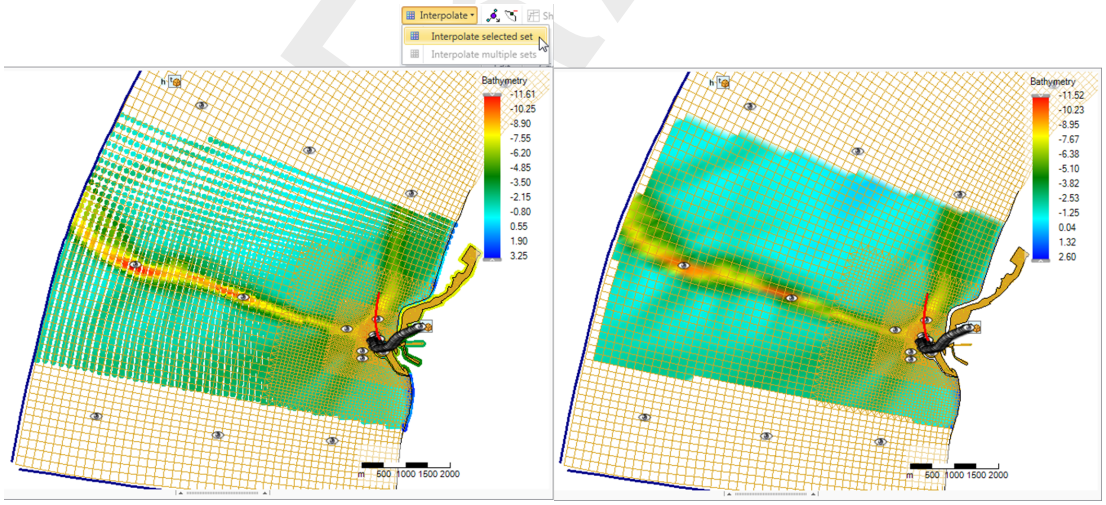


Figure F.42: *Performing an interpolation operation on a single sample set (without using a polygon) using 'Interpolate' from the 'Map' ribbon*

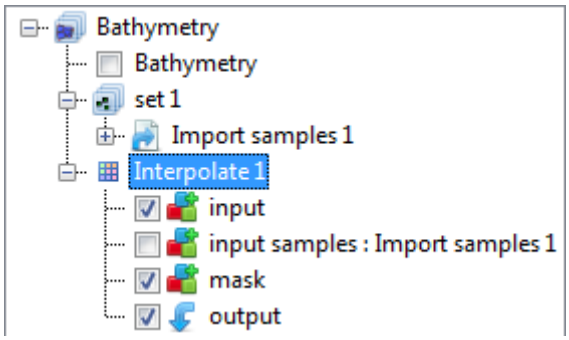


Figure F.43: *Appearance of interpolation of 'set1' to the coverage 'bed level' in the operations stack*

Interpolate multiple sets

To perform interpolation on multiple sample sets, select the active coverage (i.e. 'bed level') in the operation stack and press 'Interpolate' in the 'Map' ribbon (Figure F.44). In the popup you can select which sample sets to include in the interpolation (in this example both). Since no polygon is provided, all the samples (from the two sets) will be interpolated to the grid. Use polygons if you would like to have more control over the interpolation. After the interpolation the operation is added to the operations stack (Figure F.45). Again note that after performing the interpolation the workflow in the stack is shifting from the sample set (which was a side path to construct the coverage) to the coverage (i.e. bed level).

Note: Please note that interpolation of multiple sample sets can also be achieved by importing/combining different sample sets into the same set in the stack instead of using two separate sets. In this case you can just interpolate the single (selected) set.

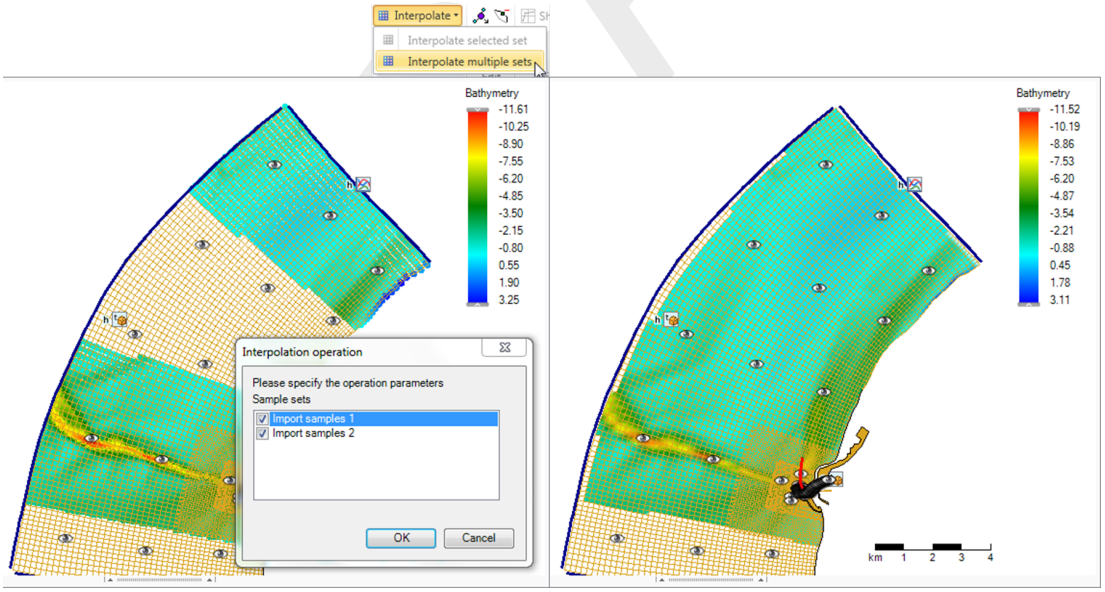


Figure F.44: *Performing an interpolation operation on multiple sample sets (without using a polygon) using 'Interpolate' from the 'Map' ribbon*

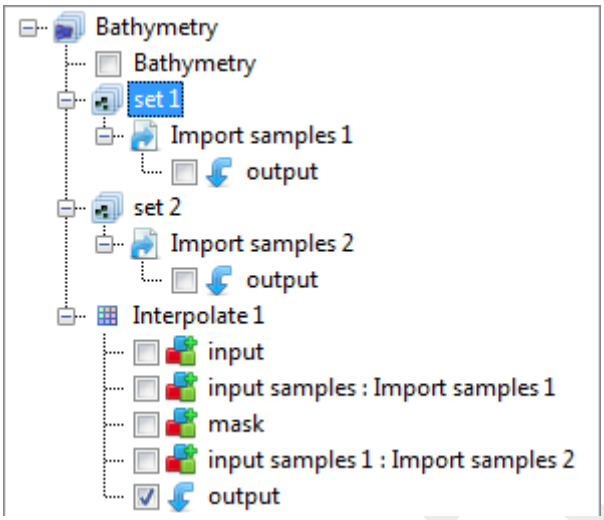


Figure F.45: *Appearance of interpolation of 'set1' and 'set2' to the coverage 'bed level' in the operations stack*

F.5.11 Smoothing

The smoothing operation smooths out (steep) gradients in a point cloud or coverage (depending on which one is active). The smoothing operation is activated from the 'Map' ribbon and only available for polygon geometries or for the total data set if no polygon is provided. You have to assign the smoothing exponent and number of smoothing steps. The higher the exponent and the number of smoothing steps, the heavier the smoothing. For an example see Figure F.46. After applying smoothing to (part of) the point cloud or coverage the operation is added to the operations stack (Figure F.47).

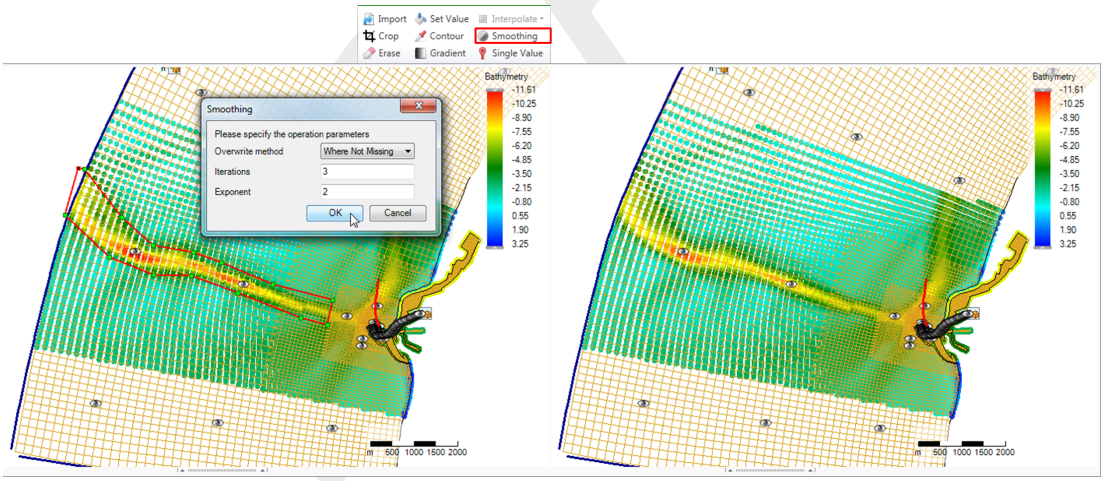


Figure F.46: *Performing a smoothing operation on a point cloud with a polygon using 'Smoothing' from the 'Map' ribbon*

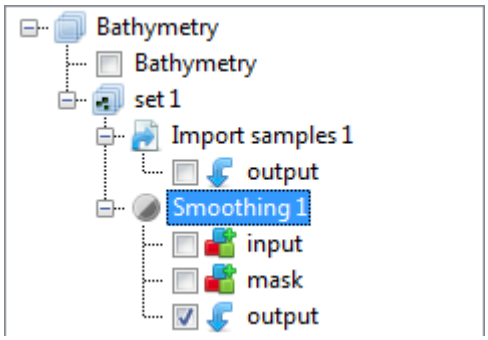


Figure F.47: *Appearance of smoothing operation in the operations stack*

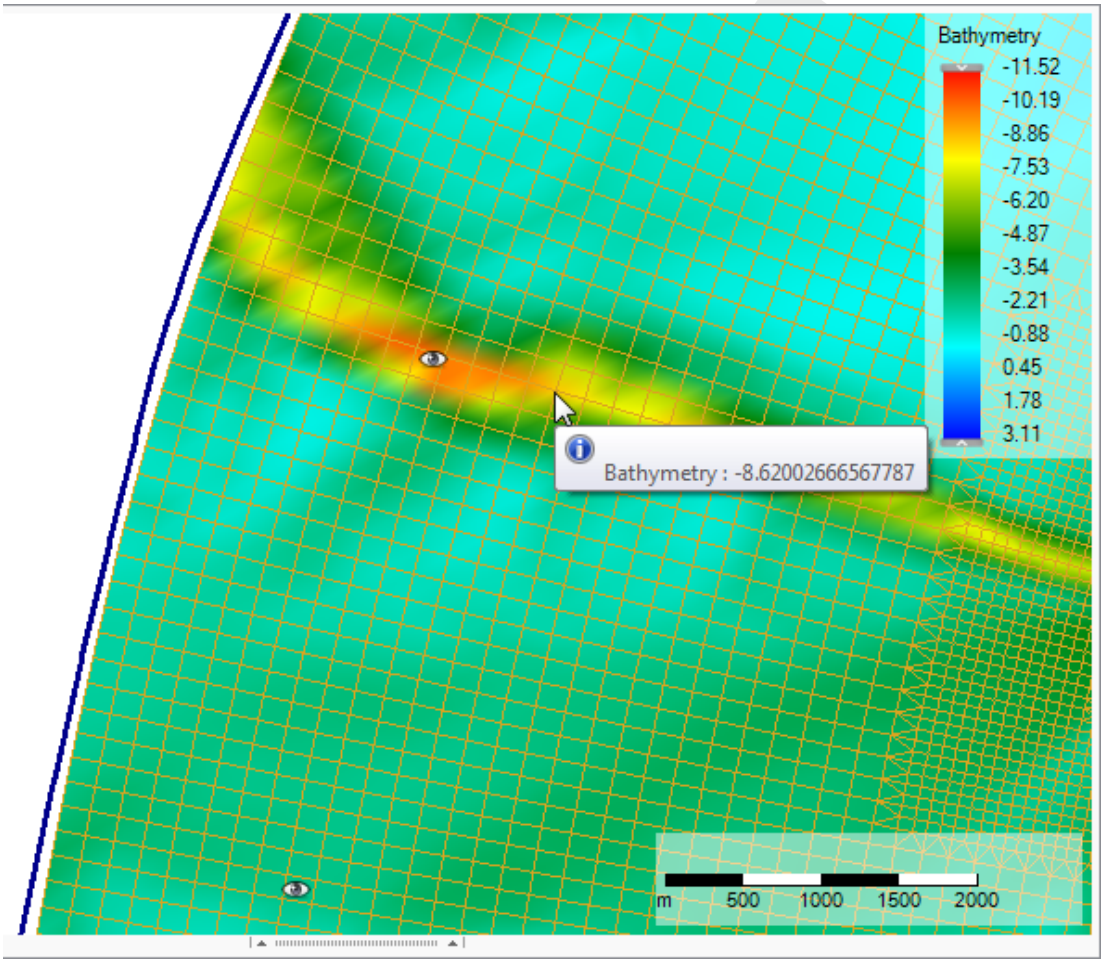


Figure F.48: *The cursor for the overwrite operation showing the value of the closest coverage point*

F.5.12 Overwrite (single) value

The ‘overwrite (single) value’ operation allows you to edit single values on the active coverage after the interpolation. The ‘overwrite (single) value’ operation is activated from the ‘Map’ ribbon. There is no geometry required for this operation. Upon selecting the operation from the ribbon a cursor will become active showing the coverage value closest to the cursor in a tooltipstring (Figure F.48). Upon clicking LMB a popup appears in which you can overwrite the value of this coverage point Figure F.49. After applying the overwrite operation it is added to the operations stack (Figure F.50).

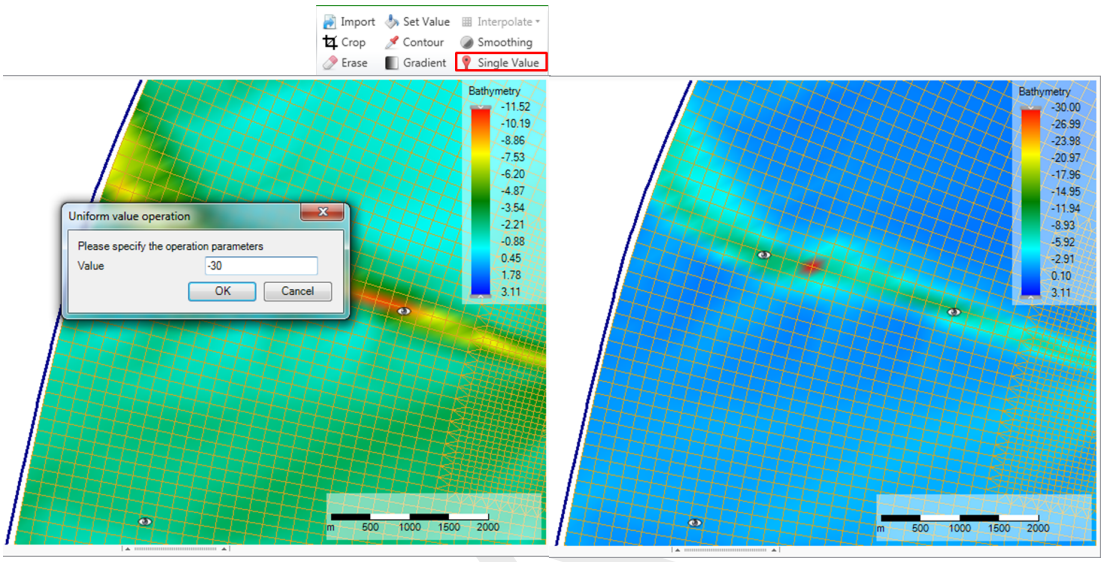


Figure F.49: *Performing an overwrite operation on a coverage point using ‘Single Value’ from the ‘Map’ ribbon*

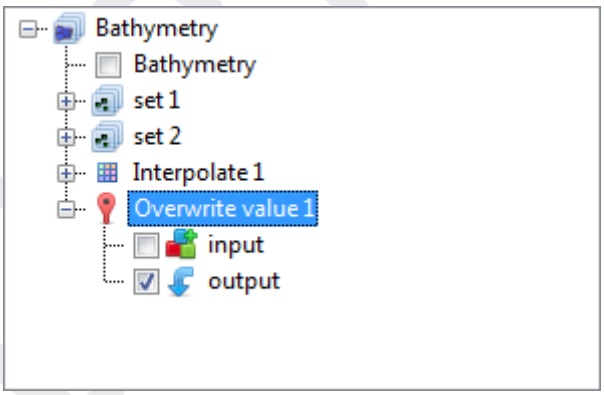


Figure F.50: *Appearance of overwrite operation in the operations stack*

F.6 Operation stack

The operation stack keeps track of the workflow of spatial operations that you performed. This helps you to make transparent how you arrived at your ‘final’ dataset without having to save all the intermediate datasets (steps) separately. Moreover, the stack is reproducible and easily editable without having to start all over again. This section describes the stack workflow (section F.6.1), how to edit operation properties (section F.6.2), how to enable/disable (section F.6.3), delete (section F.6.4), refresh(section F.6.5) operations, quick links (section F.6.6) and import/export functionality (section F.6.7).

Note: Currently, the stack is saved in the Delta Shell project upon saving the project. The next time you open the project, the stack will reappear. The stack is not (yet) saved in a human readable/editable file.

F.6.1 Stack workflow

Upon performing a spatial operation, the 'Operations' panel will open (see Figure F.51) with the operations stack (tree). The stack first shows on which point cloud or coverage you are working (in this example 'bed level'). Subesquently, all the operations on this dataset are listed. For each operation you can inspect what the input, mask (e.g. the geometry used for the operation) and output are for the operation (Figure F.52). By default the stack continues from the last operation that you performed. If you wish to work on a different dataset or operation within a dataset, you have to select that dataset or operation in the 'Operations' panel with the LMB.

When working on a coverage, point clouds (or sets) can be used to construct the coverage. In that case the stack jumps from the 'trunk' to a 'branch' and the subsequent operations are performed on the point cloud (see Figure F.51). By selecting the set or coverage in the 'Operations' panel you determine on which dataset you are working. The interpolate operation (section F.5.10) allows you to bring data from the point cloud (branch) to the coverage (trunk). See also Figure F.51.

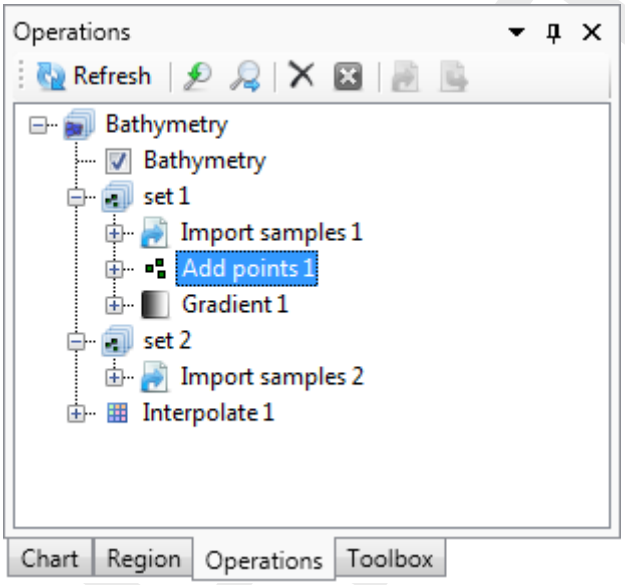


Figure F.51: *The 'Operations' panel with the operations stack. In this example 'bed level' is the coverage (e.g. trunk) that is edited. The point clouds 'set 1' and 'set 2' (e.g. branches) are used to construct the 'bed level' coverage.*

F.6.2 Edit operation properties

For each operation that you performed the properties (such as the value or 'Pointwise operation' of a 'Set Value' operation) can be edited using the 'Properties' window (Figure F.53). **Note:** Please note that the mask of an operation cannot (yet) be edited. By editing the operation properties the operation stack becomes 'out of sync' and has to be refreshed for the changes to become active (see section F.6.5).

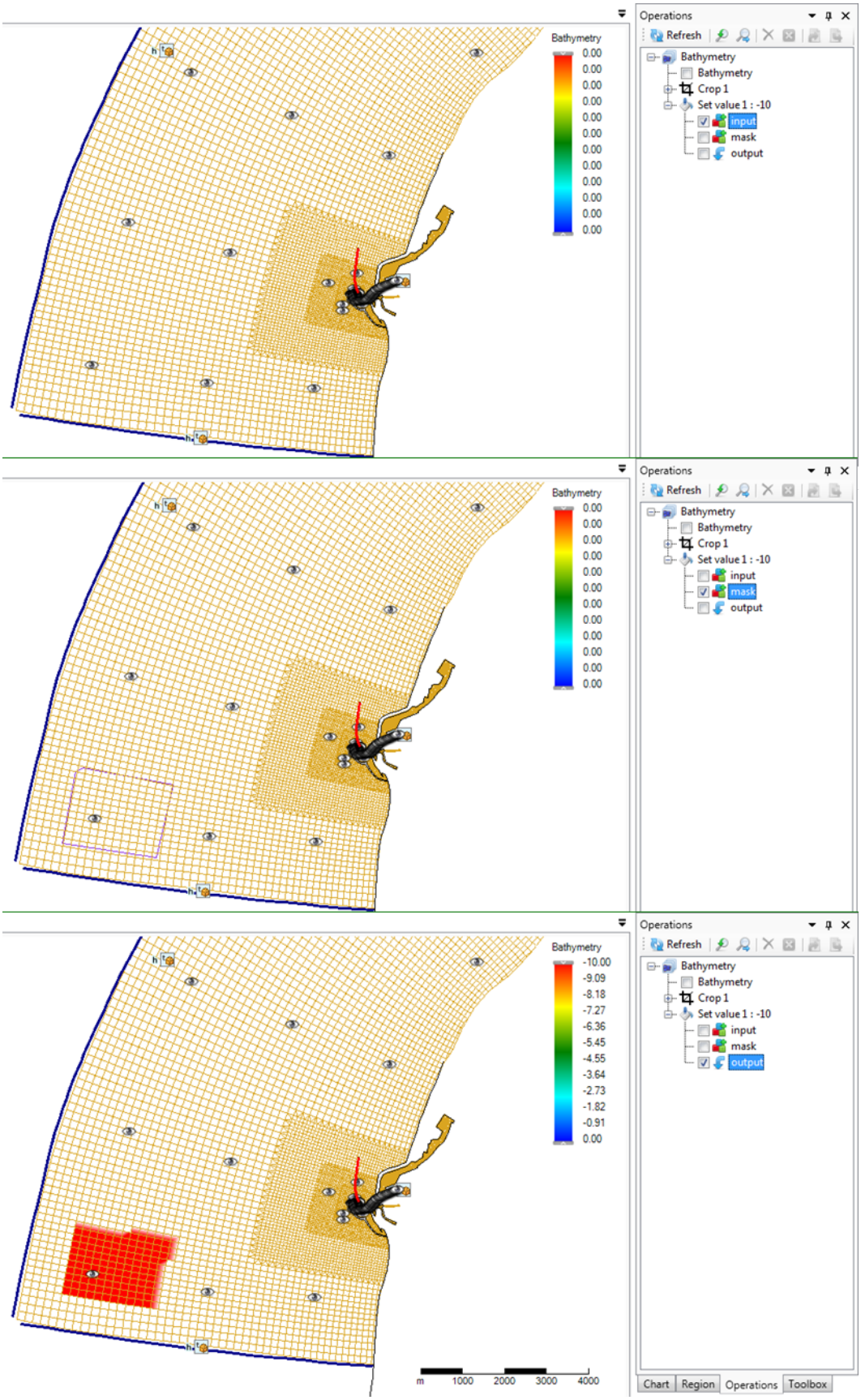


Figure F.52: *Input for the operation (top panel), mask for the operation (middle panel) and output of the operation (bottom panel)*

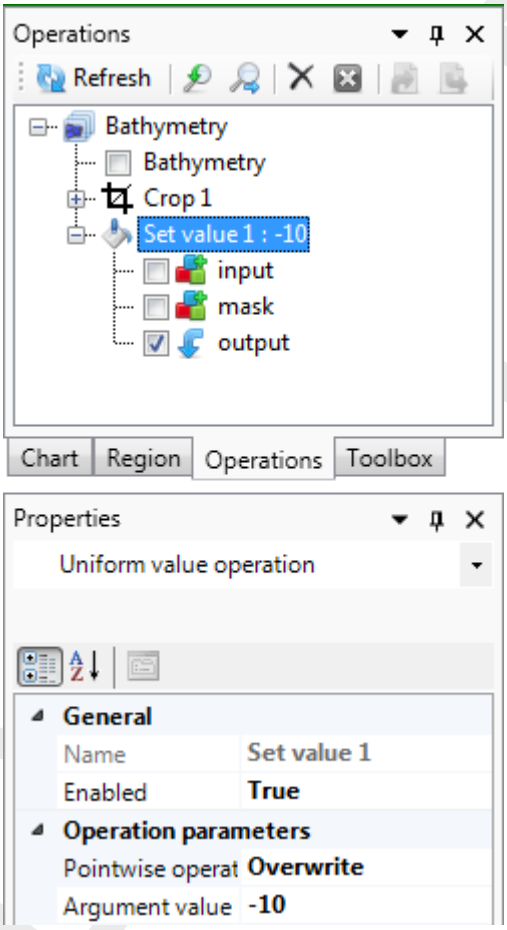


Figure F.53: *Editing the value or 'Pointwise operation' of a 'Set Value' operation using the properties panel*

F.6.3 Enable/disable operations

You can (temporarily) enable/disable operations by selecting the operation and pressing boxed cross icon in the stack menu (Figure F.54). Upon disabling an operation the operation will be made grey in the stack and the operation is not taken into account anymore upon evaluation of the overall result. The result of disabling an operation is not directly activated. This is indicated in the stack with the 'out of sync' exlamation mark (Figure F.54). You need to refresh the stack (see section F.6.5) for the changes to become active.

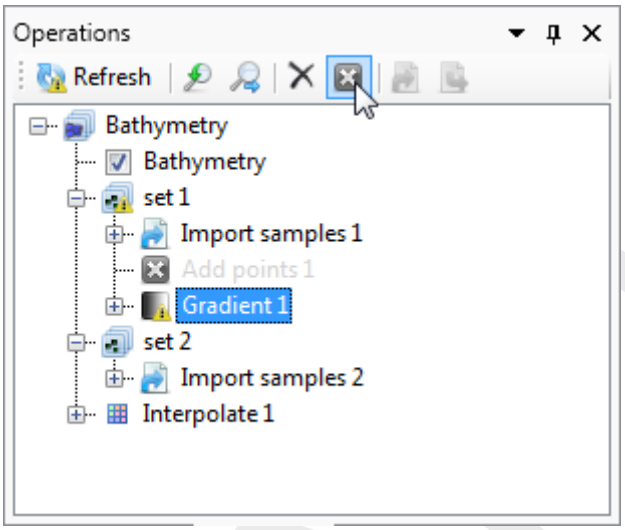


Figure F.54: *Disabling an operation using the boxed cross icon in the stack menu. The operation will become grey. Note the exlamation marks marking the stack 'out of sync'.*

F.6.4 Delete operations

To delete an operation permanently you have to select the operation and either press the cross icon (Figure F.55) or use the context menu and select delete (Figure F.56). The operation will be removed from the stack. The result of deleting an operation is not directly activated. This is indicated in the stack with the 'out of sync' exlamation mark. You need to refresh the stack (see section F.6.5) for the changes to become active.

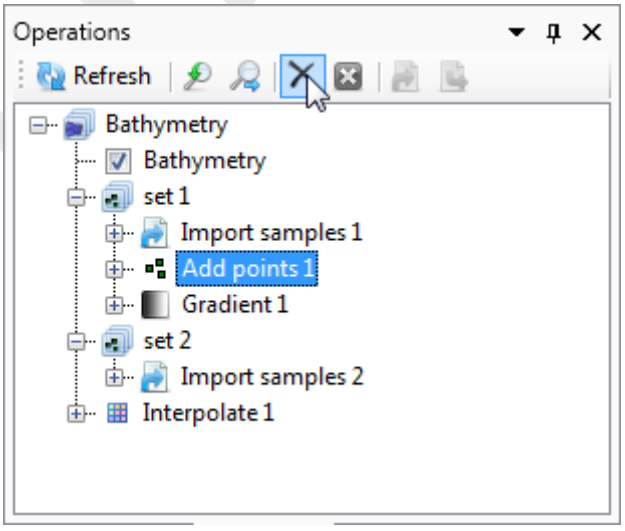


Figure F.55: *Removing an operation from the stack using the cross icon in the stack menu*

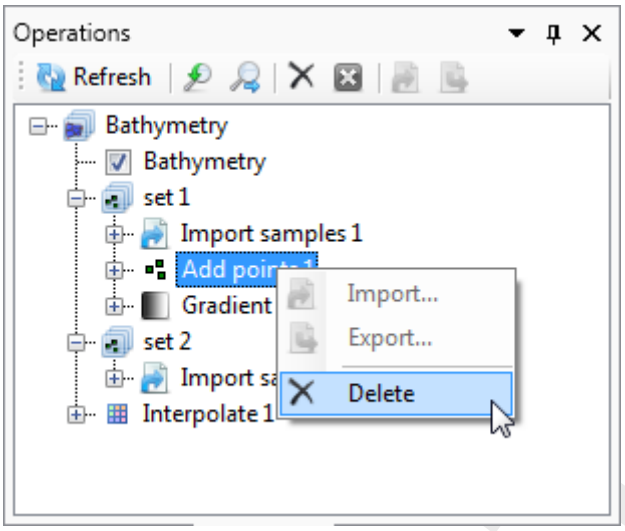


Figure F.56: *Removing an operation from the stack using the context menu on the selected operation*

F.6.5 Refresh stack

When the stack is marked 'out of sync' by exclamation marks, you can refresh the stack by pressing the 'Refresh' button for the changes to become active (Figure F.57). Upon refreshing the stack all the (enabled) operations in the stack will be (re-)evaluated. **Note:** Please note that refreshing the stack can take some time when large datasets are (re-)evaluated!

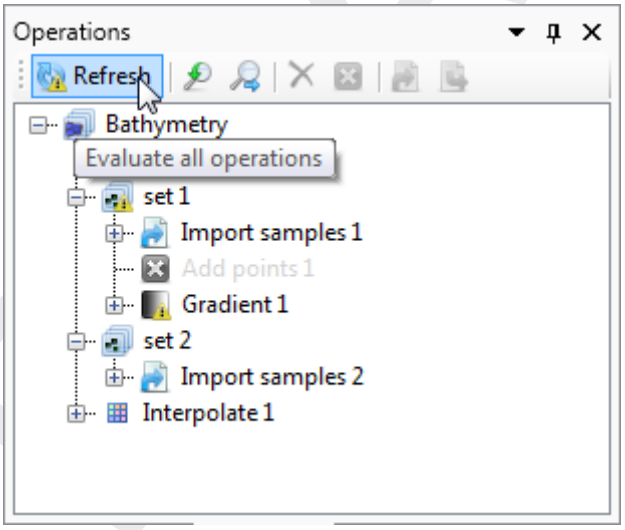


Figure F.57: *Refresh the stack using the 'Refresh' button so that all operation are (re-) evaluated*

F.6.6 Quick links

The stack menu contains two quick links to quickly show the original dataset (e.g. where you started from, Figure F.58) and the end result of the spatial operations (Figure F.59).

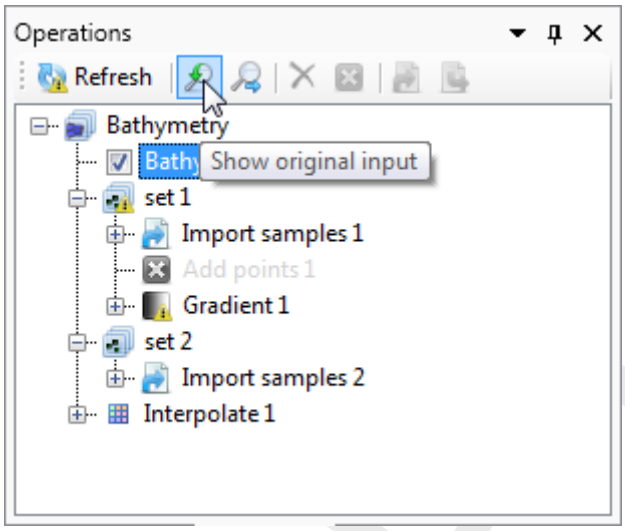


Figure F.58: *Quick link to the original dataset before performing any spatial operations*

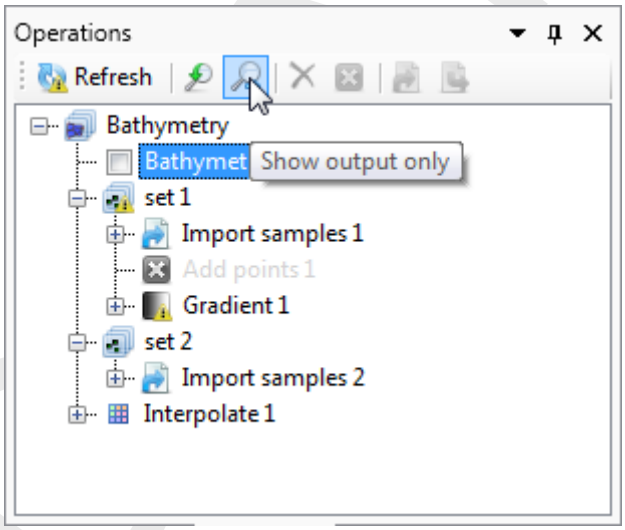
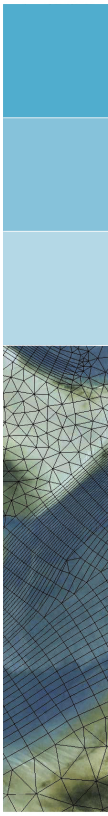


Figure F.59: *Quick link to the output after performing all (enabled) operations*

F.6.7 Import/export

Note: Importing and exporting data into or from the stack is still under construction



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