



**Dutch Delta Systems**

## D-FAST Bank Erosion

User Manual



# **D-FAST**

# **Bank Erosion**

**User Manual**

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## **D-FAST Bank Erosion, User Manual**

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## Contents

<b>List of Figures</b>	<b>v</b>
<b>List of Tables</b>	<b>vii</b>
<b>1 A guide to this manual</b>	<b>1</b>
1.1 Introduction . . . . .	1
1.2 Overview . . . . .	1
1.3 Typographical conventions . . . . .	1
<b>2 Introduction</b>	<b>3</b>
2.1 D-FAST Bank Erosion versus WAQBANK . . . . .	3
<b>3 Getting started</b>	<b>5</b>
3.1 Installation . . . . .	5
3.2 Scenario plan . . . . .	5
3.3 Steady-state hydrodynamic simulations . . . . .	5
3.4 Preparing the analysis configuration . . . . .	7
3.5 Run mode 'banklines' . . . . .	9
3.6 Run mode 'bankerosion' . . . . .	13
3.7 Running from Python source code . . . . .	25
<b>4 Detecting and shifting the bank lines</b>	<b>27</b>
4.1 Detecting the bank lines . . . . .	27
4.2 Common issues with bank line detection . . . . .	29
4.2.1 Detection of adjacent water body . . . . .	29
4.2.2 Irregularities in the detected bank line . . . . .	29
4.3 Shifting the bank lines . . . . .	30
<b>5 Estimating the bank erosion</b>	<b>33</b>
5.1 List of symbols . . . . .	33
5.2 Determining potential erosion by ship waves . . . . .	34
5.3 Determining ship induced wave height at the beginning of the foreshore . . . . .	37
5.4 Determining potential erosion by currents . . . . .	39
5.5 Total bank shift . . . . .	39
5.6 Potential bank erosion volume . . . . .	40
5.7 Variable discharge . . . . .	41
5.7.1 Erosion by ship waves . . . . .	41
5.7.2 Erosion by currents . . . . .	41
5.7.3 Total erosion . . . . .	42
5.8 Determining equilibrium bank . . . . .	43
5.9 Limitations of D-FAST Bank Erosion . . . . .	43
5.9.1 Homogeneous bank . . . . .	44
5.9.2 Only erosion along initial bank line . . . . .	44
5.9.3 Only erosion by ship waves and currents . . . . .	45
5.9.4 Profile and bed level remain constant . . . . .	45
<b>References</b>	<b>47</b>
<b>A Bank strength coefficients for different soil types</b>	<b>49</b>
<b>B File formats</b>	<b>51</b>
B.1 analysis configuration file . . . . .	51
B.2 line geometry files . . . . .	54
B.3 chainage file . . . . .	54

B.4	parameter files	54
B.5	simulation result files	55
B.6	eroded volume file	55
B.7	dialog text file	56

## List of Figures

3.1	Example of a configuration file for D-FAST Bank Erosion . . . . .	8
3.2	Example of the General settings in the GUI . . . . .	9
3.3	Example of the Detection settings in the GUI . . . . .	10
3.4	Example of output of D-FAST Bank Erosion in 'banklines' mode showing water depth, detected banklines (red lines), and river kilometers . . . . .	11
3.5	Example of the log for of D-FAST Bank Erosion in 'banklines' mode . . . . .	12
3.6	Example of input file for bank strength classes per river kilometer: from 0.0 - 75.2 km class 1, from 75.2 - 90.3 km class 3, etc. When no information is available, the closest value will be used. . . . .	13
3.7	Example of the Erosion settings in the GUI . . . . .	14
3.8	Example of the Shipping Parameters in the GUI . . . . .	15
3.9	Example of the Bank Parameters in the GUI . . . . .	15
3.10	Example of the Discharge Level dependent parameters in the GUI . . . . .	16
3.11	Example of the log for of D-FAST Bank Erosion in 'bankerosion' mode . . . . .	18
3.12	Map of water depth, initial bank lines, river kilometers and fairway axis . . . . .	19
3.13	Map of erosion sensitivity . . . . .	19
3.14	Eroded volume subdivided per discharge level . . . . .	20
3.15	Eroded volume subdivided per bank line . . . . .	20
3.16	Total erosion volume based on equilibrium bank line . . . . .	21
3.17	Control figure for water levels of each discharge (bank line 1) . . . . .	21
3.18	Control figure for water levels of each discharge (bank line 2) . . . . .	22
3.19	Control figure for velocities of each discharge (bank line 1) . . . . .	22
3.20	Control figure for velocities of each discharge (bank line 2) . . . . .	23
3.21	Map with indication of applied bank type . . . . .	23
3.22	Bank retreat at the end of the simulation period and for the equilibrium situation	24
4.1	The bank line within a transition cell where $d$ equals $z_b$ and $z$ equals $z_w$ . . . . .	27
4.2	Detection of bank lines at a shortcut in the Meuse river. Red: Baseline 'section 1-2 boundary', Blue: detected bank line from WAQUA computation ( $Q = 278.5 \text{ m}^3/\text{s}$ , average discharge) . . . . .	28
4.3	Detection of a bank line close to groynes. Red: detected bank line from WAQUA computation ( $Q=278.5 \text{ m}^3/\text{s}$ , average discharge) . . . . .	28
4.4	Detection of the initial bank line close to adjacent water bodies ( $Q=278.5 \text{ m}^3/\text{s}$ , average discharge) . . . . .	29
4.5	Detection of the initial bank line at the connection with a side channel ( $Q=278.5 \text{ m}^3/\text{s}$ , average discharge) . . . . .	30
4.6	Het verschuiven van een oeverlijn gebaseerd op het snijpunt van twee lijnsegmenten. Blauw: oorspronkelijke locatie, Groen: nieuwe locatie . . . . .	30
4.7	Het verschuiven van een oeverlijn gebaseerd op de gemiddelde verplaatsing van twee lijnsegmenten. Blauw: oorspronkelijke locatie, Rood: nieuwe locatie gebaseerd op individuele segmenten, Groen: nieuwe locatie (gemiddelde van de rode punten). . . . .	31
5.1	Graphical definition of quantities . . . . .	34
5.2	Example of bank erosion due to waves for average to good clay with a bankstrength coefficient ( $c_E = 0.0001$ ). An increase in the parameter $\mu_{fs}$ accounts for an increased effect of the shape of the foreshore on wave damping . . . . .	36
5.3	Wave height as function from the distance from the fairway for different values of the water depth. . . . .	38
5.4	Eroded volume for different water levels. . . . .	40

5.5	Erosion due to waves at different discharge levels: a) no erosion as the studied bank line is too high, b) erosion, c) erosion, d) no erosion since the bank line is below the area of influence. . . . .	42
5.6	Estimated equilibrium bank profile for 4 possible combinations of $z_{up}$ and $z_{do}$ . . . . .	44
5.7	Non-homogeneous banks. . . . .	45

## List of Tables

3.1	Probabilities of a discharge level for different scenarios (De Vries, 2012) . . . . .	6
3.2	Probabilities of discharge level in the Boven-Rijn (1989-2016) for different sce- narios . . . . .	7
5.1	Bank composition classes supported by D-FAST Bank Erosion . . . . .	35
5.2	Ship-types supported by D-Fast Bank Erosion, with $T_s$ [m] the draught of the ships . . . . .	37
A.1	Corresponding values for $c_E$ and $\tau_c$ (Verheij <i>et al.</i> , 1995). . . . .	49



# 1 A guide to this manual

## 1.1 Introduction

This User Manual describes the theory and usage of D-FAST Bank Erosion. This rapid assessment tool for bank erosion along rivers has been designed to work with simulation results obtained from D-Flow FM, but can also applied using results from Delft3D-FLOW or WAQUA.

## 1.2 Overview

This manual is split in the following sections

- ◊ [Chapter 1](#), i.e. this chapter, gives a general overview of the manual,
- ◊ [Chapter 2](#) introduces the general concepts of D-FAST Bank Erosion and describes its application domain,
- ◊ [Chapter 3](#) describes briefly how to install and use D-FAST Bank Erosion,
- ◊ [Chapter 4](#) describes the bank line detection algorithm,
- ◊ [Chapter 5](#) describes the bank erosion concepts implemented,
- ◊ [Appendix A](#) gives an overview of characteristic bank strength values,
- ◊ [Appendix B](#) describes the file formats used by the software.

## 1.3 Typographical conventions

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

Example	Description
<mydir \usecase.cfg>	Directory names, filenames, and path names are expressed between angle brackets, <>.
“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’.
dfastbe	Commands to be typed by you are given in the font Courier New, 10 points.
[ms <sup>-1</sup> ] [-]	Units are given between square brackets when used next to the formulae. Leaving them out might result in misinterpretation. Most units will be in SI notation. [m AD] stands for ‘meter Above Datum’, which denotes a level relative to the vertical reference system.

Command prompts, file listings and terminal output are shown in typewriter font:

```
> dfastbe --mode banklines
=====
Determine bank lines
=====
version: D-FAST Bank Erosion 2.1.0
source: https://github.com/Deltares/D-FAST_Bank_Erosion
-----
saving output in directory: output\banklines
```

```
reading chainage information from file : inputfiles\rivkm_20m.xyc
clipping chainage to the range 123.0 to 128.0 km
reading search line 1 from file : inputfiles\oeverlijn_links_mod.xyc
reading search line 2 from file : inputfiles\oeverlijn_rechts_mod.xyc
-----
reading simulation data from : sim270\SDS-j19_map.nc
-----
importing grid...
importing bathymetry ...
importing water level ...
...
... continued ...
```

## 2 Introduction

Since 2010 Deltares has been working on various bank erosion modules that can be used in combination with Delft3D-FLOW, WAQUA and D-Flow FM. The D-FAST Bank Erosion tool described in this document is the D-Flow FM compatible successor of WAQBANK developed for WAQUA and Delft3D-FLOW. The module computes local erosion sensitivity, visualizes the bank movement and gives an estimation of the amount of bank material that is released during a specified period (typically 1 year) and until an equilibrium is reached. D-FAST Bank Erosion can easily be used as a post processing tool of D-Flow FM simulations. Some examples for which D-FAST Bank Erosion can compute bank erosion are:

- ◊ Bank adjustments such as removal of bank protection
- ◊ Applying or removing fore shore protection
- ◊ Changes in shipping type or intensity
- ◊ Changes in currents (e.g. due to construction of side channels)

### Input

The input of D-FAST Bank Erosion is:

- 1 D-Flow FM results (netCDF map-files)
- 2 Initial bank lines or search lines for detecting bank lines
- 3 Local data: level of bank protection removal, subsoil characteristics, shipping information (quantity, location of fairway)

### Output

The output of D-FAST Bank Erosion is:

- 1 The new bank line position after specified period, and the equilibrium position.
- 2 Amount of sediment that is released from the banks over the specified period, and until the final equilibrium state is reached.

This output is presented in graphs / figures and written to text files.

#### 2.1 D-FAST Bank Erosion versus WAQBANK

D-FAST Bank Erosion will properly read the old analysis definition files of WAQBANK, but the new program is not able to read data directly from the WAQUA and Delft3D-FLOW output files. These output files need to be converted to netCDF files that mimic the map-files written by D-Flow FM; a small MATLAB based conversion 'sim2ugrid' is available for that purpose. Since the old WAQBANK code was quite slow, intermediate files were stored in local folders for caching. Since the algorithms of the new D-FAST Bank Erosion program are much faster, the caching step has been removed and `LocalDir` is ignored



## 3 Getting started

### 3.1 Installation

D-FAST Bank Erosion has been developed using Python, but it's typically distributed as a zip-file containing binaries for use on Windows 10. Unpack the content of the zip-file to any (preferably local) folder and start the software via the executable 'dfastbe.exe'. The distribution includes besides this executable a large number of supporting libraries and some configuration files. Alternatively, the tool can be run directly from the Python source code (see [Section 3.7](#) for more details).

The program can be run as a command line tool performing either the bank line detection step (see [section 3.5](#)) or the bank erosion (see [section 3.6](#)) step, or in a graphical mode which can be used to edit the analysis settings (see [section 3.4](#)) and run the analysis.

By default D-FAST Bank Erosion is looking for the definition file <dfastbe.cfg> in the current work directory. When the definition file has another name or location, this should be passed when the modules are called. See the command line option `-config` described in sections [3.5](#) and [3.6](#).

### 3.2 Scenario plan

D-FAST Bank Erosion is not calibrated for local bank erosion<sup>1</sup>. Therefore it is strongly advised to use D-FAST Bank Erosion only in a *relative* way. In this way one can determine:

- ◊ The locations at which the bank is most sensitive to erosion (by comparing different locations along the river).
- ◊ The sensitivity of a location for certain measures (by comparing different scenarios at one location).

We advise to compute different scenarios and compare the results. An example is: 1 scenario with a subsoil of sand and 1 scenario with a subsoil of clay. This means that only the type of subsoil is changed and the other input remains unchanged.

### 3.3 Steady-state hydrodynamic simulations

Before D-FAST Bank Erosion can be used, steady state hydrodynamic computations have to be performed for each discharge level. D-FAST Bank Erosion supports results coming from D-Flow FM and, after a conversion step, results coming from Delft3D-FLOW and WAQUA<sup>2</sup>.

First the discharge hydrograph should be schematised in discharge levels and a probability per discharge step. The discretisation of the discharge hydrograph is not a trivial procedure. Deltares advises to use at least ten discharge levels.

For each discharge level a netCDF map-file (D-Flow FM output file) must be provided – if Delft3D-FLOW or WAQUA simulation results are available the TRIM- or SDS-files need to be

---

<sup>1</sup>This is almost impossible, due to other uncertainties in bank properties, limited availability of field data of measured bank erosion and the fact that the simulation models have been designed for longer river reaches. Locally D-FAST Bank Erosion could be calibrated when historical data of bank erosion is available. However, this does not automatically imply that D-FAST Bank Erosion would give good results a few kilometers further downstream with the same settings, because the bank properties can be completely different.

<sup>2</sup>D-Flow FM and WAQUA models and Baseline schematisations of the Dutch river system can be requested via Helpdeskwater.nl Onderwerpen > Applicaties en modellen > Water en ruimte > Gebiedsschematisaties > Servicedesk > Meldingsformulier

converted to a netCDF map-file mimicking the D-Flow FM output. D-FAST Bank Erosion uses the water levels and flow velocities that are stored in the last time step. It is important that the hydrodynamic computations are in steady state – only the last time step of each simulation output file is used. The probability (normalized weighting of the time period) per discharge level is defined by the user in the configuration file.



**Note:** It is of utmost importance that in the netCDF map-file with the reference (average) discharge (which is used to establish the initial bank lines) the water remains within the main channel during the whole computation. Practically this means that the simulation has to be started with a low initial water level with no (or as little as possible) water in the flood plains. When this criterion is not met, the bank line detection algorithm may incorrectly identify bank lines when water is unable to recede from depressions in the flood plain. [Chapter 4](#) describes how the bank lines are detected using the reference discharge, and it indicates common pitfalls and how to avoid them.

An example of discharge levels in combination with probabilities for scenario's wet, dry or intermediate is given in [Table 3.1](#) for the river Meuse and in [Table 3.2](#) for the river Boven-Rijn.

Discharge level nr.	Discharge (m <sup>3</sup> /s)	1998-2002 (wet)	2004-2010 (dry)	2008-2011 (intermediate)
1	75	0.2932	0.1808	0.3110
2	150	0.1918	0.2466	0.2329
3	272	0.1918	0.2603	0.2055
4	400	0.0411	0.0548	0.0685
5	500	0.1507	0.1370	0.0959
6	750	0.0548	0.0712	0.0548
7	900	0.0329	0.0384	0.0164
8	1100	0.0164	0.0082	0.0055
9	1300	0.0137	0.0014	0.0021
10	1500	0.0041	0.0014	0.0021
11	1700	0.0041	0.0000	0.0021
12	1900	0.0041	0.0000	0.0021
13	2300	0.0014	0.0000	0.0014

**Table 3.1:** Probabilities of a discharge level for different scenarios (De Vries, 2012)

By default two figures are generated during D-FAST Bank Erosion computation which the user can use to check if the discharge levels are chosen properly. These are a figure with water levels and a figure with flow velocities. The figure showing the water levels highlights the elevation range at which one may expect bank erosion due to waves (water level  $z_w$  plus/minus the effective wave height  $H_0$ ). In both figures the area that is sensitive to erosion is indicated by means of bank levels and protection levels, and critical flow velocities respectively. The figure showing the velocities shows how these compare to the critical flow velocity for erosion. Based on these figures it can be decided to include or remove discharge levels from the computation.

Discharge level nr.	Discharge (m <sup>3</sup> /s)	average	16% undershot (wet)	50% undershot (intermediate)	84% undershot (dry)
1	1020	0.062	0.000	0.022	0.135
2	1203	0.160	0.066	0.193	0.245
3	1635	0.115	0.101	0.121	0.151
4	2250	0.200	0.154	0.238	0.189
5	3053	0.253	0.326	0.258	0.170
6	3824	0.116	0.179	0.086	0.063
7	4717	0.058	0.094	0.046	0.042
8	6151	0.027	0.061	0.026	0.006
9	8592	0.010	0.020	0.010	0.000

**Table 3.2:** Probabilities of discharge level in the Boven-Rijn (1989-2016) for different scenarios

### 3.4 Preparing the analysis configuration

The configuration file contains input parameters for both 'banklines' (detection) and 'bankerosion' execution modes. It is a simple ASCII file using the ini-file format. An example of the file is given in [Figure 3.1](#). These parameters are subdivided into three categories for clarity

- 1 *General* keywords are used in both execution modes,
- 2 *Detect* keywords are used only in 'banklines' detection mode, and
- 3 *Erosion* keywords are used only in 'bankerosion' mode.

The executable searches for the file 'dfastbe.cfg' in the current work directory unless another file name is given. The content of the configuration file is described in [section B.1](#). The existence, not the order, of the keywords is of importance.

The configuration file can be created or modified by means of either a text editor, or by D-FAST Bank Erosion running in gui mode. Since the gui mode is the default mode, the program can simply be started as

```
dfastbe
```

using default settings, or as

```
dfastbe --config D:\D-FAST_Bank_Erosion\Meuse\Meuse.cfg
```

when opening a specific analysis configuration file. [Figure 3.2](#) shows the graphical user interface with the tab for the general settings opened. These general settings are used by both the bank detection and bank erosion steps. Further settings specific for these two steps can be specified in the other tabs described in the following two sections. The three buttons at the bottom of the dialog will run the bank detection ('banklines'), run the bank erosion ('bankerosion') and close the program, respectively. The two analysis steps will be run using the active settings selected in the user interface at that time. When one of these actions is chosen all open figures that were generated by a previous analysis step will be closed. If you close the program via the cross in the upper right corner, the open figures will not automatically be closed.

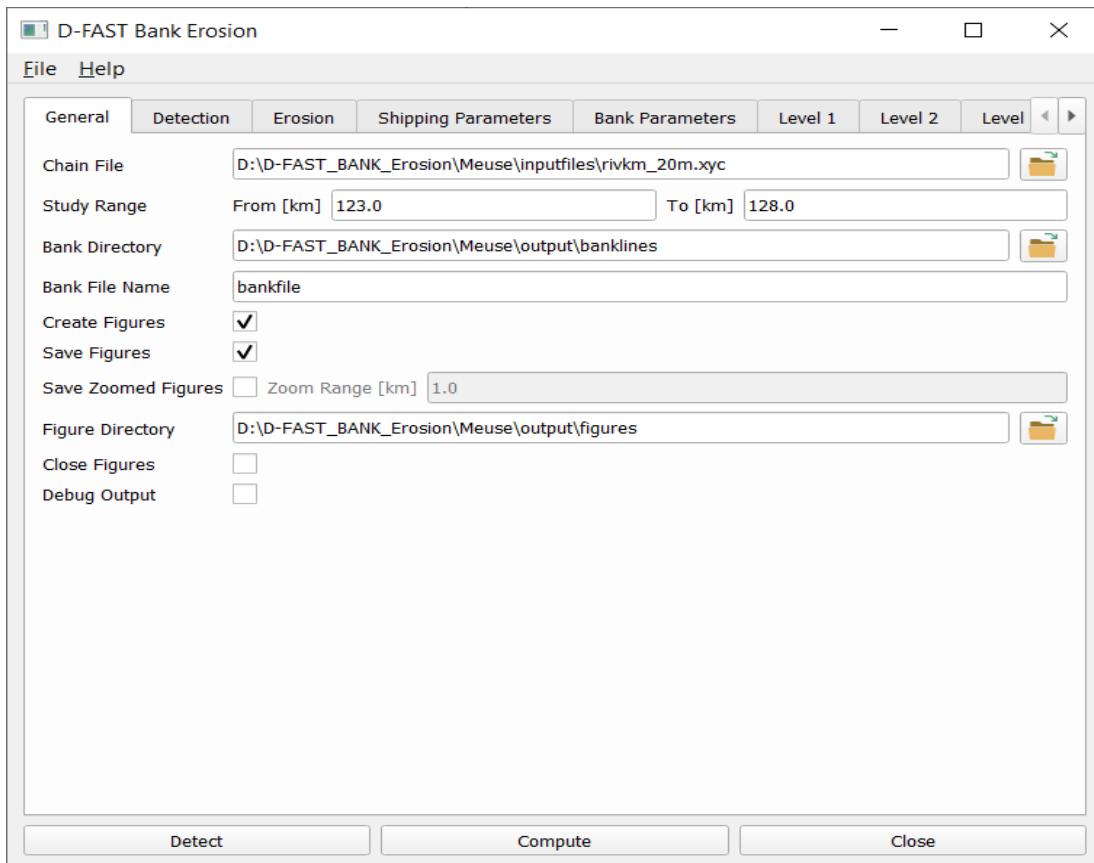
```
[General]
Version      = 1.0
RiverKM      = inputfiles\rivkm_20m.xyc
Boundaries    = 123.0:128.0
BankDir       = output\banklines
BankFile      = bankfile
Plotting      = True
SavePlots     = True
FigureDir     = output\figures
ClosePlots    = False

[Detect]
SimFile      = sim270\SDS-j19_map.nc
WaterDepth    = 0.0
NBank        = 2
Line1         = inputfiles\oeverlijn_links_mod.xyc
Line2         = inputfiles\oeverlijn_rechts_mod.xyc
DLines        = [ 50.0, 50.0 ]

[Erosion]
TErosion      = 1
RiverAxis     = inputfiles\maas_rivieras_mod.xyc
Fairway       = inputfiles\maas_rivieras_mod.xyc
OutputInterval = 1.0
OutputDir      = output\bankerosion
BankNew       = banknew
BankEq        = bankeq
EroVol        = erovol_standard.evo
EroVolEqui    = erovol_eq.evo
ShipType      = 2
VShip          = 5.0
NShip          = inputfiles\nships_totaal
NWaves         = 5
Draught        = 1.2
Wave0          = 150.0
Wave1          = 110.0
Classes        = false
BankType       = inputfiles\bankstrength_tauc
ProtectionLevel = inputfiles\stortsteen
Slope          = 20.0
Reed           = 0.0
NLevel         = 13
RefLevel       = 3
SimFile1      = sim075\SDS-j19_map.nc
PDischarge1   = 0.3110
SimFile2      = sim150\SDS-j19_map.nc
PDischarge2   = 0.2329
SimFile3      = sim270\SDS-j19_map.nc
PDischarge3   = 0.2055
SimFile4      = sim400\SDS-j19_map.nc

... continued ...
```

**Figure 3.1:** Example of a configuration file for D-FAST Bank Erosion



**Figure 3.2:** Example of the General settings in the GUI

**Note:** All files and paths are shown using absolute paths in the graphical user interface, but they will be converted as much as possible to relative paths when saving the configuration to file. The program does not verify or validate the content of the files. This is only verified by the kernel during the analysis.



### 3.5 Run mode 'banklines'

When D-FAST Bank Erosion is run in this mode, it determines the representative bank lines within the area of interest; for background information see [chapter 4](#). The input is given through the analysis configuration file, see [section 3.4](#).

When the configuration file has the name 'dfastbe.cfg' and is located in the work directory the program can be called as follows:

```
dfastbe --mode banklines
```

If the definition file has another name the following call should be used:

```
dfastbe --mode banklines --config D:\D-FAST_Bank_Erosion\Meuse\Meuse.cfg
```

with **path** the path to the directory where the configuration file is located and **other.cfg** the name of the configuration file.

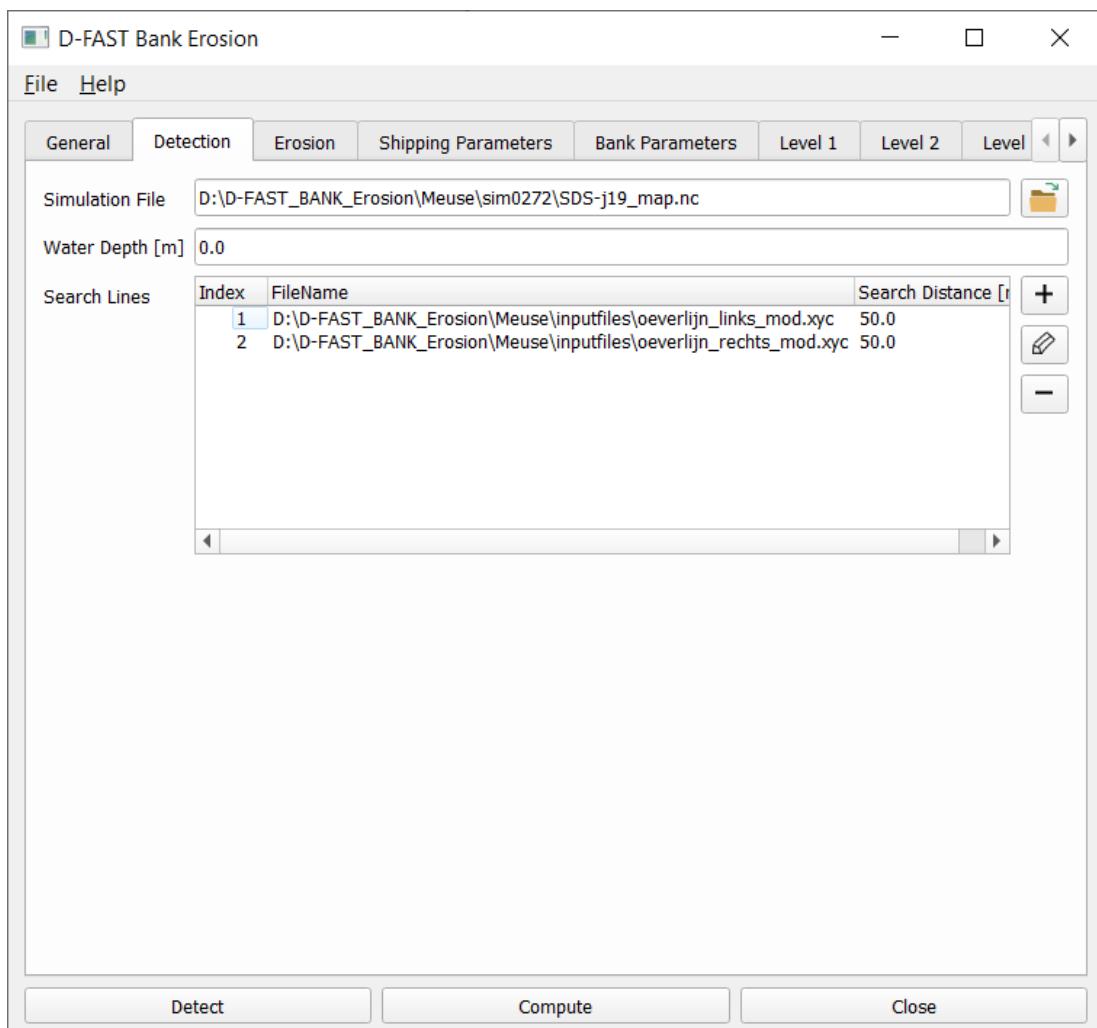
Required input parameters:

- ◊ D-Flow FM output file (netCDF map-file) at representative discharge (`SimFile`),
- ◊ Number of bank Lines (`NBank` default two, the left and right bank),
- ◊ For each of the bank lines a file with xy-coordinates of the search lines i.e. the approximate location of the bank line (`Line1`, `Line2`, ..., `LineN`, with  $N$  the number of bank lines)
- ◊ Chainage file which links river kilometres to xy-coordinates (`RiverKM`),

Output:

- ◊ XY-coordinates of the determined bank lines.
- ◊ Plot of the bank lines (optional, `Plotting` and `SavePlots`)

**Figure 3.3** shows the tab in the graphical user interface for the settings specific for the detection step. The content of the first (General) and second (Detection) tabs is relevant for the bank line detection analysis. All files and paths are shown using absolute paths in the graphical user interface, but they will be converted as much as possible to relative paths when saving the configuration to file. The program does not verify or validate the content of the files. This is only verified by the kernel during the analysis.



**Figure 3.3:** Example of the Detection settings in the GUI

An example of the graphical output of the 'banklines' mode is shown in [Figure 3.4](#). The water depth is given with colored surfaces (per grid cell) clipped to the area close to the area of interest (about twice the maximum distance of the bank lines from the fairway), the black lines are the determined bank lines and the river kilometres are displayed along the river axis. The computation has ended successfully when the message "BankLines ended successfully!" appears. A full listing of the screen output of D-FAST Bank Erosion during the bank line detection analysis is given below at the end of this section in [Figure 3.5](#). An example of the graphical output of the 'banklines' mode is shown in [Figure 3.4](#). In this figure the water depth is given with colored surfaces (per grid cell) clipped to the area close to the area of interest (about twice the maximum distance of the bank lines from the fairway), the black lines are the determined bank lines and the river kilometers are displayed along the river axis.

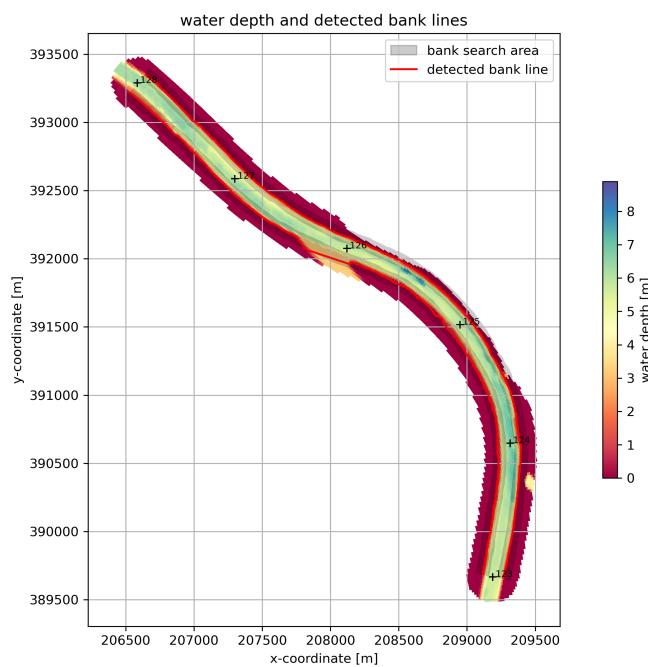
**Note:** It is advised to check the detected banklines shown in the graphical output of the 'banklines' mode before continuing with the 'bankerosion' mode. Common issues with bank line detection and their solutions are described in [section 5.4](#).



**Note:** To obtain the correct results, the search lines for the banks given by Line1, Line2, ..., LineN (obtained for example from the 'oeverlijnen' from Baseline data) should follow the actual bank line (to be detected) within a distance indicated by DLines (default 50 [m]). Large distances between the points – and thus large deviations from the actual bank lines – will result in inaccurate bank lines as the detection algorithm will not detect bank lines reaches outside the indicated area of interest.



**Note:** The chainage file containing the river kilometres should have sufficient resolution since the all data will be projected onto that line. In the analysis, the reference points will be connected by straight lines with linearly interpolated chainage values. It is suggested to provide all lines with at least the resolution of the simulation model from which the data is



**Figure 3.4:** Example of output of D-FAST Bank Erosion in 'banklines' mode showing water depth, detected banklines (red lines), and river kilometers

```
=====
Determine bank lines
=====
version: D-FAST Bank Erosion 2.1.0
source: https://github.com/Deltares/D-FAST_Bank_Erosion
-----
saving output in directory: output\banklines
WARNING: directory 'output\banklines' already exists...=> overwriting directory
saving figures in directory: output\figures
WARNING: directory 'output\figures' already exists...=> overwriting directory
reading chainage information from file : inputfiles\rivkm_20m.xyc
clipping chainage to the range 123.0 to 128.0 km
reading search line 1 from file : inputfiles\oeverlijn_links_mod.xyc
reading search line 2 from file : inputfiles\oeverlijn_rechts_mod.xyc
-----
reading simulation data from : sim270\SDS-j19_map.nc
-----
importing grid...
importing bathymetry ...
importing water level ...
importing water depth ...
importing velocity ...
importing Chezy ...
importing dry/wet information ...
-----
clipping simulation data to area of interest ...
defining coordinates of bank lines ...
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
clipping, sorting and connecting bank lines ...
- bank line 1
- bank line 2
-----
saving bank lines to file: output\banklines\bankfile.shp
=====
generating figures ...
saving figure output\figures\1_banklinedetection.png
=====
=====      Bank line detection ended successfully!      ====
=====
```

**Figure 3.5:** Example of the log for of D-FAST Bank Erosion in 'banklines' mode

### 3.6 Run mode 'bankerosion'

When D-FAST Bank Erosion is run in this mode, it determines the expected bank erosion within the area of interest; for background information see [chapter 5](#). The input is given through the analysis configuration file, see [section 3.4](#).

When the configuration file has the name 'dfastbe.cfg' and is located in the work directory the program can be called as follows:

```
dfastbe --mode bankererosion
```

If the configuration file has another name the following call should be used:

```
dfastbe --mode bankererosion --config D:\D-FAST_Bank_Erosion\Meuse\Meuse.cfg
```

with `path` the path to the directory where the configuration file is located and `other.cfg` the name of the configuration file.

Required input:

- ◊ The period during which the bank erosion acts (`TErosion`, default 1 year),
- ◊ The number of discharge levels (`NLevel`),
- ◊ D-Flow FM files (netCDF map-files) for the different discharge levels and the corresponding probability distribution (`SimFile1`, `SimFile2`, ..., `FileN` and `PDischarge1`, `PDischarge2`, ..., `PDischargeN`, with  $N$  the number of discharge levels),
- ◊ Number of bank Lines (`Nbank` default two, the left and right bank),
- ◊ File which links river chainage (kilometres) to xy-coordinates (`RiverKM`),
- ◊ XY-coordinates of the river and fairway axis (`RiverAxis`, `Fairway`),
- ◊ Information about the strength or type of the soil of the banks (`BankType`). This can be done either in the form of classes or with a critical shear stress (see [Table 5.1](#)). In the first case `Classes` should be set to `true` and in the second case to `false` (default). The bank strength information can be given either with a fixed value for the whole track or in a ASCII-file per river kilometer (first column river-km, second column bank type, see [Figure 3.6](#)),
- ◊ Shipping information (`Vship`, `Nship`, `ShipType`, `Draught`). This can be done either with a fixed value for the whole track or in a file per river kilometer (first column river-km, second column shipping information: similar to entering bank type, see [Figure 3.6](#)).

0.0	1
75.2	3
90.3	2
110.0	0
130.5	4
153.1	3
206.9	2

**Figure 3.6:** Example of input file for bank strength classes per river kilometer: from 0.0 - 75.2 km class 1, from 75.2 - 90.3 km class 3, etc. When no information is available, the closest value will be used.

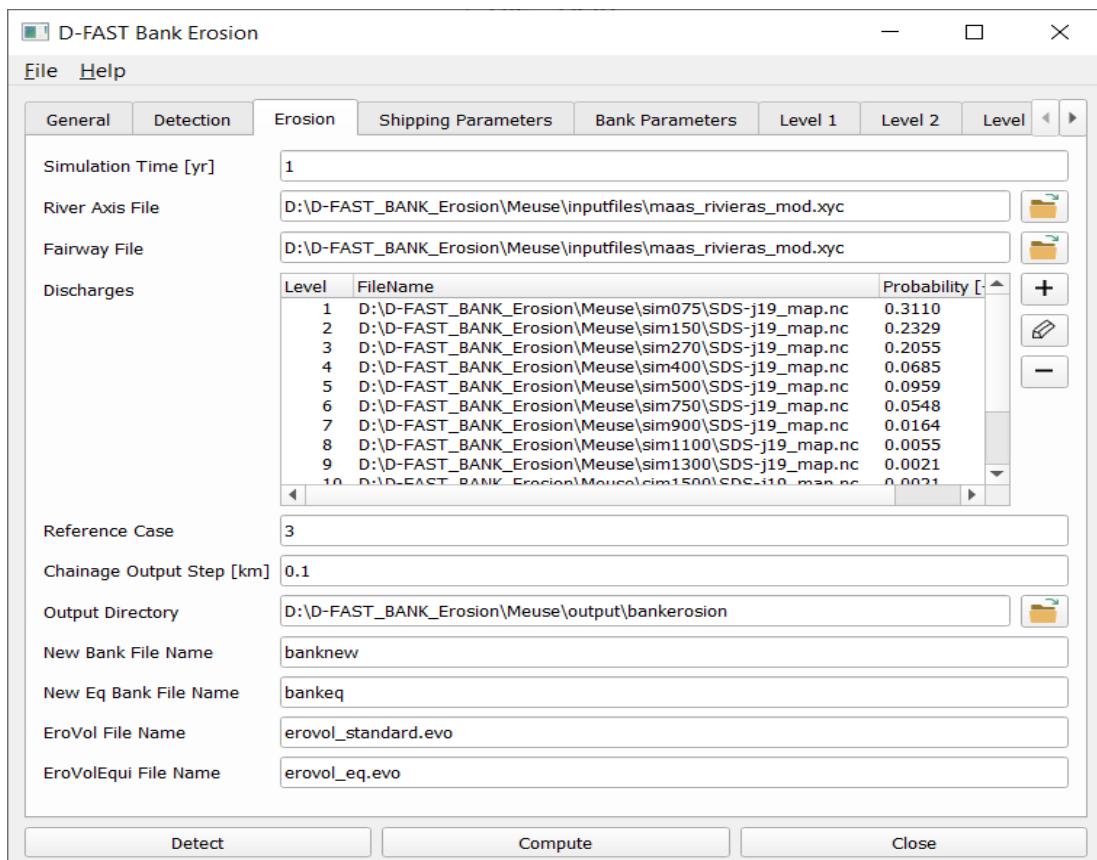


**Note:** The chainage file and the river and fairway axis files should be provided with sufficient resolution. D-FAST Bank Erosion will use straight lines between the specified reference points which deviates from the natural curved channel planform. It is, therefore, suggested to provide all lines with at least the resolution of the simulation model from which the data is used, or at least every 100 m.

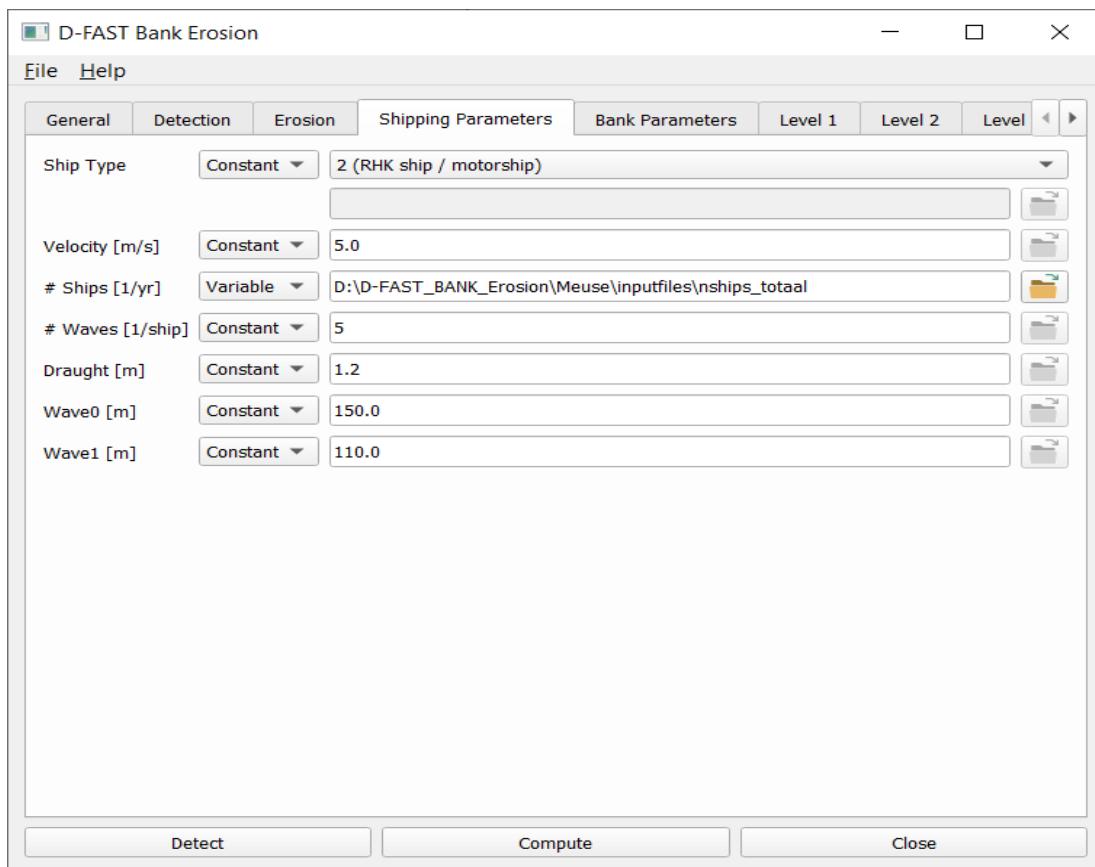


**Note:** Even if default values or default files have been provided for input parameters, the user always needs to show whether those inputs given are appropriate for the intended application.

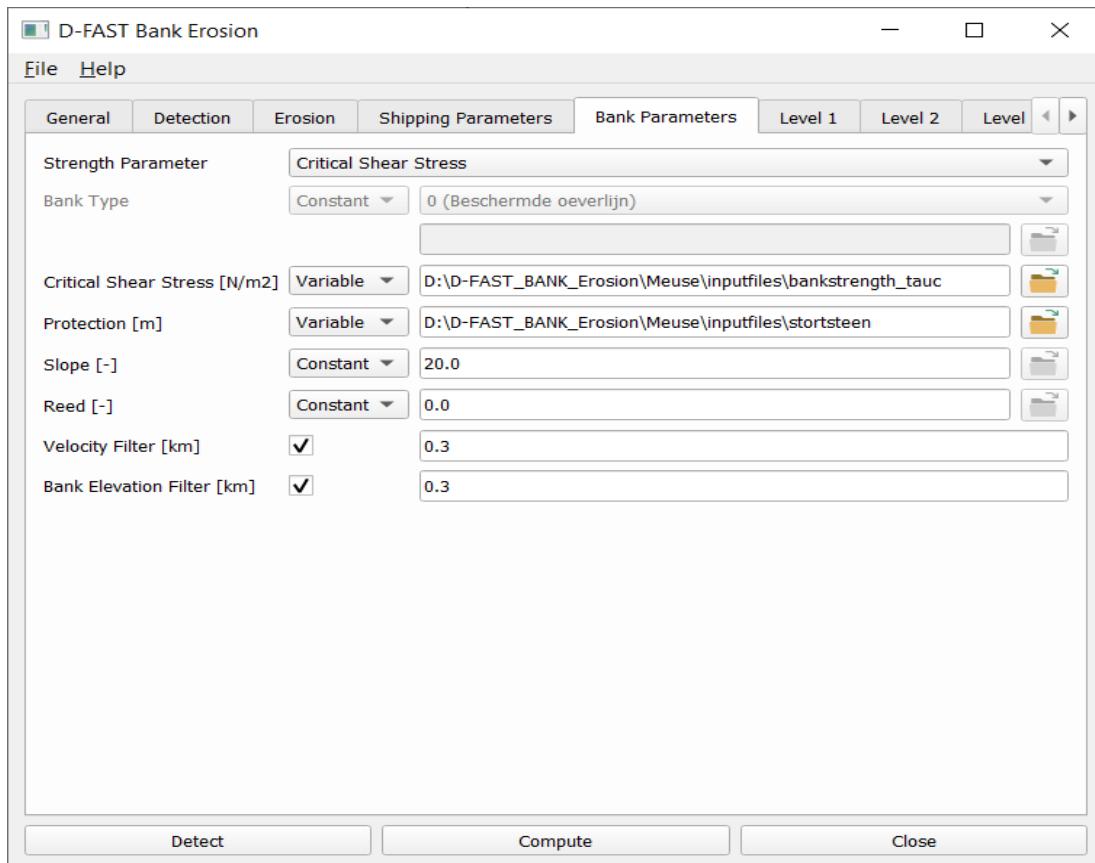
The settings for the bank erosion analysis are distributed over several tabs. All tabs except for the second (Detection) tab are relevant for the bank erosion analysis. First of all, Figure 3.7 shows the main settings for the erosion step such as the simulation period, the simulations and the associated weights. Subsequently, there are tabs for the shipping parameters (Figure 3.8), bank parameters (Figure 3.9) and shipping and bank parameters that may vary per discharge level (Figure 3.10). All quantities in the first two parameter tabs must be specified either as constants or as file based (described in section B.4). The quantities in the other level parameters tabs are optional; by default they will set to "Use Default" which means use the (discharge level independent) value(s) specified in the first two tabs. All files and paths are shown using absolute paths in the graphical user interface, but they will be converted as much as possible to relative paths when saving the configuration to file. The program does not verify or validate the content of the files. This is only verified by the kernel during the analysis.



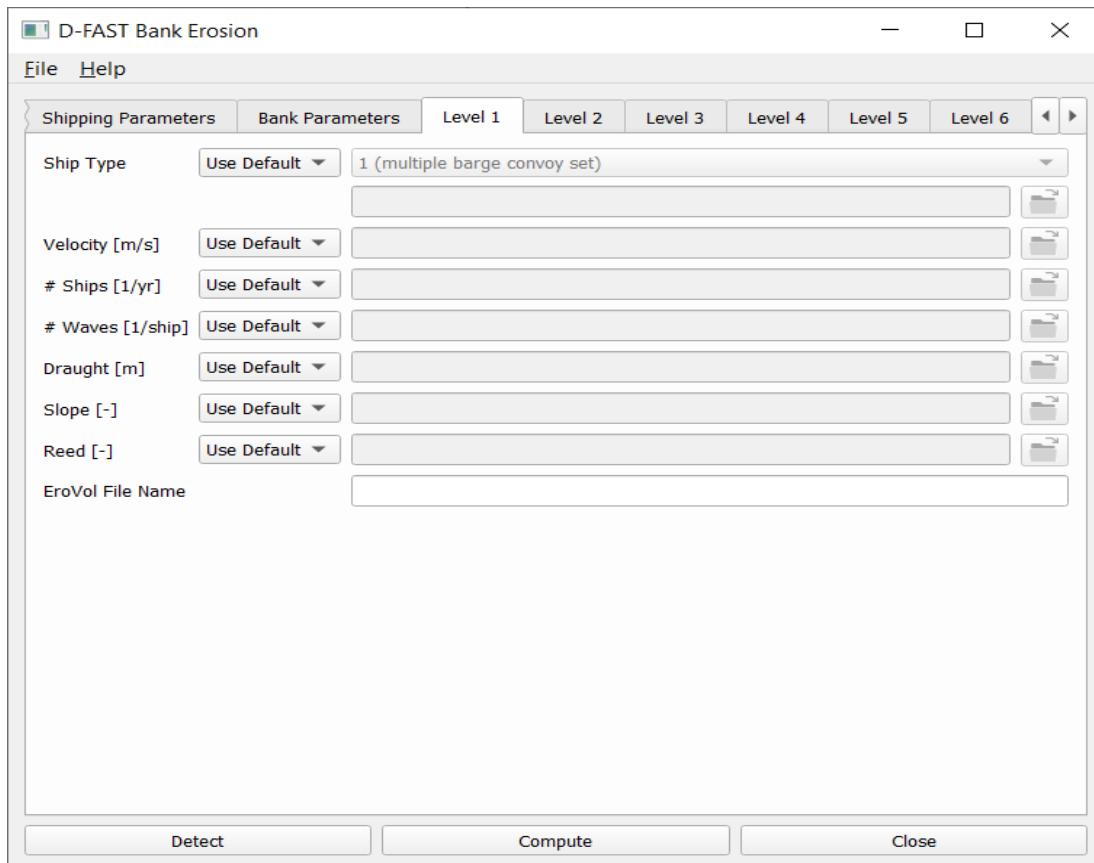
**Figure 3.7:** Example of the Erosion settings in the GUI



**Figure 3.8:** Example of the Shipping Parameters in the GUI



**Figure 3.9:** Example of the Bank Parameters in the GUI



**Figure 3.10:** Example of the Discharge Level dependent parameters in the GUI

Output:

- ◊ Map with water depth, initial bank lines, river kilometers and fairway axis (see Figure 3.12),
- ◊ Map with erosion sensitivity of the banks based on computed bank retreat (see Figure 3.13),
- ◊ The computed erosion volume during the simulation period split up per discharge level (see Figure 3.14) and per bank (see Figure 3.15),
- ◊ Total erosion volume based on equilibrium bank line (see Figure 3.16),
- ◊ Control figures for water levels of each discharge (see Figure 3.17 and Figure 3.18),
- ◊ Control figures for flow velocity of each discharge (see Figure 3.19 and Figure 3.20),
- ◊ Map with indication of applied bank type (see Figure 3.21),
- ◊ Bank retreat at the end of the simulation period and for the equilibrium situation (see Figure 3.22),
- ◊ XY-coordinates of the computed bank lines at the end of the simulation period and of the equilibrium bank lines.

The maps and graphs are only created when Plotting is on and written to file if SavePlots is on. The computation has ended successfully when the message "Bank line detection ended successfully!" appears. The listing of the screen output of D-FAST Bank Erosion during the bank erosion analysis is given below.

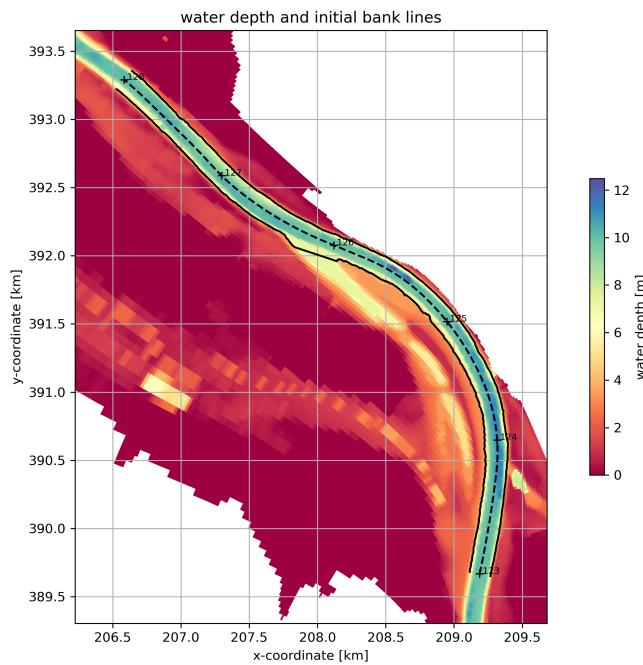
```
=====
Compute bank erosion
=====
version: D-FAST Bank Erosion 2.1.0
source: https://github.com/Deltares/D-FAST_Bank_Erosion
-----
getting input from directory: output\banklines
saving output in directory: output\bankerosion
```

```

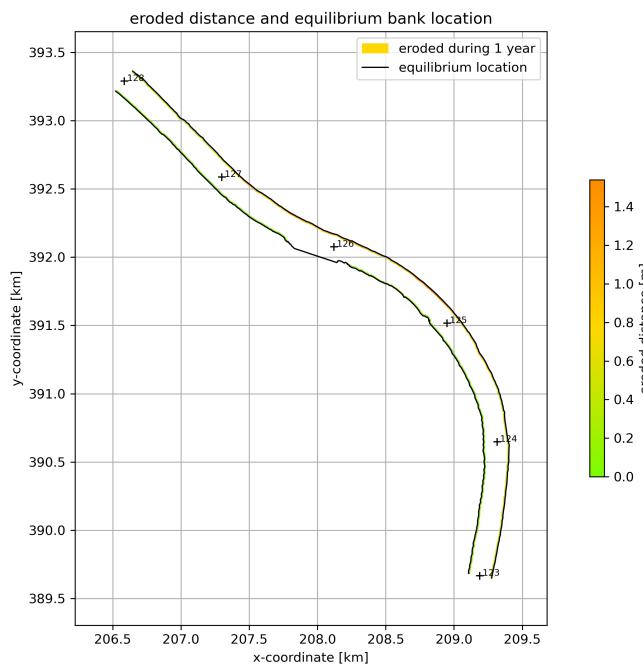
WARNING: directory 'output\bankerosion' already exists...=> overwriting directory
saving figures in directory: output\figures
WARNING: directory 'output\figures' already exists...=> overwriting directory
total simulation time: 1.00 year
-----
reading simulation data from : sim075\SDS-j19_map.nc
-----
importing grid...
importing bathymetry ...
importing water level ...
importing water depth ...
importing velocity ...
importing Chezy ...
importing dry/wet information ...
-----
deriving mesh topology arrays ...
reading chainage information from file : inputfiles\rivkm_20m.xyc
clipping chainage to the range 123.0 to 128.0 km
reading bank lines from file: output\banklines\bankfile.shp
intersect bank lines with mesh ...
- bank line 1 (244 nodes)
- bank line 2 (263 nodes)
mapping chainage to bank segments ...
- bank line 1 on the left
- bank line 2 on the right
reading location of river axis from file: inputfiles\maas_rivieras_mod.xyc
selecting river axis range of interest ...
reading location of fairway from file: inputfiles\maas_rivieras_mod.xyc
selecting fairway range of interest ...
intersect fairway with mesh (362 nodes) ...
computing distance between bank lines and fairway ...
reading NShip from file: inputfiles\nships_totaal
reading BankType of bank 1 from file: inputfiles\bankstrength_tau_c_1.btp
reading BankType of bank 2 from file: inputfiles\bankstrength_tau_c_2.btp
reading ProtectionLevel of bank 1 from file: inputfiles\stortsteen_1.bpl
reading ProtectionLevel of bank 2 from file: inputfiles\stortsteen_2.bpl
processing level information ...
#####
### Discharge 1 ###
#####
Discharge probability: 0.31
Simulation time: 0.31 year
reading level specific parameters ...
-----
reading simulation data from : sim075\SDS-j19_map.nc
-----
importing grid...
importing bathymetry ...
importing water level ...
importing water depth ...
importing velocity ...
importing Chezy ...
importing dry/wet information ...
-----
computing bank erosion ...
saving eroded volume in file: erovolQ1.evo
-----
---- repetitive mid section skipped ----
#####
### Discharge 13 ###
#####
Discharge probability: 0.00
Simulation time: 0.00 year
reading level specific parameters ...
-----
```

```
reading simulation data from : sim2300\SDS-j19_map.nc
-----
importing grid...
importing bathymetry ...
importing water level ...
importing water depth ...
importing velocity ...
importing Chezy ...
importing dry/wet information ...
-----
computing bank erosion ...
saving eroded volume in file: erovolQ13.evo
=====
average erosion distance for bank line 1 : 0.15 m
average erosion distance through flow : 0.05 m
average erosion distance through ships : 0.10 m
maximum erosion distance : 0.64 m
average equilibrium erosion distance : 11.59 m
maximum equilibrium erosion distance : 14.02 m
-----
average erosion distance for bank line 2 : 1.25 m
average erosion distance through flow : 0.62 m
average erosion distance through ships : 0.63 m
maximum erosion distance : 4.59 m
average equilibrium erosion distance : 12.69 m
maximum equilibrium erosion distance : 14.52 m
saving bank lines to file: output\bankerosion\bankfile_new.shp
saving bank lines to file: output\bankerosion\bankfile_eq.shp
saving total eroded volume in file: erovol_standard.evo
saving equilibrium eroded volume in file: erovol_eq.evo
=====
generating figures ...
saving figure output\figures\1_banklines.png
saving figure output\figures\2_erosion_sensitivity.png
saving figure output\figures\3_eroded_volume_per_discharge.png
saving figure output\figures\4_eroded_volume_per_bank.png
saving figure output\figures\5_eroded_volume_eq.png
saving figure output\figures\6_levels_bank_1.png
saving figure output\figures\7_levels_bank_2.png
saving figure output\figures\8_velocity_bank_1.png
saving figure output\figures\9_velocity_bank_2.png
saving figure output\figures\10_banktype.png
saving figure output\figures\11_erodis.png
=====
== Bank erosion analysis ended successfully! ==
=====
```

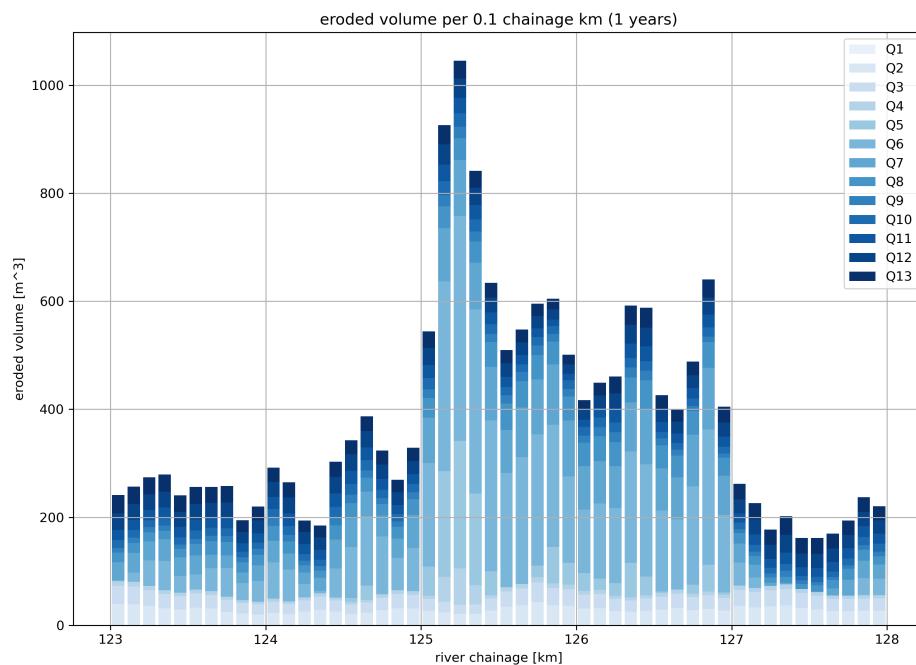
**Figure 3.11:** Example of the log for of D-FAST Bank Erosion in 'bankerosion' mode



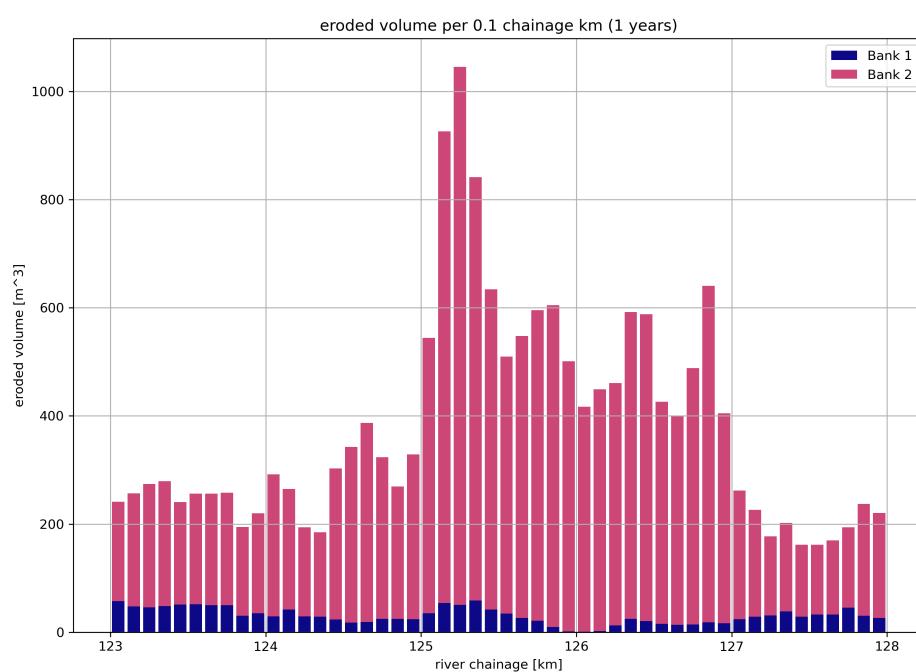
**Figure 3.12:** Map of water depth, initial bank lines, river kilometers and fairway axis



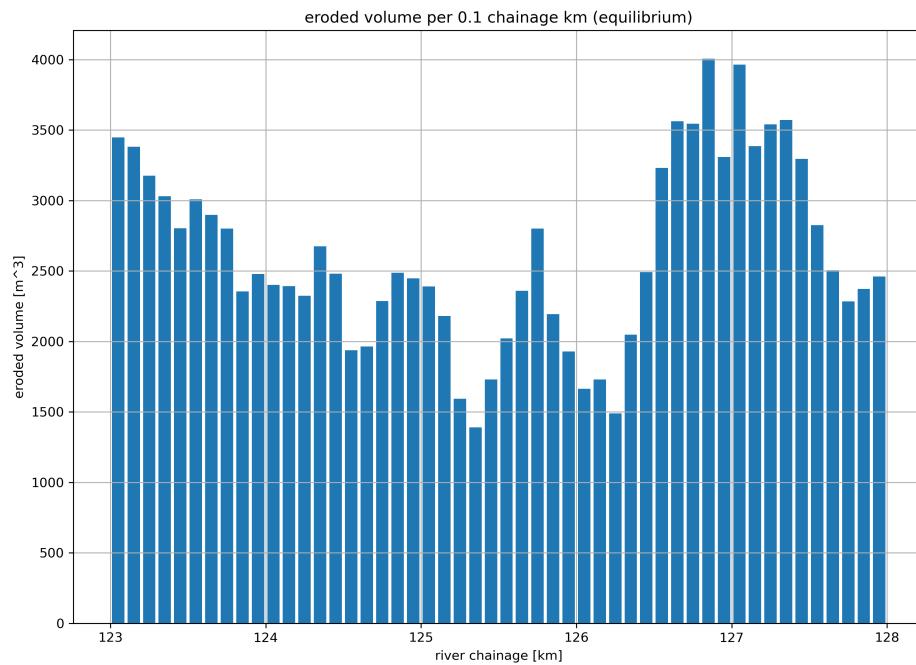
**Figure 3.13:** Map of erosion sensitivity



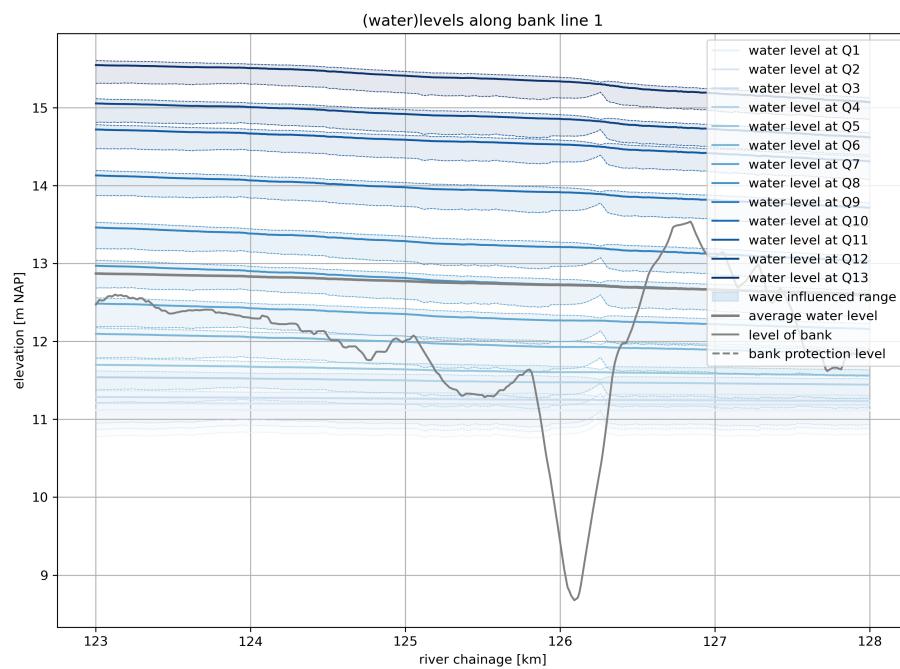
**Figure 3.14:** Eroded volume subdivided per discharge level



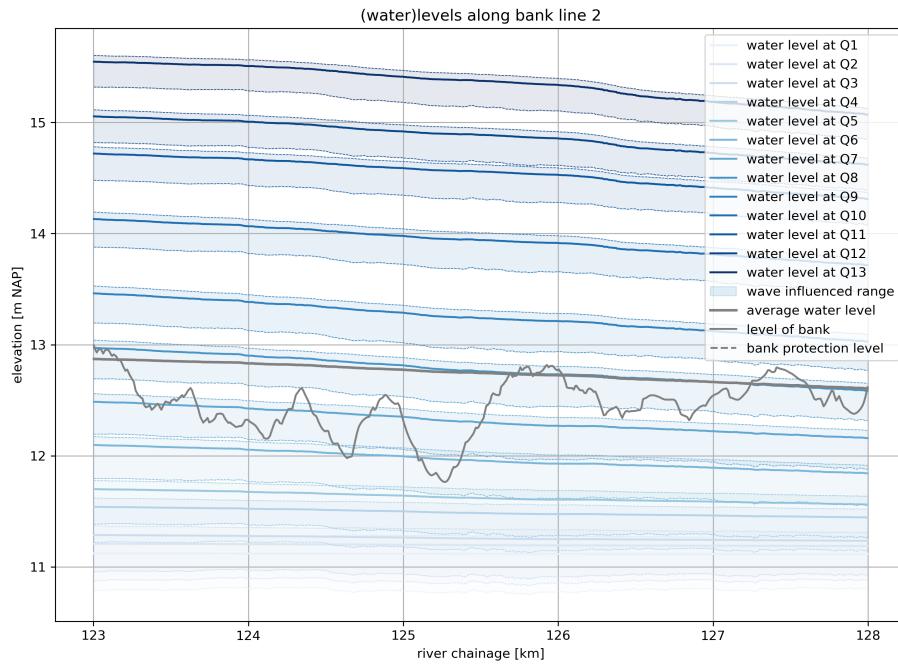
**Figure 3.15:** Eroded volume subdivided per bank line



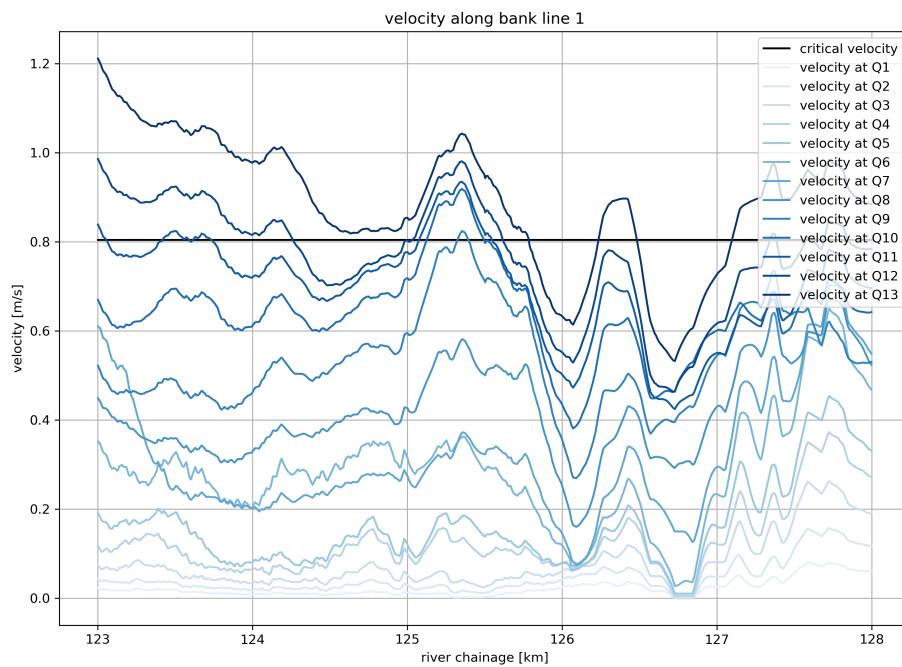
**Figure 3.16:** Total erosion volume based on equilibrium bank line



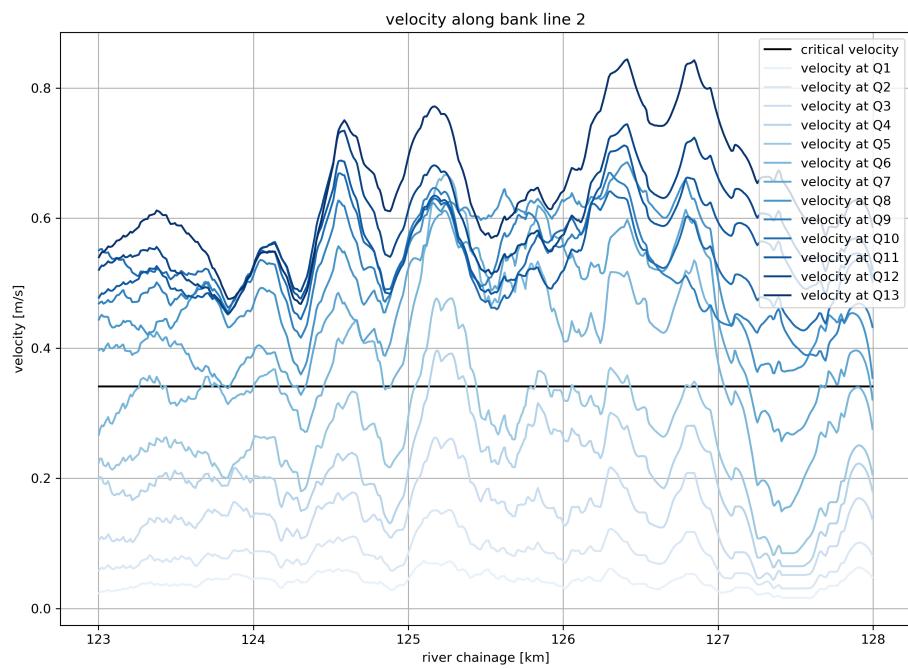
**Figure 3.17:** Control figure for water levels of each discharge (bank line 1)



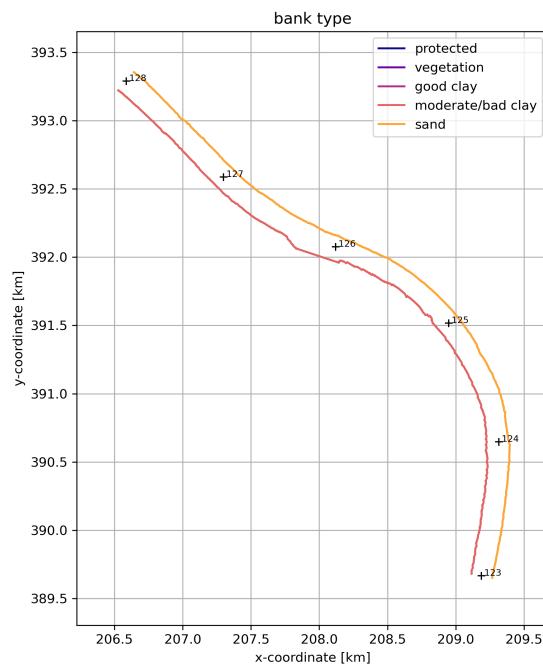
**Figure 3.18:** Control figure for water levels of each discharge (bank line 2)



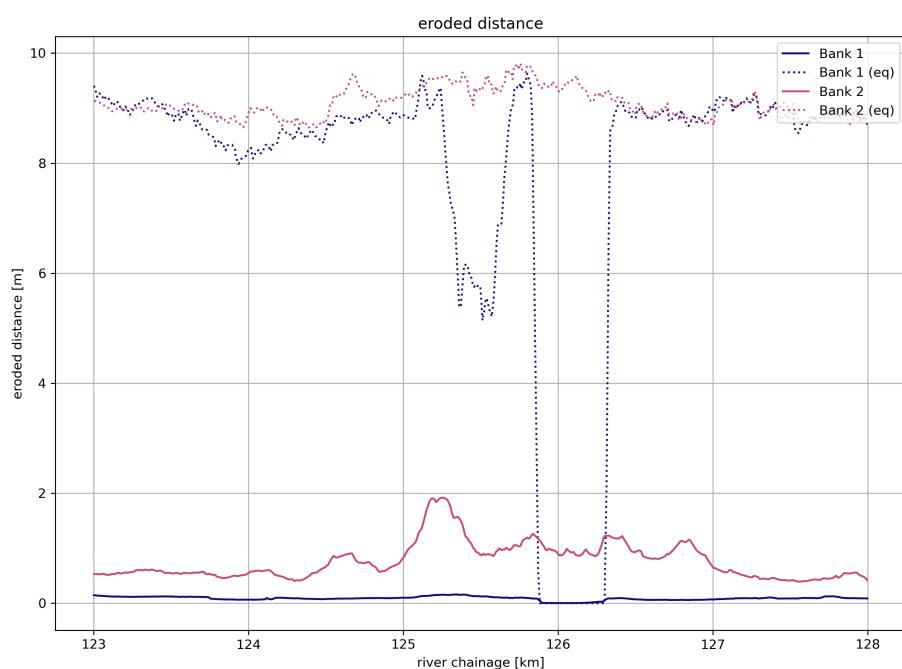
**Figure 3.19:** Control figure for velocities of each discharge (bank line 1)



**Figure 3.20:** Control figure for velocities of each discharge (bank line 2)



**Figure 3.21:** Map with indication of applied bank type



**Figure 3.22:** Bank retreat at the end of the simulation period and for the equilibrium situation

### 3.7 Running from Python source code

D-FAST Bank Erosion can also be run directly from the Python source code. For this you will need to download the source code as well as the correct version of several third party modules used by the tool. Please check the D-FAST Bank Erosion Technical Reference manual for details. When running the tool from Python source code, the program can be started from the command prompt as

```
python -m dfastbe ...options...
```

or from within a running Python environment as

```
import dfastbe.cmd  
dfastbe.cmd.run()
```

where optionally the language (default UK), runmode (default GUI) and configfile (default dfastbe.cfg) can be specified as arguments.



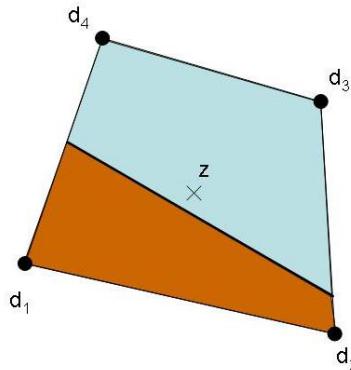
## 4 Detecting and shifting the bank lines

This chapter describes the algorithms used for detecting (see section 4.1) and shifting (see section 4.3) the bank lines. The former happens in the 'banklines' step, whereas the latter happens in the 'bankerosion' step after the local bank erosion rate has been computed.

### 4.1 Detecting the bank lines

The location of bank lines is determined by looking at the transition of water to land (wet/dry) at a reference discharge computed using D-Flow FM. The detection of the bank lines builds on the search lines provided as input to this step. The model domain is clipped to the area close to the search lines to focus the bank detection algorithm on the areas of interest only. The exact location of the bank lines starts by determining for each grid cell in the area of interest whether it has one (or more) bed levels  $z_b$  (defined at the mesh nodes) above the water level  $z_w$  in the grid cell and one (or more) bed levels below the water level (see Figure 4.1).

**Note:** D-FAST Bank Erosion currently only supports results of hydrodynamic simulations which use bed levels defined at nodes. Simulations with bed levels defined in cells (tile depth) are thus not supported.



**Figure 4.1:** The bank line within a transition cell where  $d$  equals  $z_b$  and  $z$  equals  $z_w$

For each of those grid cells, the subgrid boundary between dry and wet parts is determined as the line along which the interpolated bed level equals the water level in the grid cell. The line marking the zero water depth is a straight line in a triangle. Cells with  $N_c \geq 4$  corners are split in  $N_c - 2$  triangles to arrive at a collection of only straight line segments. The collection of all these line segments forms the basis of the final bank line.

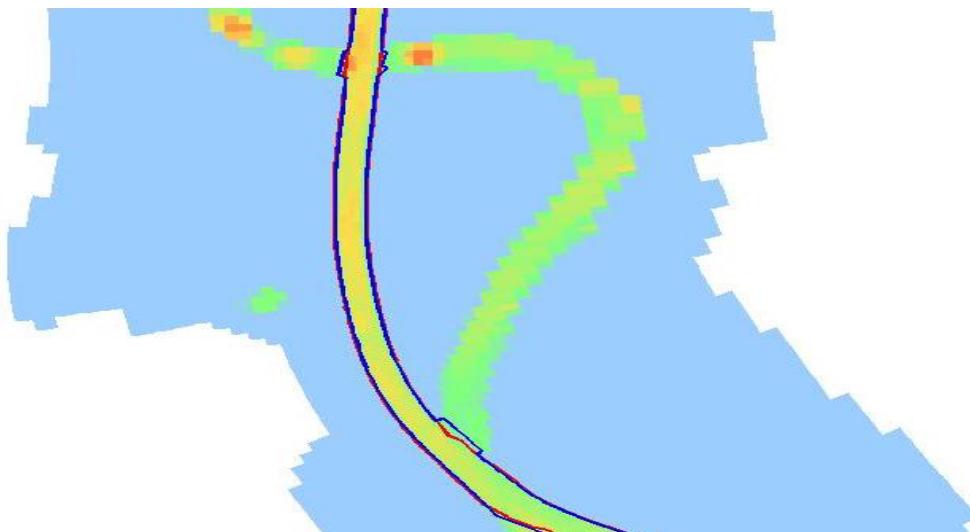
The found locations of the bank lines will clearly depend on the chosen discharge level. However, as long as the discharge is within the main channel, the locations will be fairly consistent.

Generally, bank erosion only occurs along the main channel. It is therefore possible to only take into account those cells that are within a certain distance from the predefined search lines. This is also necessary when more than one bank line is present (as is common in rivers), because otherwise it is not clear which coordinates belong to one bank or the other.

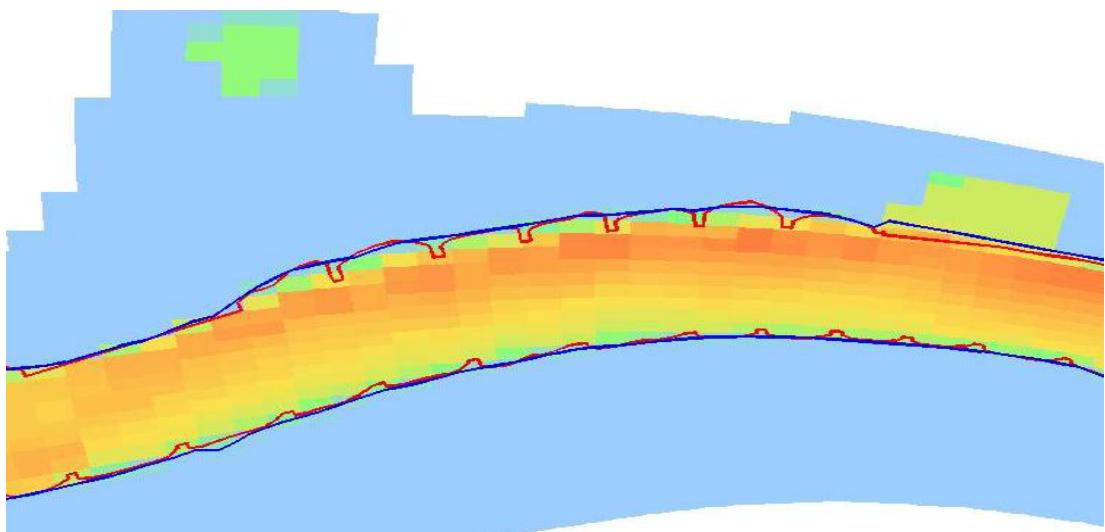
The search lines should be defined in a simple text file consisting of x- and y- coordinates (Line1, ..., LineN, in the configuration file). For the Dutch rivers the lines can be obtained from the Baseline 'oeverlijnen' for model schematisations up to Baseline 4. For modelschematisations of Baseline 5 and higher the oeverlijnen can be obtained by: 1) merging the baseline section 1 and 2 polygon in one polygon feature, 2) transferring this polygon to a polyline feature, 3) cutting this feature into two separate banklines and 4) transforming these lines to points along the lines with an interval of 10 meters.

By using the oeverlijnen, or section 1-2 boundary from Baseline the tool only depicts the main channel. Possible side channels, shortcuts or lakes will not be detected by the tool, see [Figure 4.2](#). If they are important, extra lines should be added that (globally) represent the bank lines of these individual features. For this the input NBank should be increased by the number of extra features and the location of the bank line file LineN should point to the new file(s) with the xy-coordinates of extra search line(s). It should be noted that for the analysis of these extra bank sections the tool uses the closest point in the mainchannel for which the fairway and riveraxis are specified.

Groynes are not detected as such by the tool, because they are typically defined on subgrid level in the simulations, see [Figure 4.3](#). The detected bank line is in this case following the banks within groyne sections. This is an advantage, since possible bank erosion only takes place in the groyne sections and not along the groynes themselves.



**Figure 4.2:** Detection of bank lines at a shortcut in the Meuse river. Red: Baseline 'section 1-2 boundary', Blue: detected bank line from WAQUA computation ( $Q = 278.5 \text{ m}^3/\text{s}$ , average discharge)



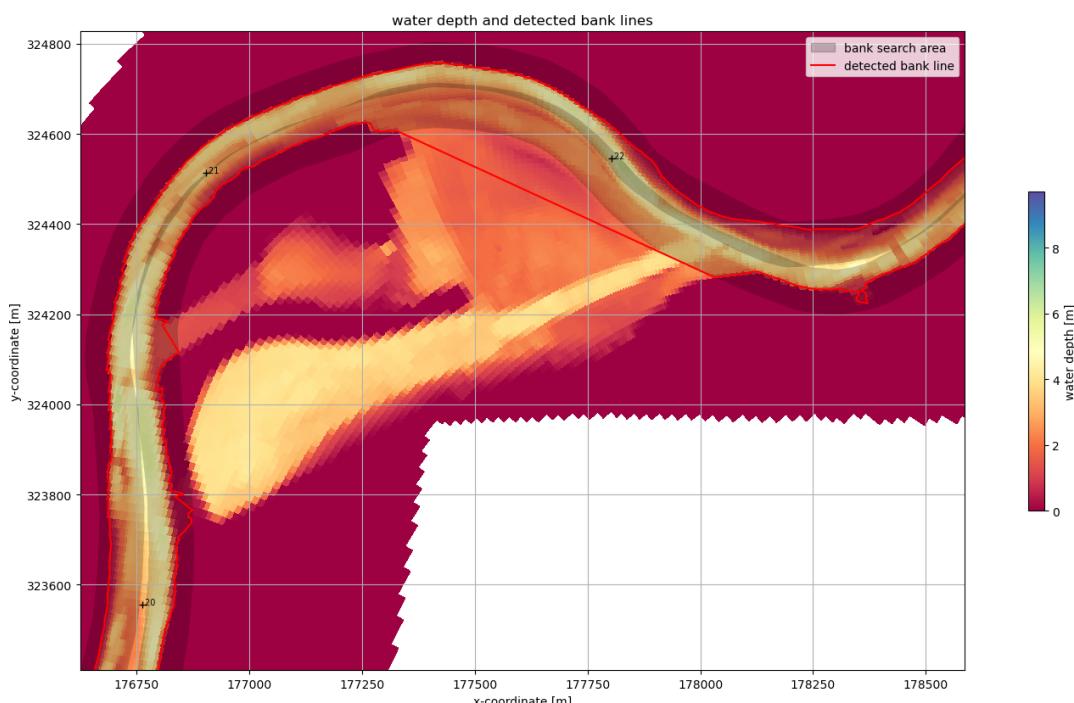
**Figure 4.3:** Detection of a bank line close to groynes. Red: detected bank line from WAQUA computation ( $Q=278,5 \text{ m}^3/\text{s}$ , average discharge)

## 4.2 Common issues with bank line detection

It is advised to check the detected banklines shown in the graphical output of the 'banklines' mode before continuing with the 'bankerosion' mode. This section describes some common issues and their solutions.

### 4.2.1 Detection of adjacent water body

At some locations an adjacent water body is located within the given search distance from the pre-defined banklines (parameter Dlines). As a result the bankline of the adjacent water body is found, instead of the bankline of the main river channel. As a result the initial bankline shows strange variations. This is the case between kilometer 20 and 21 in [Figure 4.4](#).



**Figure 4.4:** Detection of the initial bank line close to adjacent water bodies ( $Q=278,5 \text{ m}^3/\text{s}$ , average discharge)

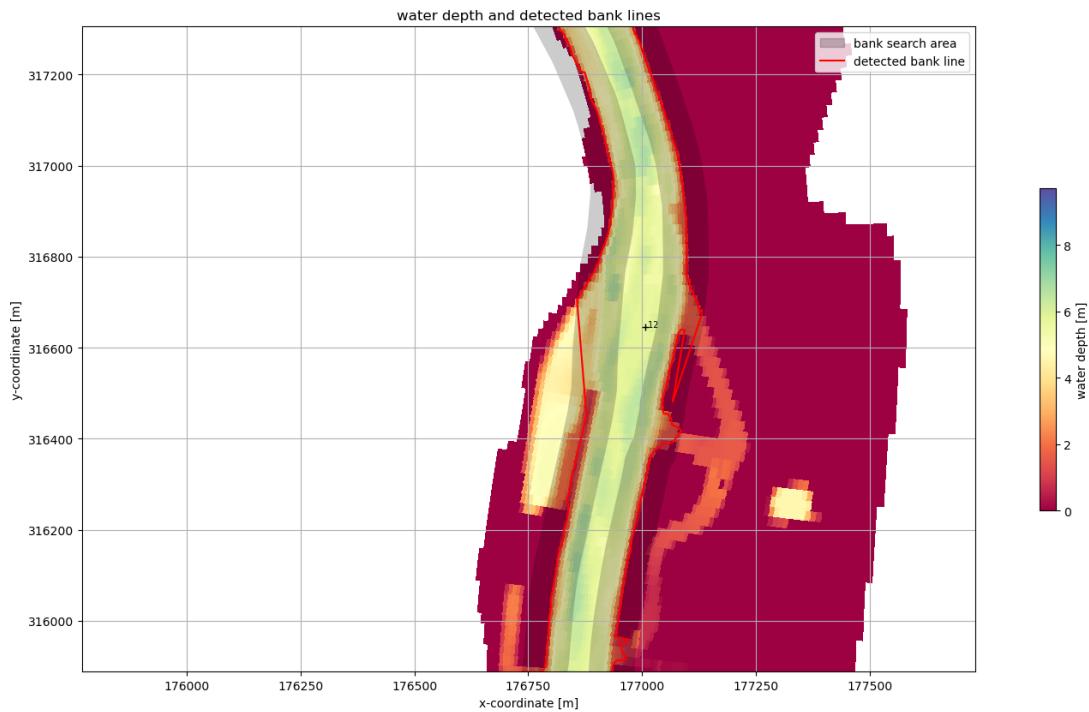
By decreasing the parameter Dlines you decrease the search distance from the pre-defined lines for determining the bank lines. As a result, you decrease the chance that the bankline of an adjacent water body is found. However, you won't find a correct initial bankline if you make the parameter Dlines too small, this can be especially the case close to groins, at wide shallow areas or along banks with a relatively flat slope (see left bank between kilometer 22 and 23 in [Figure 4.4](#)).

Another option is to edit the initial bankline manually by removing the points that fall in the adjacent water body, so only the points along the main channel remain.

### 4.2.2 Irregularities in the detected bank line

[Figure 4.4](#) shows at the right outer bank after kilometer 22.5 a strange irregularity in the detected initial bank line. This type of irregularities develop either by the detection of adjacent water body's, by the cut of connections with side channels (see [Figure 4.5](#)) or harbours or other irregularities along the bank. It is advised to edit the initial bankline manually by removing some of the points so a smooth bankline along the main channel remains, because

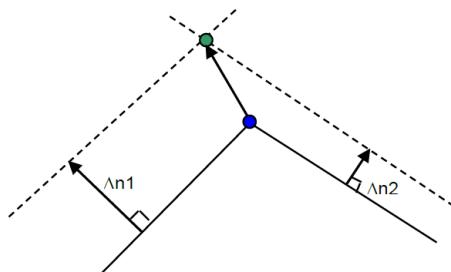
these irregularities influence the distance between the bank and the fairway and thus result in strange irregular patterns in wave heights and erosion along that bank.



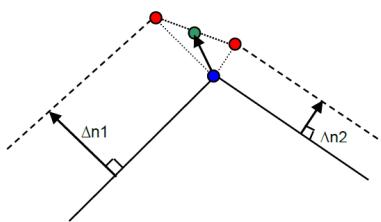
**Figure 4.5:** Detection of the initial bank line at the connection with a side channel  
( $Q=278,5 \text{ m}^3/\text{s}$ , average discharge)

### 4.3 Shifting the bank lines

The new location of the bank line is determined by shifting each bank line segment individually by its local erosion distance. In the case of a concave bend the eroding segments move apart; a new bank segment is inserted connecting the two end points of the previously connected segments. In case of a convex bend the eroding segments overlap; in this case the new bank line follows the outline of furthest erosion.



**Figure 4.6:** Het verschuiven van een oeverlijn gebaseerd op het snijpunt van twee lijnsegmenten. Blauw: oorspronkelijke locatie, Groen: nieuwe locatie



**Figure 4.7:** Het verschuiven van een oeverlijn gebaseerd op de gemiddelde verplaatsing van twee lijnsegmenten. Blauw: oorspronkelijke locatie, Rood: nieuwe locatie gebaseerd op individuele segmenten, Groen: nieuwe locatie (gemiddelde van de rode punten).



## 5 Estimating the bank erosion

D-FAST Bank Erosion is intended to be a tool to help to estimate the potential for bank erosion and not to accurately predict the actual bank erosion. Two bank erosion mechanisms are included: erosion due to ship waves and erosion due to currents.

These two mechanisms are discussed in more detailed in the first two sections of this chapter, followed by a brief description of the total bank line shift and the algorithm for moving the bank lines for a constant discharge in section 5.5. Subsequently, section 5.6 describes the way in which the total potential bank erosion volume is determined. section 5.7 explains how to deal with variations in the discharge, and section 5.8 introduces the equilibrium bank erosion concept and the corresponding volume of eroded material. Finally, a number of limitations of the software are listed in section 5.9.

### 5.1 List of symbols

$C$	Chézy coefficient representing hydraulic roughness [ $\text{m}^{1/2}/\text{s}$ ]
$c_E$	strength coefficient of the bank material [ $\text{m}^{-1}\text{s}^{-1}$ ]
$E$	erosion coefficient [ $\text{m}/\text{s}$ ]
$g$	gravitational acceleration, i.e. 9.81 [ $\text{m}/\text{s}^2$ ]
$H$	wave height at the bank [m]
$H_0$	initial wave height at the toe of the foreshore [m]
$h$	water depth [m]
$h_s$	bank height above the top level $z_{\text{up}}$ of the range of influence for equilibrium erosion [m]
$h_t$	elevation range directly affected by equilibrium erosion: $z_{\text{up}} - z_{\text{do}}$ [m]
$N$	number of empty ships per year [1/year]
$N_r$	number of reed stems per square meter [ $\text{m}^{-2}$ ]
$N_{\text{sec}}$	number of seconds in a year: 31536000 [-]
$n$	number of waves per ship [-]
$n_Q$	number of discharge levels included [-]
$p(Q_i)$	yearly probability of discharge $Q_i$ [-]
$s$	distance from ship to shore [m]
$s_0$	distance from ship at which the ship waves have reduced to zero [m]
$s_1$	distance from ship at which the ship waves start to reduce [m]
$t$	time [s]
$T$	period of the ship waves [s]
$T_s$	draught of the ship [m]
$t_{\text{eros}}$	bank erosion analysis period [s]
$u_b$	flow velocity along the bank line [ $\text{m}/\text{s}$ ]
$u_c$	critical flow velocity for erosion [ $\text{m}/\text{s}$ ]
$v_s$	ship velocity [ $\text{m}/\text{s}$ ]
$V_{\text{eq}}$	eroded sediment volume until equilibrium [ $\text{m}^3$ ]
$V_{\text{erosion}}$	eroded sediment volume over a period $t_{\text{eros}}$ [ $\text{m}^3$ ]
$y$	width of the bank area [m]
$z_{\text{bank}}$	level of the top of the bank [m]
$z_{\text{do}}$	bottom level of the range of influence for equilibrium erosion [m]
$z_{\text{prot}}$	top level of the bank protection [m]
$z_{\text{up}}$	top level of the range of influence for equilibrium erosion [m]
$z_w$	water level [m]
$\alpha$	coefficient in the relation between critical shear stress for erosion and the erosion coefficient [ $\text{m}^{-3/2} \text{kg}^{1/2}$ ]
$\alpha_1$	ship dependent wave generation coefficient [-]
$\delta h_{\text{above}}$	bank erosion distance above the water surface [m]

$\delta h_{\text{below}}$	bank erosion distance below the water surface [m]
$\Delta n(Q_i)$	total shift of the bank line at discharge $Q_i$ [m]
$\Delta n_{\text{eq}}$	erosion distance until equilibrium [m]
$\Delta n_{\text{flow}}$	bank line shift due to currents over a period $t_{\text{eros}}$ [m]
$\Delta n_{\text{flow}}(Q_i)$	shift of the bank line due to currents at discharge $Q_i$ [m]
$\Delta n_{\text{tot}}$	total shift of the bank line [m]
$\Delta n_{\text{wave}}$	shift of bank line due to ship waves [m]
$\Delta n_{\text{wave}}(Q_i)$	shift of the bank line due to ship waves at discharge $Q_i$ [m]
$\mu$	wave damping parameter [ $\text{m}^{-1}$ ]
$\mu_{\text{fs}}$	wave damping due to sloping foreshore [ $\text{m}^{-1}$ ]
$\mu_r$	wave damping due to reed [ $\text{m}^{-1}$ ]
$\mu_{\text{tot}}$	total wave damping parameter [ $\text{m}^{-1}$ ]
$\tau_c$	critical shear stress for erosion of bank material [Pa]

## 5.2 Determining potential erosion by ship waves

Ship waves are one of the most important causes of bank erosion (Verheij, 2000) and they are therefore included as the first bank erosion mechanism in the D-FAST Bank Erosion. The bank erosion formula due to ship waves has been copied from the BEM module (Verheij (2000), Stolker and Verheij (2001)) and the quantities are defined by Figure 5.1.

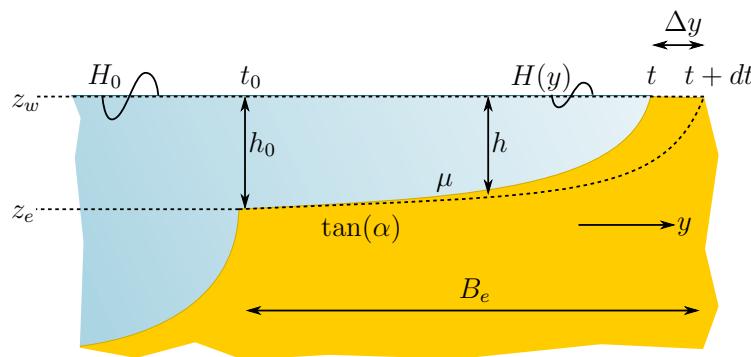


Figure 5.1: Graphical definition of quantities

Based on large scale Delta flume experiments, in which slopes of various materials were subject to perpendicular waves, it has been derived that the erosion rate increases quadratically as function of the wave height at the bank

$$\frac{dy}{dt} = c_E H^2 \quad (5.1)$$

where

$y$	width of the bank area [m]
$c_E$	strength coefficient of the bank material [ $\text{m}^{-1}\text{s}^{-1}$ ]
$H$	wave height at the bank [m]

The value  $c_E$  representing the bank strength depends on the composition of the bank and can thus vary spatially. The  $c_E$  values for the five supported bank compositions classes are given in Table 5.1; for additional values see Appendix A. For the computations, the user specifies the bank composition class in a simple text file along the analyzed reach.

Class	Bank composition	$c_E$ [m <sup>-1</sup> s <sup>-1</sup> ]	$\tau_c$ [Pa]
0	Protected bank	0	$\infty$
1	Vegetated bank	$0.02 \cdot 10^{-4}$	95
2	Good quality clay	$0.6 \cdot 10^{-4}$	3
3	Medium to poor quality clay	$2 \cdot 10^{-4}$	0.95
4	Sand	$12.5 \cdot 10^{-4}$	0.15

**Table 5.1:** Bank composition classes supported by D-FAST Bank Erosion

Generally, it's assumed that the wave height decreases negative exponentially as function of the width of the bank area

$$H = H_0 e^{-\mu y} \quad (5.2)$$

where

H <sub>0</sub>	initial wave height at the toe of the foreshore [m] (see <a href="#">section 5.3</a> )
μ	wave damping parameter [m <sup>-1</sup> ]

Substitution of [Equation \(5.2\)](#) in [Equation \(5.1\)](#) results in a differential equation with general solution

$$\Delta n_{\text{wave}} = \frac{1}{2\mu} \ln(2\mu c_E H_0^2 t + 1) \quad (5.3)$$

where

Δn <sub>wave</sub>	shift of bank line due to ship waves [m]
t	time [s]

This equation can be used for waves due to both wind and ships. Since  $\mu c_E H_0^2$  is typically small, the equation implemented in D-FAST Bank Erosion is therefore linearized to

$$\Delta n_{\text{wave}} = c_E H_0^2 t \quad (5.4)$$

In the latter case the effective time t can be expressed as

$$t = TNnt_{\text{eros}} = 0.51 \frac{v_s}{g} Nnt_{\text{eros}} \quad (5.5)$$

where

T	period of the ship waves [s]
N	number of empty ships per year [1/year]
n	number of waves per ship [-]
v <sub>s</sub>	ship velocity [m/s]
g	gravitational acceleration, i.e. 9.81 [m/s <sup>2</sup> ]
t <sub>eros</sub>	bank erosion analysis period [s]

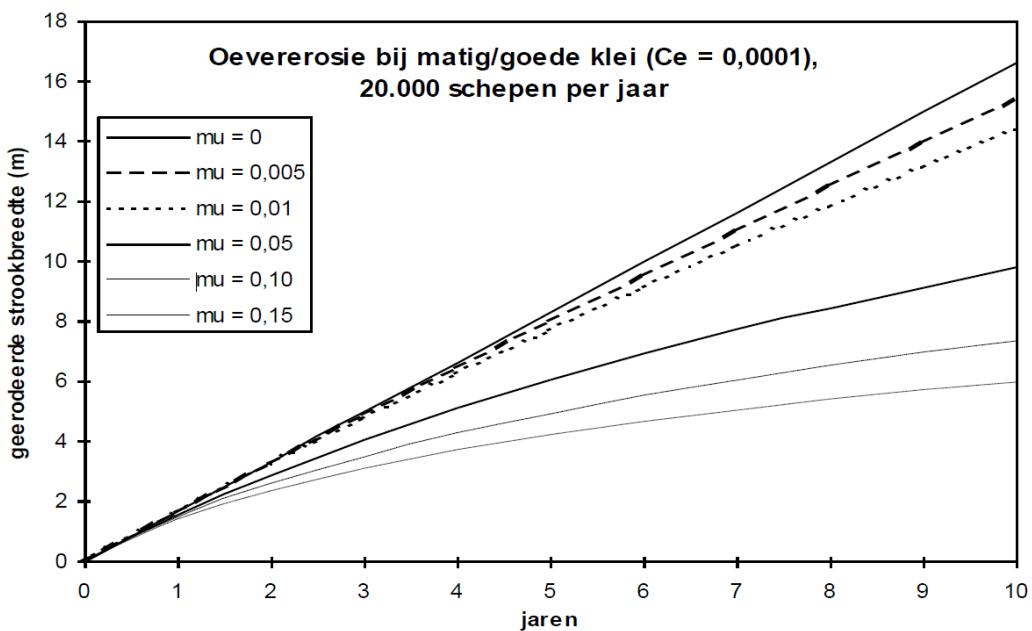
The value of the initial wave height  $H_0$  at the toe of the foreshore can be computed using equations such as included in DIPRO based on the characteristic vessel type, its sailing speed and draught, the distance between the navigation channel and the bank and the water depth (see [section 5.3](#)).

The parameter  $\mu$  can be used to account for not only the effect of the shape of the foreshore on wave damping, but also for the wave damping effect of foreshore constructions, vegetation,

and deposits of bank material. The bank erosion module includes the effect of the slope of the foreshore and the vegetation on the wave damping. The wave damping due to a gently sloping foreshore is given by Verheij (2000) as

$$\mu_{fs} = \frac{\tan(\alpha)}{H_0} \quad (5.6)$$

where  $\tan \alpha = \frac{1}{n}$  for a foreshore with  $1:n$  slope (see also Figure 5.1). For an initial wave height  $H_0 = 0.4$  a slope between 1:100 and 1:20 results in values for  $\mu_{fs}$  between 0.025 and 0.125. Figure 5.2 shows an example of the influence of the wave damping parameter  $\mu_{fs}$  on the bank erosion due to waves.



**Figure 5.2:** Example of bank erosion due to waves for average to good clay with a bankstrength coefficient ( $C_E = 0.0001$ ). An increase in the parameter  $\mu_{fs}$  accounts for an increased effect of the shape of the foreshore on wave damping

Besides wave damping due to foreshore slope, the incoming waves can also be damped by the presence of vegetation. The following equation can be used to estimate the wave damping due to reed

$$\mu_r = 8.5 \cdot 10^{-4} N_r^{0.8} \quad (5.7)$$

where  $N_r$  is the reed stem density (number of stems per square metre). The combined wave damping effect due to foreshore slope and reed is given by

$$\mu_{tot} = \mu_{fs} + \mu_r \quad (5.8)$$

### 5.3 Determining ship induced wave height at the beginning of the foreshore

To determine the ship induced wave height  $H_0$  [m] at the beginning of the foreshore, the following formula is used (source: Handleiding DIPRO, 1997)

$$H_0 = \alpha_1 h \left( \frac{s}{h} \right)^{-1/3} Fr^4 \quad (5.9)$$

with

$\alpha_1$	ship dependent coefficient [-]
$Fr$	Froude number ( $Fr < 0.8$ ) [-]
$h$	water depth (considering a trapezoidal profile) [m]
$s$	distance from ship to shore [m]

The Froude number, a dimensionless quantity indicating the mean flow velocity relative to the speed of free surface waves, is computed as:

$$Fr = \frac{v_s}{\sqrt{gh}} \quad (5.10)$$

with

$g$	gravity acceleration 9.81 [m/s <sup>2</sup> ]
$v_s$	ship velocity [m/s]

The value of the Froude number is limited to 0.8 and Table 5.2 shows the values used for the coefficient  $\alpha_1$ , with

$T_s$  the draught of the ships [m]

By using these formulas, the value of  $H_0$  can be computed based on the dominant ship type, their velocity and draught, the distance between fairway and shore and the water depth.

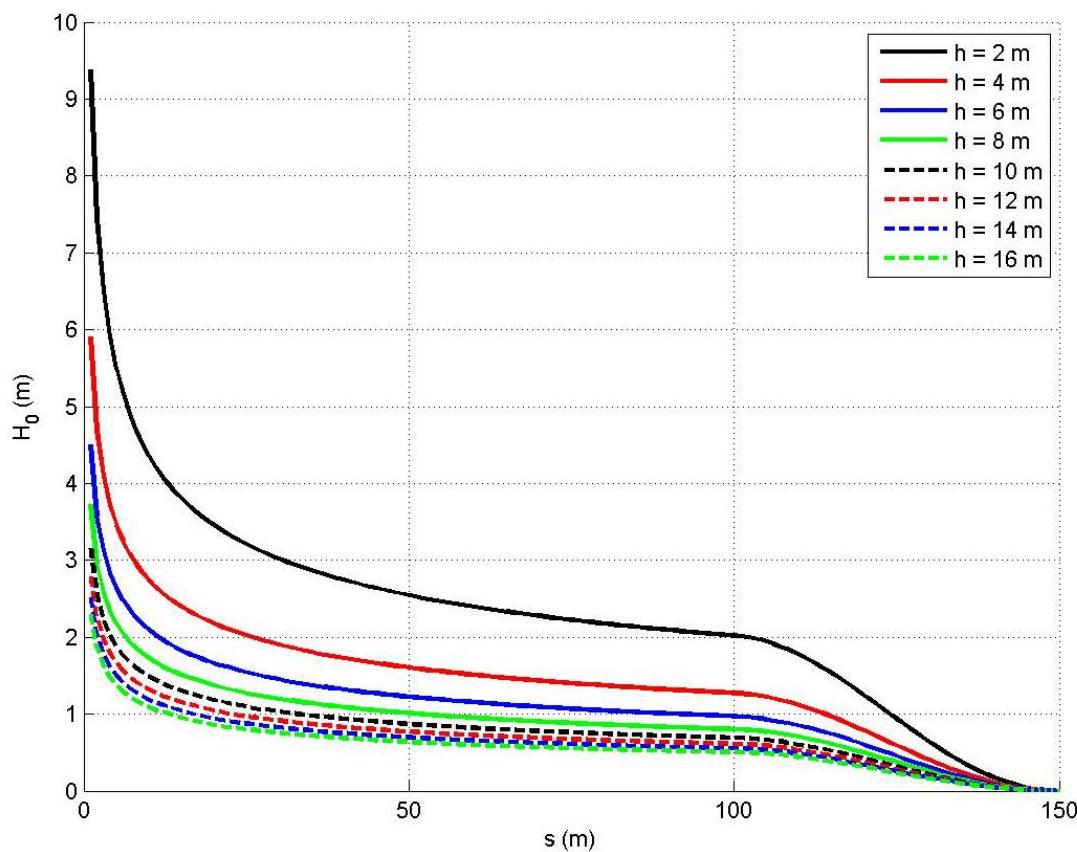
Ship type	$\alpha_1$
Push barge	0.5
RHK ship / Motorship	$0.28 T_s^{1.25}$
Towboat	1.0

**Table 5.2:** Ship-types supported by D-Fast Bank Erosion, with  $T_s$  [m] the draught of the ships

To prevent wave load on smaller channels far from the main channel, the wave height is smoothly reduced to zero from distance  $s_1$  to  $s_0$  from the fairway. This is accomplished by multiplying  $H_0$  with the following function:

$$f(s) = \begin{cases} 1 & 0 < s < s_1 \\ \cos\left(\frac{s-s_1}{s_0-s_1}\pi\right) & s_1 < s < s_0 \\ 0 & s > s_0 \end{cases} \quad (5.11)$$

The value for  $s_0$  will be in the order of 150 - 200 m and for the following relation is used:  $s_1 = s_0 - 50$ . In Figure 5.3 the wave height  $H_0$  as function of the distance from the fairway  $s$  is depicted for various values of the water depth  $h$  for a motor ship with a draught of 1.2 m with a relative velocity of  $v_s = 6$  m/s. The wave height is reduced to zero between  $s_1 = 100$  m and  $s_0 = 150$  m.



**Figure 5.3:** Wave height as function from the distance from the fairway for different values of the water depth.

## 5.4 Determining potential erosion by currents

Bank erosion can besides by ship waves also be caused by a strong current along the bank. This mechanism is also included in the D-FAST Bank Erosion analysis. For a bank line the potential for bank erosion due to currents at a certain discharge  $Q$ -level can be determined by the flow velocities from the model results and:

$$\Delta n_{\text{flow}} = E \left( \frac{u_b^2}{u_c^2} - 1 \right) N_{\text{sec}} t_{\text{eros}} \quad (5.12)$$

where

$\Delta n_{\text{flow}}$	bank line shift due to currents over a period $t_{\text{eros}}$ [m]
$E$	erosion coefficient [m/s]
$N_{\text{sec}}$	number of seconds in a year: 31536000 [-]
$u_b$	flow velocity along the bank line [m/s]
$u_c$	critical flow velocity for erosion [m/s]
$t_{\text{eros}}$	bank erosion analysis period [s]

The erosion coefficient  $E$  can be determined as

$$E = \alpha \sqrt{\tau_c} \quad (5.13)$$

where  $\alpha = 2 \cdot 10^{-7}$  [ $\text{m}^{-3/2} \text{ kg}^{1/2}$ ] and  $\tau_c$  [ $\text{N/m}^2$ ] the critical shear stress for erosion. This value for the erosion coefficient is similar to values for erosion coefficients found in literature, e.g. Crosato (2007).

However, this relationship between the critical shear stress for erosion and the erosion coefficient is not universally valid and the user may, therefore, also specify its value directly in the input.

The critical flow velocity for erosion is related to the critical shear stress for erosion as

$$u_c = \sqrt{\frac{\tau_c C^2}{\rho g}} \quad (5.14)$$

where  $C$  [ $\text{m}^{1/2}/\text{s}$ ] is the Chézy coefficient representing the hydraulic roughness. The Chézy value is copied from the D-Flow FM calculation.

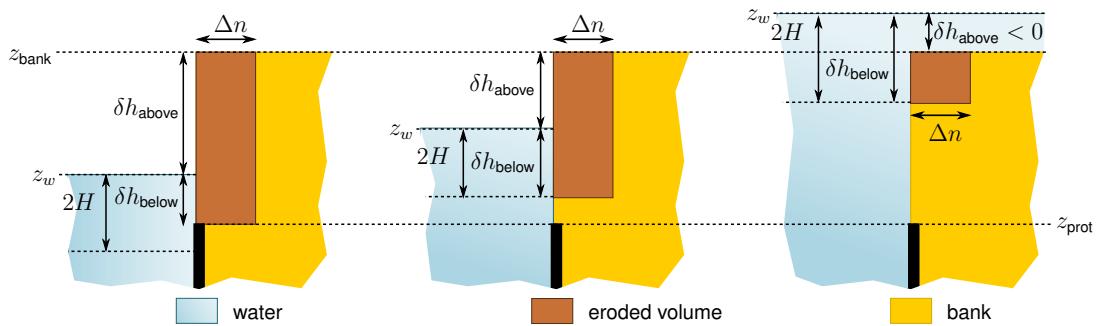
The flow velocity along the bank line is derived from the D-Flow FM flow velocities. The value of the critical shear stress for erosion,  $\tau_c$ , is linked to the strength coefficient of the bank material,  $c_E$ , as given by Table 5.1 and Appendix A.

## 5.5 Total bank shift

The total bank line shift is determined by adding the contributions of the bank line shifts due to waves and currents

$$\Delta n = \Delta n_{\text{flow}} + \Delta n_{\text{wave}} \quad (5.15)$$

The new location of the bank line is determined by locally shifting the bank line over the computed erosion distance  $\Delta n$ ; see section 4.3 for a description how that is done.



**Figure 5.4:** Eroded volume for different water levels.

## 5.6 Potential bank erosion volume

Besides the potential bank line shift, it's also important to know the total volume of sediment that would be associated by that potential erosion since that volume will eventually end up in the river, which may subsequently influence the bed levels and eventually trigger the need for additional dredging activities. The potential volume of sediment released by the erosion can be estimated using

$$V_{\text{erosion}} = (\delta h_{\text{above}} + \delta h_{\text{below}}) \Delta n \quad (5.16)$$

where

$\Delta n$	total shift of the bank line [m]
$\delta h$	the area influenced by the bank erosion (above and below the water surface).

It's assumed that the bank recedes in its entirety and that's why the area of influence above the water surface is determined by

$$\delta h_{\text{above}} = z_{\text{bank}} - z_w \quad (5.17)$$

where

$z_w$	water level [m]
$z_{\text{bank}}$	level of the top of the bank [m]

Note that  $\delta h_{\text{above}} < 0$  if the bank is flooded ( $z_{\text{bank}} < z_w$ ). The extent of the area of influence below the water surface is determined by the wave height and the level up to where the stone protection stays in place. The following relation is used here

$$\delta h_{\text{below}} = \min(z_w - z_{\text{prot}}, 2H) \quad (5.18)$$

where

$z_w$	water level [m]
$z_{\text{prot}}$	top level of the bank protection [m]
$H$	wave height at the bank [m]

Figure 5.4 shows schematically what the eroded volume will be for different water levels.

The retreat of the bank is completely determined by the bank erosion irrespective of the fate of the sediment – whether the material is (temporarily) deposited on the bed in front of the bank or immediately transported away doesn't matter. Material deposited in front of the bank

does influence subsequent erosion as it may protect the bank to some degree. However, this influence cannot be quantified based on just a sediment balance based on a sediment transport formula since sometimes large blocks of clay remain behind which first need to disintegrate before the current can transport it away. The influence of the eroded material on the wave height (and consequently on the erosion due to ship waves) can be included by increasing the parameter  $\mu$  for wave damping.

## 5.7 Variable discharge

A variable discharge can be taken into account by schematizing the discharge distribution by means of hydrograph consisting of  $n_Q$  discharge levels and their probability of occurrence. For every discharge level a separate D-Flow FM simulation will be carried out. The flow velocities along the banks and the water levels will be extracted from these simulations. The discharge level which was used to detect the initial bank lines should be included in this analysis (the mean discharge).

Subsequently the bank line shifts for the individual discharge levels are determined and the overall bank line shift is determined by means of a weighted average of the individual shifts where the weights are determined by the occurrence probability of the various levels. Hence, first the total erosion  $\Delta n(Q_i)$  is determined for each individual discharge level  $Q_i$  by summing up the contributions due to ship waves and currents. Thereafter, all effects are accumulated and finally the total bank shift is applied to determine the new bank line.

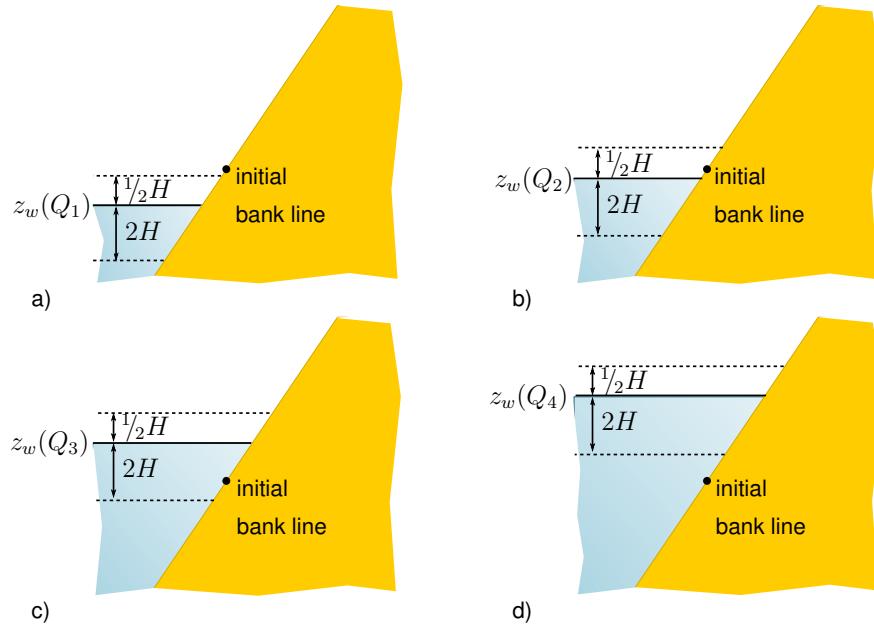
A variable discharge results obviously also in a variable water level and hence the location of the “bank” (defined by the dry-wet interface) and thus the location of the erosion would change. However, in D-FAST Bank Erosion it’s assumed that all erosion occurs along the initial bank erosion line (corresponding to a mean discharge). The magnitude of the erosion along this line does obviously vary as function of the discharge.

### 5.7.1 Erosion by ship waves

A varying discharge level results in a varying water level. The initial bank line is, however, only subject to erosion due to waves at a discharge  $Q_i$  if the height is within the range of influence  $[z_w(Q_i) - 2H, z_w(Q_i) + \frac{1}{2}H]$  where  $H$  is the wave height at the bank and  $z_w(Q_i)$  is the water level at discharge  $Q_i$ . Out of the four cases shown in Figure 5.5, the bank line is only subject to erosion due to waves for discharge levels  $Q_2$  and  $Q_3$ . Whether a bank line is within the range of influence for erosion due to waves may depend on the location and vary along the bank lines. In the downstream area the water levels change usually less than upstream and also upstream of a barrier with prescribed target level the water level may vary little over a wide range of discharges.

### 5.7.2 Erosion by currents

For every discharge level the erosion due to currents is determined based on the flow velocity along the bank line for that specific discharge. Obviously, flow along the bank line is only non-zero if the bank line is located at or below the water level. Out of the four cases shown in Figure 5.5 the bank line is thus only subject to erosion due to currents for discharge levels  $Q_3$  and  $Q_4$ .



**Figure 5.5:** Erosion due to waves at different discharge levels: a) no erosion as the studied bank line is too high, b) erosion, c) erosion, d) no erosion since the bank line is below the area of influence.

### 5.7.3 Total erosion

The total shift of the bank line in case of multiple discharge levels is determined by a weighted sum of the bank line shifts for all the individual discharge levels as

$$\Delta n_{\text{tot}} = \sum_{i=1}^{n_Q} p(Q_i) \Delta n(Q_i) \quad (5.19)$$

$$= \sum_{i=1}^{n_Q} p(Q_i) [\Delta n_{\text{wave}}(Q_i) + \Delta n_{\text{flow}}(Q_i)] \quad (5.20)$$

where

- $\Delta n_{\text{tot}}$  total shift of the bank line [m]
- $n_Q$  number of discharge levels included [-]
- $p(Q_i)$  yearly probability of discharge  $Q_i$  [-]
- $\Delta n(Q_i)$  total shift of the bank line at discharge  $Q_i$  [m]
- $\Delta n_{\text{wave}}(Q_i)$  shift of the bank line due to ship waves at discharge  $Q_i$  [m]
- $\Delta n_{\text{flow}}(Q_i)$  shift of the bank line due to currents at discharge  $Q_i$  [m]

The bank line is subsequently shifted using the same method described in section 5.5 but now based on the total bank line shift given by Equation (5.20).

Analogous to the bank line shifting, the potential bank erosion volume is first determined for each discharge level individually (see section 5.6). Thereafter, the total potential bank erosion volume is determined by a sum of those intermediate volumes weighted by the yearly occurrence probability of that discharge level (compare with Equation (5.20)).

## 5.8 Determining equilibrium bank

Chapter 3 of [Mark et al. \(2011\)](#) describes an analysis of the most likely bank erosion along the River IJssel. The most probable equilibrium bank slope is 1:20. Based on these numbers one can obtain an estimate of the erosion distance  $\Delta n_{\text{eq}}$  under equilibrium conditions (see [Figure 5.6](#)):

$$\Delta n_{\text{eq}} = \frac{h_t}{\mu_{\text{slope}}} \quad (5.21)$$

where

$\mu_{\text{slope}}$	the inverse of the slope of the equilibrium bank (typically 1/20)
$h_t$	elevation range directly affected by equilibrium erosion [m]

with

$$h_t = \max(z_{\text{up}} - z_{\text{do}}, 0) \quad (5.22)$$

where

$z_{\text{up}}$	top level of the range of influence for equilibrium erosion [m]
$z_{\text{do}}$	bottom level of the range of influence for equilibrium erosion [m]

The top level of the range of influence for equilibrium erosion is determined as the minimum of twice the initial wave height at the toe of the foreshore ( $H_0$ ) above the reference water level ( $z_w(Q_{\text{ref}})$ ) and the level of the top of the bank ( $z_{\text{bank}}$ ):

$$z_{\text{up}} = \min(z_{\text{bank}}, z_w(Q_{\text{ref}}) + 2H_0) \quad (5.23)$$

The bottom level of the range of influence for equilibrium erosion is determined as the maximum of twice the initial wave height at the toe of the foreshore ( $H_0$ ) above the reference water level ( $z_w(Q_{\text{ref}})$ ) and the level up to where the stone protection stays in place ( $z_{\text{prot}}$ ):

$$z_{\text{do}} = \max(z_{\text{prot}}, z_w(Q_{\text{ref}}) - 2H_0) \quad (5.24)$$

The total eroded volume to reach the equilibrium bank will be equal to:

$$V_{\text{eq}} = \left(\frac{1}{2}h_t + h_s\right)\Delta n_{\text{eq}} \quad (5.25)$$

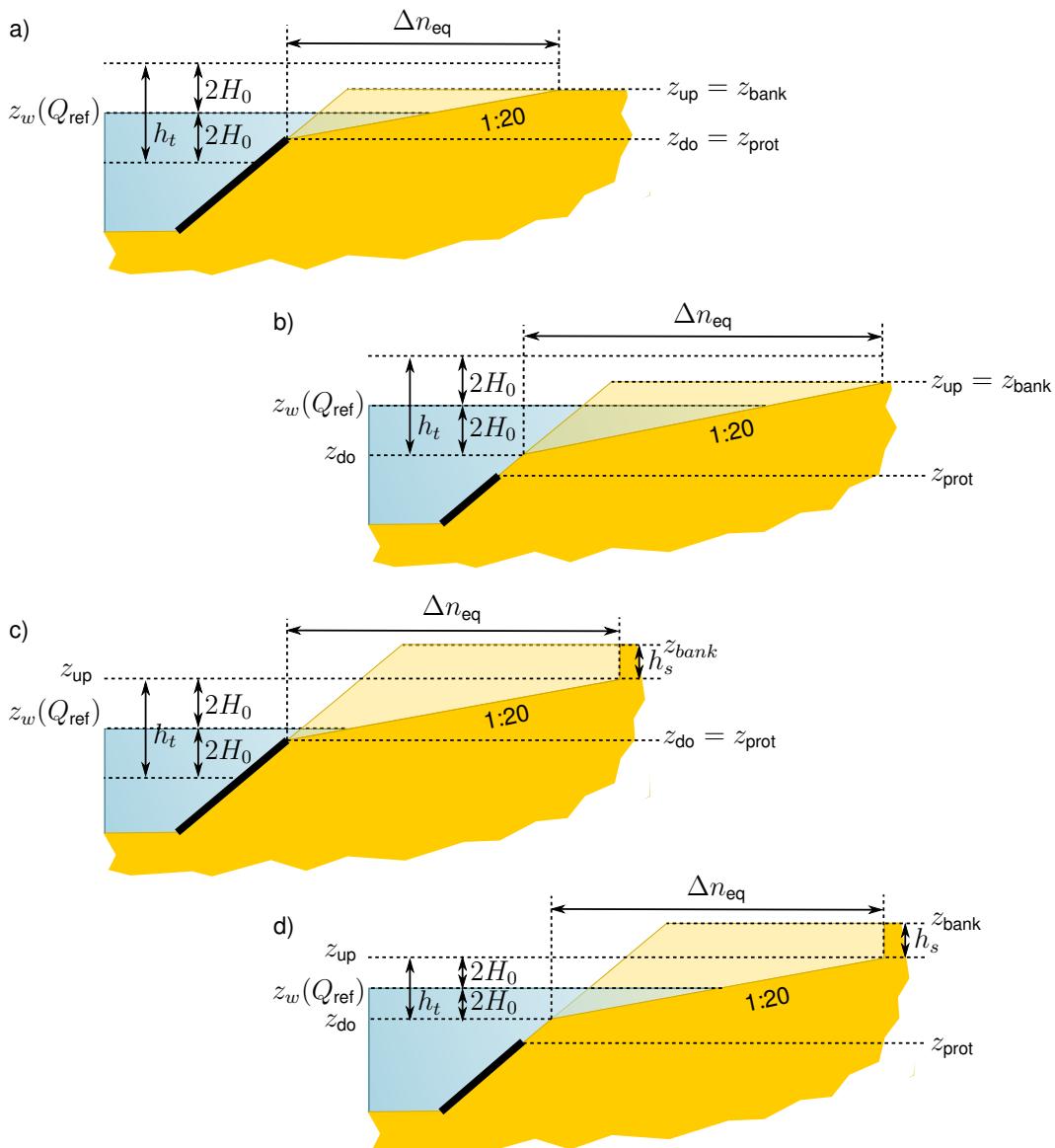
where

$$h_s = \max(z_{\text{bank}} - z_w(Q_{\text{ref}}) - 2H_0, 0) \quad (5.26)$$

A total of four different equilibrium bank profiles are possible, because both the top and bottom level of the range of influence for equilibrium erosion are located at either the minimum or maximum of two elevations (see equations [Equation \(5.24\)](#) and [Equation \(5.23\)](#)). The four possible profiles are shown in [Figure 5.6](#).

## 5.9 Limitations of D-FAST Bank Erosion

D-FAST Bank Erosion is intended to be a tool for estimating where bank erosion may occur and not to predict actual bank erosion. This section lists a number of limitations of the implemented approach.



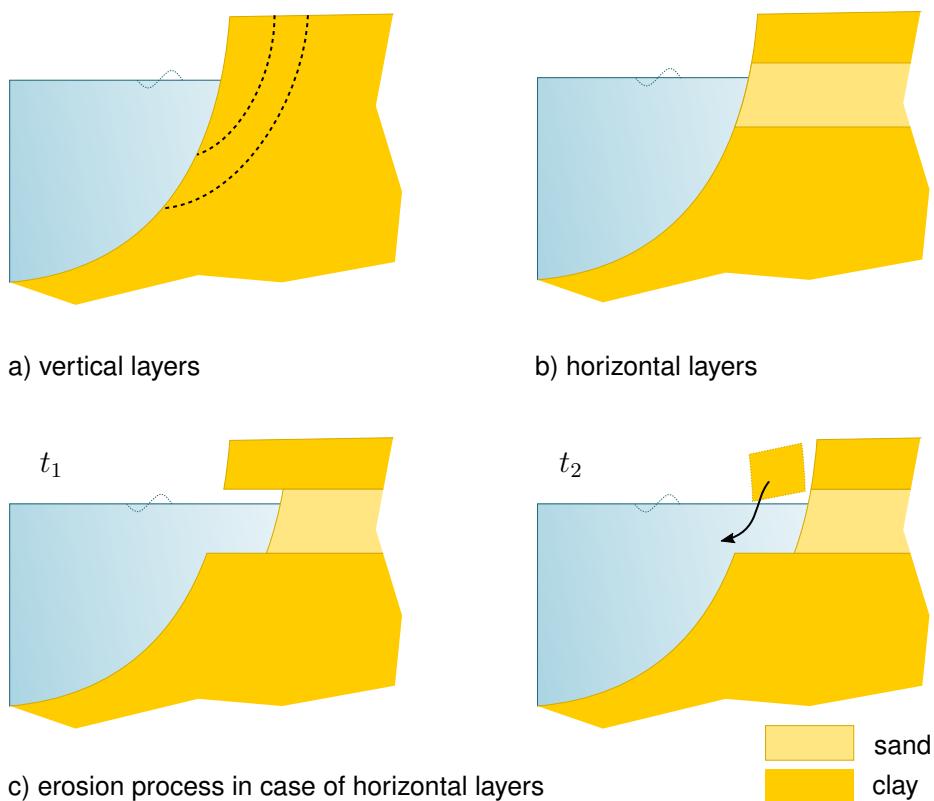
**Figure 5.6:** Estimated equilibrium bank profile for 4 possible combinations of  $z_{\text{up}}$  and  $z_{\text{do}}$ .

### 5.9.1 Homogeneous bank

One of the most important limitations is that the bank composition is assumed to be homogeneous. This is usually not true in reality. In many cases the bank has a horizontally and vertically layered composition. Both situations are sketched in Figure 5.7 as well as the way in which the erosion process may evolve in the case of horizontal layers. Vertical layers can be represented by different values of  $c_E$  for each layer along the bank line. The case with horizontal layers is more complex because in this case large quantities of sediment may suddenly slide down into the river.

### 5.9.2 Only erosion along initial bank line

D-FAST Bank Erosion only estimates the bank erosion along the specified initial bank line (corresponding to the mean discharge). However, in reality bank erosion may also occur at different heights.



*Figure 5.7: Non-homogeneous banks.*

### 5.9.3 Only erosion by ship waves and currents

D-FAST Bank Erosion only estimates the bank erosion due to the mechanisms of ship waves and currents. Other bank erosion mechanisms such as wind waves, ground water, freezing or trampling by cattle are currently not included.

### 5.9.4 Profile and bed level remain constant

The bank erosion affects the local river width and the eroded bank material also results in a bed level change. This also affects the flow conditions in the river and along the banks in particular. Since the analysis is based on the results of D-Flow FM simulations using the initial geometry, the dynamic feedback via banks and bed levels is not included.



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## A Bank strength coefficients for different soil types

The strength coefficient of the bank material,  $c_E$ , and the critical shear stress for erosion,  $\tau_c$ , for different soil types are given in Table A.1 based on (Verheij *et al.*, 1995; Vergeer, 1996; Verheij *et al.*, 1998; Vroeg, 1999).

The following relation can be used

$$c_E = \frac{\beta}{\tau_c} \quad (\text{A.1})$$

where  $\beta = 1.85 \cdot 10^{-4}$  [kg / (m<sup>2</sup> s<sup>3</sup>)].

Bank type	$c_E$ [m <sup>-1</sup> s <sup>-1</sup> ]	$\tau_c$ [Pa]
Protected bank	0	$\infty$
Sturdy grass	$0,01 \cdot 10^{-4}$	185
Mediocre grass	$0,02 \cdot 10^{-4}$	93
Bad grass	$0,03 \cdot 10^{-4}$	62
Very good clay (compact)	$0,5 \cdot 10^{-4}$	4
Clay with 60% sand (firm)	$0,6 \cdot 10^{-4}$	2,5
Good clay with little structure	$0,75 \cdot 10^{-4}$	2
Strongly structure good clay (mediocre)	$1,5 \cdot 10^{-4}$	1,5
Bad clay (weak)	$3,5 \cdot 10^{-4}$	0,65
Sand with 17% silt	$10 \cdot 10^{-4}$	0,20
Sand with 10% silt	$12,5 \cdot 10^{-4}$	0,15
Sand with 0% silt	$15 \cdot 10^{-4}$	0,10

**Table A.1:** Corresponding values for  $c_E$  and  $\tau_c$  (Verheij *et al.*, 1995).



## B File formats

The software distinguishes 9 files:

- ◊ The *analysis configuration file* defines the settings that are relevant for the execution of the software, it will point to other data files for bulk data.
- ◊ The *line geometry files* specify the coordinates of a line.
- ◊ The *chainage file* defines the river chainage along a line.
- ◊ The *parameter files* define optional spatial variations in the analysis input parameters.
- ◊ The *simulation result files* define the spatial variations in the velocities and water depths as needed by the algorithm.
- ◊ The *eroded volume file* reports on the eroded volumes along the analyzed river reach per chainage bin.
- ◊ The *dialog text file* defines all strings to be used in the interaction with the users (GUI, report, or error messages).
- ◊ The *shape file* specify the detected and shifted bank lines; this format is also used for various debug output.
- ◊ The *image file* stores the figures created by the software; by default the PNG format is used.

Each file type is addressed separately in the following subsections. The shape and image files follow commonly used formats and are hence not explained.

### B.1 analysis configuration file

The analysis configuration file of WAQBANK looked a lot like an ini-file, but deviated slightly due to different comment style and missing chapter blocks. D-FAST Bank Erosion still supports the old files, but it's recommended to upgrade them to the newer file format described here which conforms to the usual ini-file format. The user interface reads old (and obviously new) files, but always writes new files.

The file must contain a [General] block with a keyword Version to indicate the version number of the file. The initial version number will be 1.0.

Details on the other keywords supported are given below. The order of the keywords in the file doesn't matter, but each block and each keyword should occur only once.

Block	Keyword	Description
General	Version	Version number. Must be 1.0
	RiverKM	Text file with river chainage (kilometres) and corresponding xy-coordinates
	Boundaries	River chainage of the region of interest specified as rkm-start:rkend, e.g. 81:100 (default: all)
	BankDir	Directory for storing bank lines (default: current directory)
	BankFile	Text file(s) in which xy-coordinates of bank lines are stored (default 'bankfile')
	Plotting	Flag indicating whether figures should be created (default: true)
	SavePlots	Flag indicating whether figures should be saved (default: true)

	ClosePlots	Flag indicating whether figures should be closed when the run ends (default: false)
	FigureDir	Directory for storing figures (default relative to work dir: figure)
	FigureExt	String indicating the file extension and type to be used for the figures saved (default: .png)
	DebugOutput	Flag indicating whether additional debug output should be written; this includes various shape and csv files with intermediate results (default: false)
Detect	SimFile	Name of simulation output file to be used for determining representative bank line
	WaterDepth	Water depth used for defining bank line (default: 0.0)
	NBank	Number of bank lines, (default: 2)
	Line $<i>$	Textfile with xy-coordinates of search line $<i>$
	DLines	Distance from pre-defined lines used for determining bank lines (default: 50)
Erosion	TErosion	Simulation period [years]
	RiverAxis	Textfile with xy-coordinates of river axis
	Fairway	Textfile with xy-coordinates of fairway axis
	OutputInterval	Bin size for which the eroded volume output is given (default: 1 km) [km]
	NLevel	Number of discharge levels
	RefLevel	Reference level: discharge level with SimFile $<i>$ that is equal to SimFile (only used when Nlevel > 1) (default: 1)
	SimFile $<i>$	NetCDF map-file for computing bank erosion for discharge $<i>$ (only used when Nlevel > 1)
	PDischarge $<i>$	Probability of discharge $<i>$ (sum of probabilities should be 1)
	OutputDir	Directory for storing output files
	BankNew	Text file(s) in which new xy-coordinates of bank lines are stored (default 'banknew')
	BankEq	Text file(s) in which xy-coordinates of equilibrium bank lines are stored (default: 'bankeq')
	EroVol	Text file in which eroded volume per river-km is stored (default: 'erovol.evo')
	ShipType	Type of ship (per river-km)
	Vship	Relative velocity of the ships (per river-km) [m/s]
	Nship	Number of ships per year (per river-km)
	Nwave	Number of waves per ship (default 5)
	Draught	Draught of the ships (per river-km) [m]
	Wave0	Distance from fairway axis at which wave height is zero (default 200 m)

Wave1	Distance from fairway axis at which reduction of wave height to zero starts (default Wave0-50 m)
Classes	Use classes (true) or critical shear stress (false) in BankType (default: true)
BankType	Bank strength definition (for each bank line per river-km)
ProtectionLevel	Text file(s) with level of bank protection for each bank line per river-km (default: -1000)
Slope	Text file(s) with equilibrium slope for each bank line per river-km (default: 20)
Reed	Text file(s) with reed wave damping coefficient for each bank line per river-km (default: 0)
VelFilterDist	Specifies the distance/width of a moving average filter for the near bank velocities [km] (default 0, meaning no filter applied)
BedFilterDist	Specifies the distance/width of a moving average filter for the bank levels [km] (default 0, meaning no filter applied)

## Example

```
[General]
Version      = 1.0
RiverKM      = inputfiles\rivkm_20m.xyc
Boundaries    = 68:230
BankDir       = files\outputbanklines
BankFile      = bankline

[Detect]
SimFile      = inputfiles\SDS-krw3_00-q0075_map.nc
WaterDepth    = 0.0
NBank        = 2
Line1         = inputfiles\oeverlijn_links_mod.xyc
Line2         = inputfiles\oeverlijn_rechts_mod.xyc
DLines        = [20,20]

[Erosion]
TErosion      = 1
RiverAxis     = inputfiles\maas_rivieras_mod.xyc
Fairway       = inputfiles\maas_rivieras_mod.xyc
NLevel        = 2
RefLevel      = 1
SimFile1      = inputfiles\SDS-krw3_00-q0075_map.nc
PDischarge1   = 0.25
SimFile2      = inputfiles\SDS-krw3_00-q1500_map.nc
PDischarge2   = 0.75
OutputDir     = files\outputbankerosion
BankNew       = banknew
BankEq        = bankeq
EroVol        = erovol_standard.evo
OutputInterval = 0.1
ShipType      = 2
Vship         = 5.0
Nship          = inputfiles\nships_totaal
Nwave         = 5
Draught        = 1.2
Wave0          = 150.0
Wave1          = 110.0
```

```
Classes      = false
BankType    = inputfiles\bankstrength_tauc
ProtectionLevel = inputfiles\stortsteen
```

## B.2 line geometry files

This file specifies the coordinates of a single line. It is used to specify

- ◊ RiverAxis
- ◊ Fairway
- ◊ Initial bank (search) lines

The file format is equal to the file format used by WAQBANK. It consists of two data columns: the first column specifies the x-coordinate and the second column the y-coordinate of each node of the line.

### Example

```
1.1887425781300000e+005 4.1442128125000000e+005
1.1888840213863159e+005 4.1442400328947371e+005
1.1890254646426316e+005 4.1442672532894736e+005
1.1891669078989474e+005 4.1442944736842107e+005
1.1893083511552632e+005 4.1443216940789472e+005
1.1894497944115789e+005 4.1443489144736843e+005
1.1895912376678947e+005 4.1443761348684208e+005
1.1897326809242106e+005 4.1444033552631579e+005
1.1898741241805263e+005 4.1444305756578950e+005
```

...continued...

Shape files are used for all geospatial output, such as the detected bank lines and the shifted bank lines.

## B.3 chainage file

This file defines the river chainage along a line. The file format is equal to the file format used by WAQBANK. It consists of three data columns: the first column specifies the chainage, the second and third columns specify the x- and y-coordinates of each node of the line.

### Example

```
3      175908.078100 308044.062500
6      176913.890600 310727.781300
10     176886.578100 314661.750000
15     176927.328100 319589.687500
16     176357.000000 320335.375000
```

...continued...

## B.4 parameter files

These files may be used to define spatial variations in the input parameters needed by the analysis. Many parameters may be varied along the analyzed river reach.

- ◊ wave0:  $s_0$  distance from ship at which the ship waves have reduced to zero [m]
- ◊ wave1:  $s_1$  distance from ship at which the ship waves start to reduce [m]

- ◊ vship:  $v_s$  ship sailing speed [m/s]
- ◊ nship:  $N$  number of empty ships per year [1/year]
- ◊ nwave:  $n$  number of waves per ship [-]
- ◊ draught:  $T_s$  draught of the ship [m]
- ◊ shiptype: ship type [-]
- ◊ slope:  $\mu_{fs}$  wave damping due to sloping foreshore [ $m^{-1}$ ]
- ◊ reed:  $\mu_r$  wave damping due to reed [ $m^{-1}$ ]
- ◊ banktype: bank type [-]
- ◊ protectionlevel: top level of the bank protection [m]

The file format is independent of the parameter for which it's used. The file format is equal to the file format used by WAQBANK. It consists of two data columns: the first column specifies the chainage and the second column the value at that location. The chainage values should be increasing. The values are used from the chainage specified on that line until the chainage specified on the next line. The first value is also used before the chainage specified on the first line. The last value is used for all chainages larger than the chainage specified on the last line.

### Example

65.3	20912
67.6	18529
100.7	20375
146.8	24758
175.5	13911
201	15613

## B.5 simulation result files

For the bank line detection and bank erosion analysis, the program needs results from a hydrodynamic model. The WAQBANK program was able to read data from the WAQUA SDS-output files or the Delft3D-FLOW trim-files. D-FAST Bank Erosion now supports the results of D-Flow FM in netCDF map-files following UGRID conventions. The model needs the following data fields:

- ◊ x-coordinates of the mesh nodes
- ◊ y-coordinates of the mesh nodes
- ◊ face\_node\_connectivity of the mesh
- ◊ bed levels zb at the mesh nodes
- ◊ water levels zw at the mesh faces
- ◊ water depths h at the mesh faces
- ◊ velocity vector (ucx,ucy) at the mesh faces

The simulation result files may contain multiple time steps; the final time steps will be used for the analysis.

## B.6 eroded volume file

This file reports on the eroded volumes per bank along the analyzed river reach per user defined chainage bin. The file consists  $1 + N$  tab-separated data columns where  $N$  is the number of bank lines processed: the first column specifies the chainage and the other columns report on the eroded bank volume per bank line accumulated by chainage bin. The chainage coordinate provided is the upper limit of the chainage bin for which the volume is reported on that line. The file format differs slightly from the file format used by WAQBANK

since that file contained  $N$  identical chainage columns followed by the  $N$  eroded volume columns.

### Example

```
68.00  2.21  0.00
68.10  6.44  0.00
68.20  7.81  0.00
68.30  43.63 161.39
68.40  14.24 0.00
68.50  8.88  0.00
68.60  0.00  0.00
68.70  0.00  0.00
68.80  2.39  0.00
68.90  0.00  0.00
69.00  0.88  0.00
69.10  7.40  69.27
69.20  5.64  65.47
69.30  11.98 55.78
```

...continued...

## B.7 dialog text file

The dialog text file uses the block labels enclosed by square brackets of the common ini-file format, but the lines in between the blocks are treated verbatim and don't list keyword/value pairs. Every print statement in the program is associated with a short descriptive identifier. These identifiers show up in the dialog text file as the block labels. The text that follows the block label will be used at that location in the program. The order of the blocks in the file is not important. Please note that every line is used as is, so don't add indentations or blank lines unless you want those to show up during the program execution. Most blocks may contain any number of lines, but some blocks may only contain a single line. Some data blocks may contain one or more Python-style placeholders used for inserting values.

### Example

The following excerpt of the default messages.UK.cfg dialog text file shows the string definition for 3 identifiers, namely " (the identifier for an empty line), 'header\_banklines' and 'end\_banklines'. The header string contains two placeholders, namely {version} for the the version number and {location} for the url to the source code location.

```
[]

[header_banklines]
=====
Determine bank lines
=====
version: {version}
source: {location}
-----
[end_banklines]

=====
=====      BankLines ended successfully!      ===
=====
... continued ...
```





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