



Dutch Delta Systems

D-FAST Morphological Impact

User Manual

D-FAST

Morphological Impact

User Manual

Version: 1.0
SVN Revision: 00

14 February 2022

D-FAST Morphological Impact, User Manual

Published and printed by:

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1 Introduction

This manual describes D-FAST Morphological Impact which provides a first estimate of the bed level changes to be anticipated in the main channel due to the implementation of local river adjustments outside the main channel (so-called measures). The program implements the rule of thumb developed in the context of Rijkswaterstaat programme Stroomlijn by (Sieben, 2008-2011) which is only valid for the estimation of the effect of individual measures (at most one flood plain section in length) on the bed level of the main channel. It assumes a seasonal discharge variation that can be represented by means of three stages (normal/low flow, flood flow, and transitional flow) and it adopts a pragmatic approach to the spatial structure. Bed level changes outside the immediate vicinity of influence of the measure are ignored in this analysis. The bed level changes are indicative for the effects over a sufficiently long cycle of high and low flow seasons.

The typical analysis cycle consists of the following steps:

- 1 Use D-FAST Morphological Impact to determine the steady-state hydrodynamic simulations that will provide the necessary input for the morphological impact analysis. D-FAST Morphological Impact provides the discharge values for those conditions.
- 2 For the discharges obtained in step 1, steady-state simulations will be run using WAQUA or D-Flow FM for both the reference situation and the scenario with only the measure to be evaluated implemented. All simulations need to be carried out using the same mesh and the same hydrodynamic model. In case of WAQUA simulations the result files need to be processed before continuing with step 3.
- 3 Using the (processed) simulation results of step 2, D-FAST Morphological Impact determines an estimate of the
 - ◇ year-averaged bed level changes,
 - ◇ maximum bed level changes (representative for the end of flood season) and
 - ◇ minimum bed level changes (representative for the end of low flow season).

The D-FAST Morphological Impact analysis can be adjusted for any deviations between the discharges proposed by D-FAST Morphological Impact in step 1 and the actual simulated discharges in step 2.

The methodology provides an indication of magnitude and location of the bed level changes, but can't always replace a complete morphodynamic simulation. The purpose of the rule of thumb is to provide a simple and consistent first estimate to avoid unnecessary morphodynamic simulations or to identify critical aspects in the design of the measure early on and to underpin the need for more extensive analysis.

The appropriate use of the results – the estimated bed level changes – for the Dutch rivers is described in the “rivierkundig beoordelingskader”. D-FAST Morphological Impact is the second implementation of the rule of thumb. It replaces the initial implementation (WAQMORF) which could only perform the analysis using WAQUA simulations. An evaluation of the rule of thumb (Paarlberg, 2009) states the following

- ◇ Based on a comparison of the tool and Delft3D results for 2 case studies it's concluded that the rule of thumb can provide a reliable and robust indication of the bed level changes in the main channel. However, the rule of thumb should only be applied in those cases for which it is intended and the user should be aware of the assumptions and restrictions of the method and understand the effect that those have on the computed bed level changes.
- ◇ If the estimated bed level changes are critical for navigation and/or safety, or if the measure is outside the applicability domain of the rule of thumb, then the tool is not appropriate. In such cases further research is needed by means of a 1D and/or 2D morphodynamic

model in consultation with the river manager.

- ◇ The tool is most suited for the estimation of the morphological impact on the main channel by river-widening measures which
 - 1 influence the main channel currents in a limited reach and
 - 2 withdraw only a limited amount of water from the main channel.

The user should take care to analyze the results in case of measures that deviate from these conditions and to verify how the assumptions and limitations of the methodology influence the results.

- ◇ The tool can be applied for different types of river-widening measures. It is critical that the flow-carrying capacity of the measure is well represented by the three discharge levels.
- ◇ The rule of thumb can probably also be applied for river reaches with (more) strongly graded sediments.

Finally, we reproduce below the introductory section of the text included in every report written by the tool:

This program implements the "WAQUA vuistregel" for the estimation of the local morphological effects of a local measure (i.e. an adjustment to the river). See "RWS-WD memo WAQUA vuistregel 20-10-08" for details).

It is based on an estimation of the equilibrium bed level changes in the main channel that would occur eventually when river maintenance would not be adjusted.

The effect is expressed in [m] as:

- year-averaged bed level change without dredging
- maximum bed level change (after flood season) without dredging
- minimum bed level change (after low season) without dredging

By means of these estimates bottlenecks can be identified. The results are not suitable for direct estimation of the impact on the maintenance of the navigation channel!

The yearly sediment load of the river determines the period in which the equilibrium can be reached.

This is version

The results are not valid for a combination of multiple measures, or for a single measure extending over a distance more than 4 km!

2 Getting started

2.1 Introduction

This chapter gives an overview of how D-FAST Morphological Impact can be used. The program can run in one of three modes:

- 1 *batch mode*: in this mode the program runs the analysis without user interaction for a configuration file of which the name as command line argument,
- 2 *cli mode*: in this (legacy) mode the configuration for the analysis is obtained by asking the user questions via a command line interface which support simulation results from WAQUA only, and
- 3 *gui mode*: in this mode the user specifies the configuration via a graphical user interface from which the analysis can either be started directly or the configuration can be saved for batch mode execution at a later time.

The program runs by default in the gui mode; other run modes can be selected via the command line argument.

short	long	description
-h	--help	show help text and exit
	--rivers	name of river configuration file (default: Dutch_rivers.ini)
	--language	language selection: NL or UK (default: UK)
	--mode	run mode batch, cli or gui (default: gui)
	--config	name of analysis configuration file
	--reduced_output	write reduced SIMONA BOX files (applies to legacy cli mode only)

By default the program runs for the Dutch Rhine and Meuse river branches, but a different river configuration can be provided by means of the `--rivers` command line switch; this option is supported by all run modes. For details on the format of the river configuration file, see the appropriate section in the appendix. The language setting influences all texts displayed by the program in cli and gui modes as well as the texts written to the report file as well as the names of the various output files. The following list indicates the English and Dutch names:

- ◇ Text file with summary report of the analysis
English: `report.txt`
Dutch: `verslag.run`
- ◇ Average yearly change in SIMONA BOX file format (when the analysis runs using WAQUA input)
English: `yearavg_dzb.out`
Dutch: `jaargem.out`
- ◇ Maximum change in SIMONA BOX file format (when the analysis runs using WAQUA input)
English: `max_dzb.out`
Dutch: `maxmorf.out`
- ◇ Minimum change in SIMONA BOX file format (when the analysis runs using WAQUA input)
English: `min_dzb.out`
Dutch: `minmorf.out` UGRID netCDF file containing variables for average yearly change, maximum change, and minimum change (when the analysis runs using D-Flow FM input)

English: `dfastmi_results.nc`
Dutch: `dfastmi_resultaten.nc`

The following sections describe the three options.

2.2 Running in batch mode

The batch mode runs an analysis using either WAQUA or D-Flow FM results without user interaction. The program should be started with the run mode set to `batch` and a configuration file specified on the command line as follows

```
> dfastmi --mode batch --config myfile.cfg
```

You may choose to run the program in either Dutch `--language NL` or English `--language UK`; the latter is the default. Please note that the language does not only affect the text in the report, but also the names of the output files as indicated in the opening section of this chapter. The content of the configuration file is described in Appendix X; it can be generated using either a text editor or D-FAST Morphological Impact running in gui mode. The `--reduced_output` option for smaller SIMONA BOX file output is currently not supported in this run mode.

2.3 Running in interactive command line mode

The cli mode runs an interactive command line analysis using WAQUA results; this run mode does not support D-Flow FM files. The program should be started with the run mode set to `cli` on the command line as follows

```
> dfastmi --mode cli
```

You may choose to run the program in either Dutch `--language NL` or English `--language UK`; the latter is the default. Please note that the language does not only affect the text in the report, but also the names of the output files as indicated in the opening section of this chapter. You may also choose to select the `--reduced_output` option for smaller SIMONA BOX file output. Although this is an interactive run mode, you may use this mode also as a batch mode by redirecting standard input to read from file as follows

```
> dfastmi --mode cli < myfile.in
```

In this case each line in the file `<myfile.in>` should contain the appropriate answer to the question. This run mode is included for backward compatibility and comparison with its predecessor WAQMORF. We recommend to use either the gui mode or the batch mode instead.

2.4 Running in gui mode

This is the default mode for the program, so no command line argument needed. It supports analysis using either WAQUA or D-Flow FM results. As with the other run modes, you may choose to run the program in either Dutch `--language NL` or English `--language UK`; the latter is the default. Please note that the language does not only affect the text in the report, but also the names of the output files as indicated in the opening section of this chapter. Furthermore, you may specify a configuration file to load upon start. For example

Parameter	Value
Data files	D-Flow FM map
Branch	Bovenrijn & Waal
Reach	Bovenrijn km 859-867
Discharge location	Lobith
Flow-carrying above 1000 m3/s?	<input checked="" type="checkbox"/>
Minimum Flow-carrying Discharge [m3/s]	3000.0
Bankfull Discharge [m3/s]	4000.0
Discharge Q1 [m3/s]	3000.0
Q1: Name of reference file (without measure)	<input type="text"/>
Q1: Name of file with measure	<input type="text"/>
Discharge Q2 [m3/s]	4000.0
Q2: Name of the reference file (without measure)	<input type="text"/>
Q2: Name of file with measure	<input type="text"/>
Discharge Q3 [m3/s]	6000.0
Q3: Name of the reference file (without measure)	<input type="text"/>
Q3: Name of file with measure	<input type="text"/>
Critical flow velocity [m/s]	0.3
Impacted length [m]	1384

Figure 2.1: Example of the main dialog

```
> dfastmi --language NL --config myfile.cfg
```

runs the program in Dutch and loads the myfile.cfg configuration file into the graphical user interface. The `--reduced_output` option for smaller SIMONA BOX file output is currently not supported in this run mode.

The following text describes the functionality of the graphical user interface from top to bottom. The **File** menu provides access to options to load a configuration file and to save the current selection in the gui to a configuration file. The **Help** menu provides access to about boxes for D-FAST Morphological Impact itself and for the PyQt5 graphical framework.

The data files option enables the user to select the type of hydrodynamic result files to be used, namely D-Flow FM map or WAQUA export. When the user selects the latter the names of the input files are predefined as `xyz_<quantity>-zeta.00<1/2>.Q<i>` and the file name fields in the bottom part of the dialog will therefore be disabled. The user may choose to change the selection at any time.

Subsequently, the user specifies the branch and reach. Changing this selection will affect all fields below overwriting any previously entered values. Note that at the bottom of the dialog, the length [m] of the impacted river stretch by the measure is indicated. It is dynamically

updated with each change you make.

The next three fields are used to determine the characteristic discharges needed for the analysis. Depending on the river reach conditions, the first question may read "Flow-carrying above 1000 m³/s?" or "Flow-carrying when all barriers are open?". When the answer is negative (box unchecked) the second field will be activated which asks for the minimum discharge [m³/s] for which the measure is flow-carrying; this value is not needed when the answer to the first question is affirmative. The third field asks for the river discharge [m³/s] for which the measure reaches bankfull. The default value specified is the default bankfull discharge for the selected river reach. This question is disabled if the minimum discharge specified is already larger than the typical bankfull discharge. Based on the foregoing questions the discharges Q1, Q2 and Q3 are specified. Under certain conditions the number of discharges may reduce from three to two or even one. In such cases the corresponding fields are disabled.

For each of the three discharges Q1, Q2 and Q3, the user may override the specified value. The weighing coefficients to determine the impacted length and resulting bed level change are not affected by such changes. The values are only used to indicate the discharge for which simulation results are used in the analysis. When the user has selected to run the analysis based on D-Flow FM results, the corresponding simulation result files for the various reference simulations and simulations with measure are to be specified here.

The last input item for the analysis is the critical flow velocity [m/s] for sediment transport. The resulting impacted length [m] was already mentioned above. Finally, we find at the bottom of the dialog a button to run the analysis in the folder from which the program was started, and a button to end the program.

2.5 Running from Python source code

D-FAST Morphological Impact can also be run directly from the Python source code. In that case the program can be started from the command prompt as

```
python -m dfastmi ...options...
```

or from within a running Python environment as

```
import dfastmi.cmd
dfastmi.cmd.run()
```

where optionally the language (default UK), runmode (default GUI), configfile (default dfastmi.cfg), rivers_file (default Dutch_rivers.ini) and reduced_output (default false) can be specified as arguments.

3 Conceptual framework

This chapter describes the conceptual framework of the method used by D-FAST Morphological Impact and the derivation of the river parameters used for the Dutch rivers.

3.1 Characteristics of bed level changes due to river measures

A river measure, i.e. a local river adjustment (typically a flow capacity enlarging adjustment) outside the main channel, may result in changes in the flow pattern within the main channel. The bed levels within the main channel will react to such changes depending on the

magnitude, duration and length scale of these flow pattern changes in the main channel.

Hence, the core focus of the rule-of-thumb is to determine and characterize the changes in the flow pattern within the main channel. Here, we define the main channel as the part of the river between the groyne heads.

At the upstream end of the floodplain adjustment part of the main channel discharge will leave the main channel, which will flow through the enlarged floodplain, secondary channel or bank area, and return to the main channel at the downstream end of the project area. The resulting changes in the main channel flow pattern cause sedimentation in the main channel at the upstream "offtake" of the new outflow and erosion at the downstream "confluence" when the flow enters the main channel again. Because the river discharge varies, the pattern will also vary during the year. As a result a part of the main channel bed level adjustment is stationary and a part of the adjustment is transitional and it will migrate downstream. A reduction in the water depth may thus not only be observed locally where the flow diverges into the flood plain, but also downstream thereof.

The bed level change due to river enlargement can largely be characterized as follows

- ◇ The magnitude of the bed level change varies over the seasons; the maximum change is observed at the end of the flood season and the adjustment reaches a minimum at the end of the low flow period.
- ◇ Local evaluation of the bed level changes is insufficient because of partial downstream migration of the bed level changes.
- ◇ The maximum impact is observed on that side of the river which is closest to the adjustment.

Because part of the bed level changes migrate downstream, the morphological impact on projects located downstream may be increased. After all, the maximum bed level change of one single river enlarging measure is reached at the end of the flood period and it's the result of that flood period. However, when a series of measures along the river are combined (for instance, lowering of the groynes along a reach) the downstream bed level changes may be increased by accumulation of downstream migrating bed waves, such that the accumulated bed level change may be significantly larger. In other words, river measures extending over longer reaches may result in a larger morphodynamic response than comparable but more isolated measures.

The aforementioned observations result in the following premisses. The rule-of-thumb described in the following sections

- ◇ will only be valid for the estimation of the impact of local measures with a length of at most one flood plain,
- ◇ should take into account seasonal variations, and

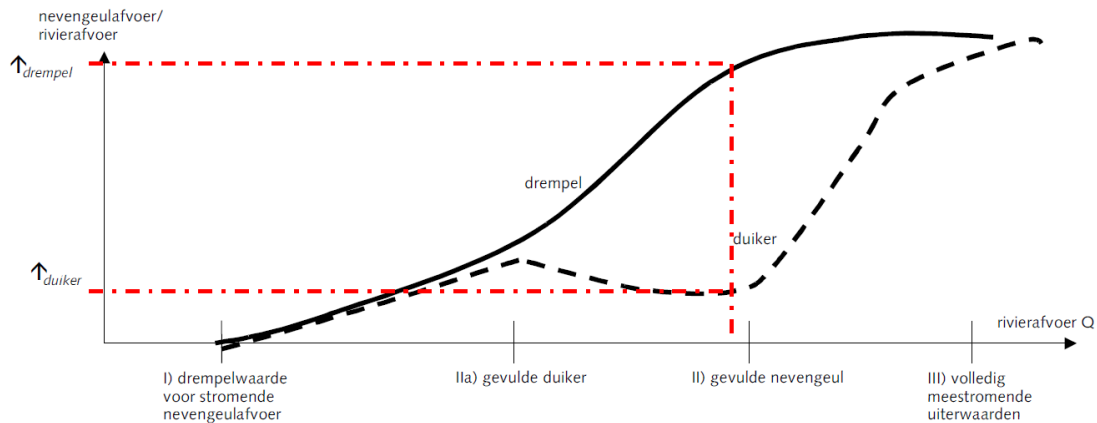


Figure 3.1: Schematic of the controlled discharge through a secondary channel.

◇ needs to be estimate the spatial pattern of the bed level change.

3.2 Characterization of the changes in the main channel flow pattern

When a measure in the floodplains does not include something like a permanently active secondary channel, the flow pattern in the main channel will only be affected during flood conditions. If on the other hand, such a secondary channel (or other measure active under medium to low flow conditions such as groyne adjustments) is included in the design then the flow pattern will also be influenced during transitional or even low flow conditions. It's therefore critical to determine the effect of the measure on the main channel flow pattern at different discharge levels.

Secondary channels may have a major impact on the morphodynamics of the main channel. The magnitude of the discharge through the secondary channel varies as function of the river discharge. Because the hydraulic conditions of the secondary channel can change over time (e.g. due to vegetation, siltation, or erosion) the discharge through a secondary channel is typically controlled by some hydraulic structure. The typical characteristics of a weir (overlaat, drempel) and orifice (onderlaat, duiker) are shown in Figure 3.1.

The discharge through a secondary channel is characterized by a number of special conditions as illustrated by Figure 3.1:

- 1 the beginning of flow through the secondary channel
- 2 the bankfull secondary channel
- 3 the fully developed flow in the secondary channel and surrounding floodplain.

When the discharge through the secondary channel is controlled by an orifice, the fully flooded condition may add an additional characteristic discharge.

In order to characterize the flow patterns during flood it's necessary to distinguish the condition in which the flood plains just start to carry flows, and the condition of fully developed flow in the flood plains. Based on results of 1D simulations shown in Figure 3.2 it has been concluded that for the Rhine branches a discharge of 6000 m³/s at Lobith can be used as the boundary between those two conditions. The flow through the bank zone (Figure 3.3) is also largely developed for discharges at Lobith larger than 6000 m³/s.

These characteristic discharge values can be used to schematize the river hydrograph effectively by means of a limited number of discrete discharge conditions. Three discharge blocks

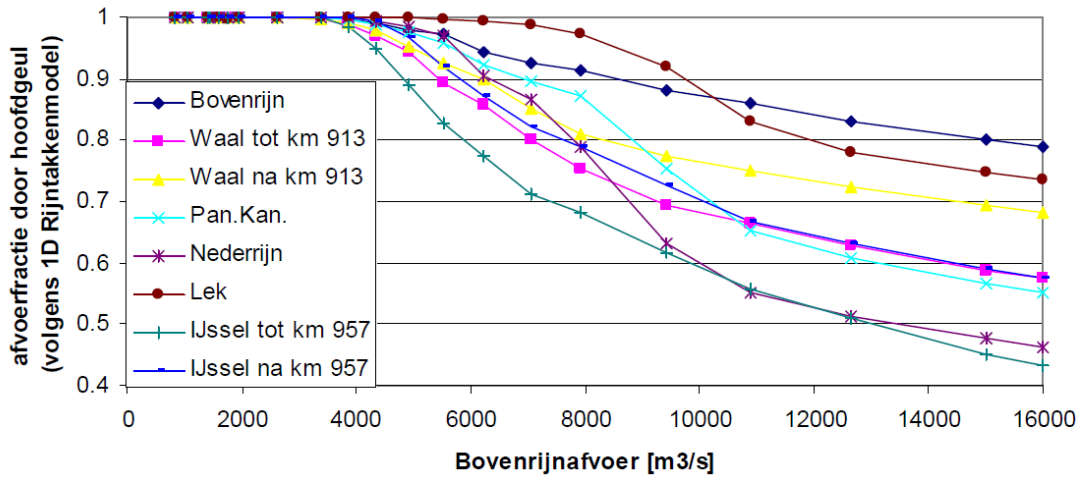


Figure 3.2: Reach-averaged discharge fraction through the main channel (based on 1D model of the Rhine branches).

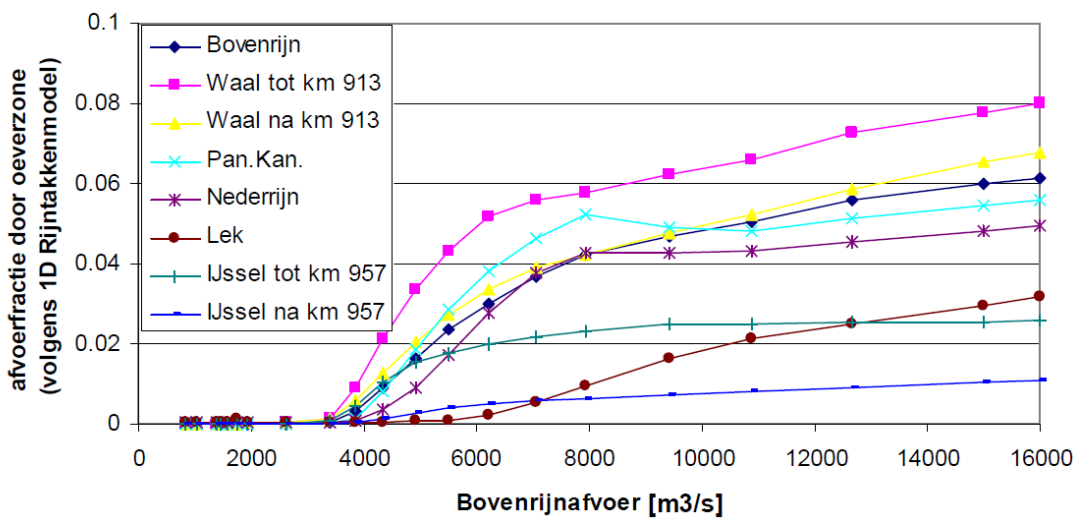


Figure 3.3: Reach-averaged discharge fraction through the bank zone (based on 1D model of the Rhine branches).

	first block	second block	third block
periodically flowing secondary channel with weir	from minimum river flow to minimum discharge for secondary channel	from minimum discharge for secondary channel to bankfull secondary channel	from bankfull secondary channel to fully developed flood plain flow
periodically flowing secondary channel with orifice	from minimum river flow to minimum discharge for secondary channel	from minimum discharge for secondary channel to fully flooded orifice	from fully flooded orifice to fully developed flood plain flow
permanently flowing secondary channel	from minimum river flow to bankfull secondary channel	from bankfull secondary channel to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
local lowering of groynes (less than flood plain length)	from minimum river flow to flooded groynes	from flooded groynes to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
lowering of the flood plain	from minimum river flow to minimum discharge for new flood plain threshold	from new flood plain threshold to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
lowering of levees	from minimum river flow to minimum discharge for new levee threshold	from new levee threshold to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow

Table 3.1: Overview of discharge conditions for various measures in a free flowing Rhine branch.

turn out to be sufficient for many measures as may be concluded from Table 3.1. That is why it has been concluded that *three flow conditions are sufficient to schematize the yearly hydrograph for the purpose of estimating the morphological impact of local measures.*

For a river reach in which water levels (and hence flow conditions) are controlled by means of barriers for a period T_{stuw} , the minimum river discharge is determined by the river discharge at which the barriers are opened. Figure 3.8 shows that the barriers in the Nederrijn are opened at a discharge of 1500 m³/s in the Bovenrijn at Lobith (this value is exceeded during 57 % of the year) and that the branch is approximately free flowing for discharges above 2200 m³/s in the Bovenrijn at Lobith (exceeded during 33 % of the year).

In order to quickly estimate the yearly exceedance period for a given discharge, the discharge exceedance curve for the Bovenrijn has been approximated by a curve fitted through the observational data for the period 1970-2000 (Figure 3.4). The number of days that the discharge $Q_{Bovenrijn}$ in the Bovenrijn at lobith is exceeded is given by

$$T_{\text{exceedance, Bovenrijn}} = 365e^{\left(\frac{800 - Q_{\text{Bovenrijn}}}{1280}\right)} \quad (3.1)$$

For the Meuse, in which — due to imbrication (Grensmaas) and barriers (Zandmaas) — the higher discharges are more important for the morphological development, the exceedance period for discharges at Borgharen can be estimated as

$$T_{\text{exceedance, Meuse}} = 365e^{\left(\frac{-Q_{\text{Borgharen}}}{300}\right)} \quad (3.2)$$

	first block	second block	third block
periodically flowing secondary channel with weir	from 1500 m ³ /s at Lobith to minimum discharge for secondary channel	from minimum discharge for secondary channel to bankfull secondary channel	from bankfull secondary channel to fully developed flood plain flow
periodically flowing secondary channel with orifice	from 1500 m ³ /s at Lobith to minimum discharge for secondary channel	from minimum discharge for secondary channel to fully flooded orifice	from fully flooded orifice to fully developed flood plain flow
permanently flowing secondary channel	from 1500 m ³ /s at Lobith to bankfull secondary channel (about 4000 m ³ /s at Lobith)	from bankfull secondary channel (about 4000 m ³ /s at Lobith) to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
local lowering of groynes (less than flood plain length)	from 1500 m ³ /s at Lobith to flooded groynes	from flooded groynes to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
lowering of the flood plain	from 1500 m ³ /s at Lobith to minimum discharge for new flood plain threshold	from new flood plain threshold to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow
lowering of levees	from 1500 m ³ /s at Lobith to minimum discharge for new levee threshold	from new levee threshold to 6000 m ³ /s at Lobith	from 6000 m ³ /s at Lobith to fully developed flood plain flow

Table 3.2: Overview of discharge conditions for various measures along the Nederrijn.

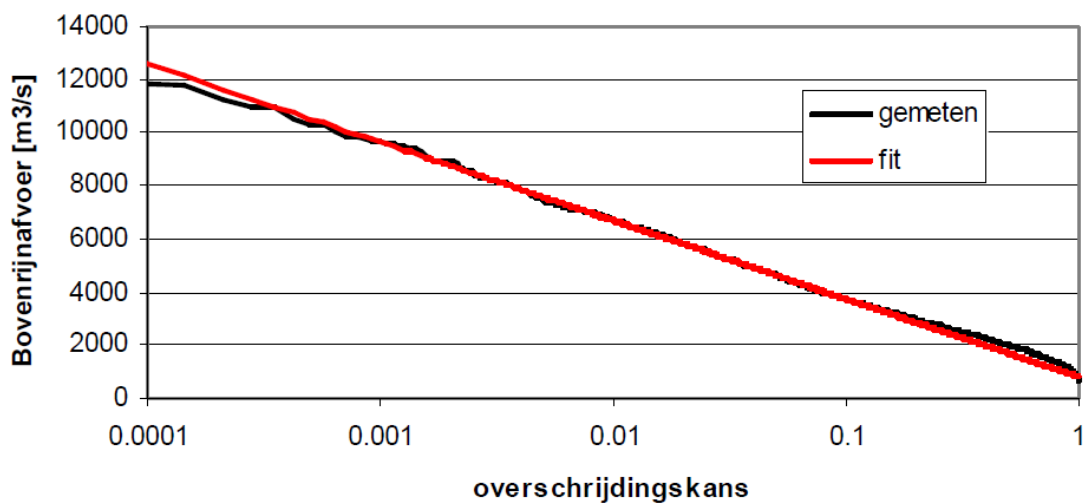


Figure 3.4: Discharge exceedance curve for the Bovenrijn at Lobith (1970-2000).

	first block	second block	third block
periodically flowing secondary channel with weir	from 1000 m ³ /s at Borgharen to minimum discharge for secondary channel	from minimum discharge for secondary channel to bankfull secondary channel	from bankfull secondary channel to fully developed flood plain flow
periodically flowing secondary channel with orifice	from 1000 m ³ /s at Borgharen to minimum discharge for secondary channel	from minimum discharge for secondary channel to fully flooded orifice	from fully flooded orifice to fully developed flood plain flow
permanently flowing secondary channel	from 1000 m ³ /s at Borgharen to bankfull secondary channel	from bankfull secondary channel to 2000 m ³ /s at Borgharen	from 2000 m ³ /s at Borgharen to fully developed flood plain flow
local lowering of groynes (less than flood plain length)	from 1000 m ³ /s at Borgharen to flooded groynes	from flooded groynes to 2000 m ³ /s at Borgharen	from 2000 m ³ /s at Borgharen to fully developed flood plain flow
lowering of the flood plain	from 1000 m ³ /s at Borgharen to minimum discharge for new flood plain threshold	from new flood plain threshold to 2000 m ³ /s at Borgharen	from 2000 m ³ /s at Borgharen to fully developed flood plain flow
lowering of levees	from 1000 m ³ /s at Borgharen to minimum discharge for new levee threshold	from new levee threshold to 2000 m ³ /s at Borgharen	from 2000 m ³ /s at Borgharen to fully developed flood plain flow

Table 3.3: Overview of discharge conditions for various measures along the Meuse.

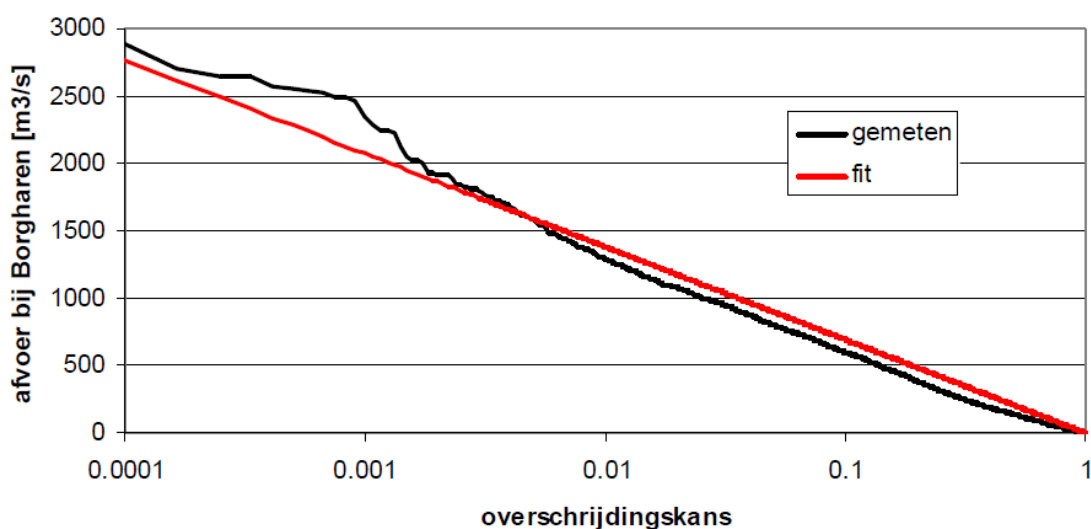


Figure 3.5: Discharge exceedance curve for the Meuse at Borgharen (1975-2007).

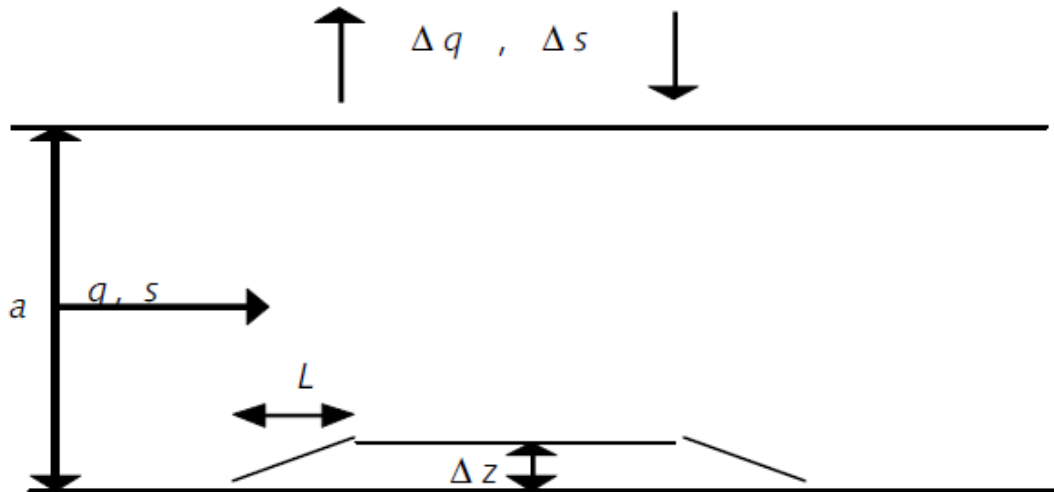


Figure 3.6: Schematic representation of the outflow of water and sediment

3.3 Scientific background of the relaxation model for morphological change

The rule-of-thumb used to determine the first estimate of the morphological effects within the main channel is based on a highly simplified model of the morphodynamics. That model and the resulting rule-of-thumb are described in this section.

We start by assuming a quasi-stationary flow pattern and an outflow of discharge and sediment from the main channel while the local water level is independent of the hydraulic and morphological changes in the main channel (a *rigid-lid* approximation).

The response of the main channel is represented here by a bed level change Δz_b [m] (raise or lowering) which is small relative to the local water depth. The mass balance of the water and the sediment in the main channel can be written as

$$\text{water} \quad \frac{\partial q_{mc}}{\partial s} = -q_{out} \quad (3.3)$$

$$\text{sediment} \quad \frac{\partial z_b}{\partial t} + \frac{\partial s_{mc}}{\partial s} = -s_{out} \quad (3.4)$$

in which

q_{mc}	main channel unit discharge [m^2/s]
q_{out}	outflow of unit discharge to the flood plain per unit length [m^2/sm]
s	streamwise coordinate [m]
z_b	bed level change due to measure [m]
s_{mc}	main channel unit sediment transport [m^2/s]
s_{out}	outflow of unit sediment to the flood plan per unit length [m^2/ms]

The unit sediment transport capacity in the main channel, s_{mc} , is approximated by $s_{mc} = m (q_{mc}/h)^b$ with h the water depth [m] in the main channel, m a dimensionless calibration factor and a dimensionless sediment transport exponent b about 5 (Engelund and Hansen, 1967). Using this approximation the gradients in the sediment transport capacity can be

written as

$$\frac{\partial s_{mc}}{\partial s} = mb \left(\frac{q_{mc}}{h} \right)^{b-1} \frac{\partial(q_{mc}/h)}{\partial s} \quad (3.5)$$

$$= mb \left(\frac{q_{mc}}{h} \right)^{b-1} \left[\frac{1}{h} \frac{\partial q_{mc}}{\partial s} - \frac{q_{mc}}{h^2} \frac{\partial h}{\partial s} \right] \quad (3.6)$$

$$= b \frac{s_{mc}}{q_{mc}} \frac{\partial q_{mc}}{\partial s} - b \frac{s_{mc}}{h} \frac{\partial h}{\partial s} \quad (3.7)$$

$$\approx b \frac{s_{mc}}{q_{mc}} \frac{\partial q_{mc}}{\partial s} + b \frac{s_{mc}}{h} \frac{\partial z_b}{\partial s} \quad (3.8)$$

if we assume that the water level gradient is negligible ($\frac{\partial z_w}{\partial s} \approx 0$). Substitution of Equation (3.8) and Equation (3.3) into Equation (3.4) gives

$$\frac{h}{bs_{mc}} \frac{\partial z_b}{\partial t} + \frac{\partial z_b}{\partial s} = h \frac{q_{out}}{q_{mc}} - h \frac{s_{out}}{bs_{mc}} \quad (3.9)$$

The dynamic bed level changes will develop starting from the upstream end of the measure. The length L over which this sedimentation occurs corresponds to the reach in which the main channel discharge is reduced and in which the flow pattern is adjusted by the reduced discharge. Hence, this length L is thus *not* always equal to the length of the measure or the distance between the inflow and outflow openings of a secondary channel. The integration of Equation (3.9) over this length L results in a relaxation model for the dynamic bed level change due to the measure

$$\frac{d\Delta z_b}{dt} = \frac{\Delta z_{b,eq} - \Delta z_b}{T} \quad (3.10)$$

with a morphological time scale [s]

$$T_m \approx \frac{hL}{bs_{mc}} \quad (3.11)$$

and an equilibrium bed level change [m] given by

$$\Delta z_{b,eq} = -h \left(\frac{\Delta q_{mc}}{q_{mc}} + \frac{\Delta s_{mc}}{bs_{mc}} \right) \quad (3.12)$$

This relaxation behaviour can also be observed in the results of the numerical models (both 1D and 2D).

The rule-of-thumb is derived by posing that the bed level change Δz_b can be interpreted as the bed level change due to a measure over a distance L along a line perpendicular to the stream line at the upstream end of the measure. The equilibrium value $\Delta z_{b,eq}$ depends according Equation (3.12) on the (original) water depth, the relative change in unit discharge and the relative change in the sediment transport. The latter term is the result of the sediment flux into the secondary channel which dampens the effect of reduced sediment transport capacity in the main channel. Ignoring this relatively minor dampening term results in a more conservative estimate. For measures over a short distance (i.e. for the type of measures for which the rule-of-thumb is applicable) the water level changes are an order of magnitude smaller than the bed level changes. Therefore, one can rewrite Equation (3.12) to state that the equilibrium bed level change $\Delta z_{b,eq}$ equals the product of the water depth and the relative change in the main channel velocity u [m/s]:

$$\Delta z_{b,eq} \approx -h \left(\frac{\Delta u}{u} \right) \quad (3.13)$$

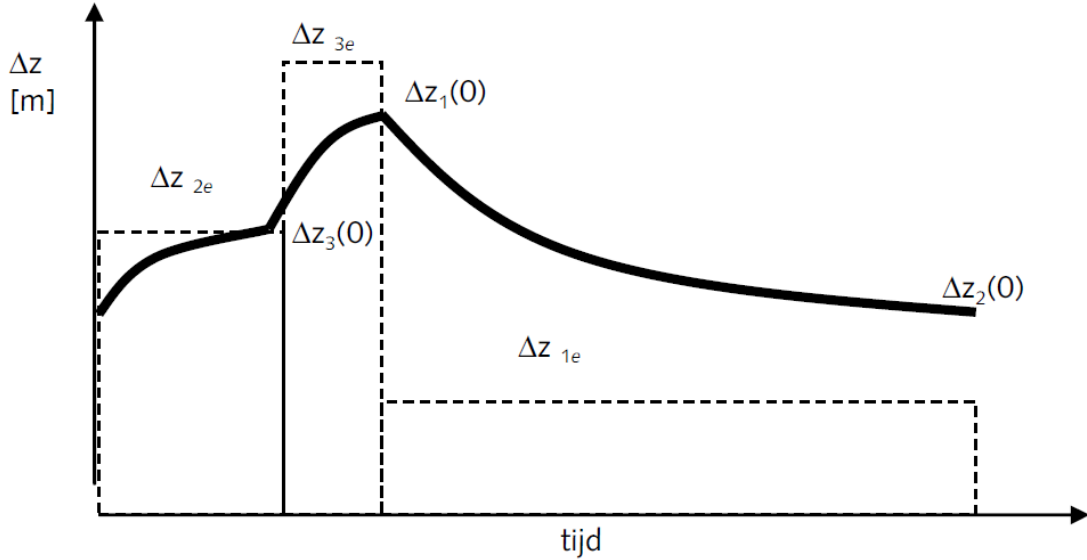


Figure 3.7: Schematic maximum bed level changes at the upstream end.

A similar result can be obtained for graded bed material (sand/gravel mixtures) if it's assumed that the individual sediment fractions don't influence each other's mobility (Appendix C in [Sieben \(2008\)](#)). Such an assumption is valid at sufficiently high bed shear stresses, such as during flood conditions.

3.4 The relaxation model applied to seasonal variability

The bed level development during a relaxation period is (as a solution of [Equation \(3.10\)](#)) given by

$$z_{b,i} = z_{b,i}(0) + [z_{b,i,eq} - z_{b,i}(0)](1 - e^{-t/T_{m,i}}) \quad (3.14)$$

with

$z_{b,i}$	[m] the morphological effect of the measure during period i
$z_{b,i}(0)$	[m] the morphological effect at the start of period i
$z_{b,i,eq}$	[m] the equilibrium effect of the measure during period i
t	[day] time
$T_{m,i}$	[day] the morphological time scale during period i

[Equation \(3.14\)](#) implies that at the end of period i (lasting for a period of T_i days) the morphological effect of the measure is given by

$$z_{b,i+1}(0) = z_{b,i}(0)\sigma_i + z_{b,i,eq}(1 - \sigma_i) \text{ with } \sigma_i = e^{-T_i/T_{m,i}} \quad (3.15)$$

If the yearly hydrograph is schematized using three periods, one obtains the following set of three equations for the three periods by assuming periodicity (the final bed level of the third period equals the initial bed level of the first period)

$$z_{b,2}(0) = z_{b,1}(0)\sigma_1 + z_{b,1,eq}(1 - \sigma_1) \quad (3.16)$$

$$z_{b,3}(0) = z_{b,2}(0)\sigma_2 + z_{b,2,eq}(1 - \sigma_2) \quad (3.17)$$

$$z_{b,1}(0) = z_{b,3}(0)\sigma_3 + z_{b,3,eq}(1 - \sigma_3) \quad (3.18)$$

We can solve these three equations for the unknown bed levels $z_{b,1}(0)$, $z_{b,2}(0)$ and $z_{b,3}(0)$. This gives the following three expressions

$$z_{b,1}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2\sigma_3 + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3 + z_{b,3,\text{eq}}(1 - \sigma_3)}{1 - \sigma_1\sigma_2\sigma_3} \quad (3.19)$$

$$z_{b,2}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1) + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3\sigma_1 + z_{b,3,\text{eq}}(1 - \sigma_3)\sigma_1}{1 - \sigma_1\sigma_2\sigma_3} \quad (3.20)$$

$$z_{b,3}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2 + z_{b,2,\text{eq}}(1 - \sigma_2) + z_{b,3,\text{eq}}(1 - \sigma_3)\sigma_1\sigma_2}{1 - \sigma_1\sigma_2\sigma_3} \quad (3.21)$$

The lower bound for the morphological impact of the measure will be equal to $\min[z_{b,1}(0), z_{b,2}(0), z_{b,3}(0)]$ and the upper bound is given by $\max[z_{b,1}(0), z_{b,2}(0), z_{b,3}(0)]$. For the schematized hydrograph shown in [Figure 3.7](#) the bed level change is

- ◇ maximum at $z_{b,1}(0)$ ([Equation \(3.19\)](#)) after flood period 3 (the third block in [Table 3.2](#))
- ◇ minimum at $z_{b,2}(0)$ ([Equation \(3.20\)](#)) after the low flow period 1 (the first block in [Table 3.2](#)).

The influence of barriers can be included by inserting a yearly period without bed level changes in between flood period 3 and low flow period 1.

We can't only obtain expressions for the two extreme (minimum, maximum) values but we can also determine an expression for the year-averaged bed level change by integrating [Equation \(3.14\)](#) per constant discharge period to

$$\bar{z}_{b,i} = \frac{1}{T_i} \int_0^{T_i} z_{b,i}(0) + [z_{b,i,\text{eq}} - z_{b,i}(0)](1 - e^{-t/T_{m,i}}) dt \quad (3.22)$$

$$= \frac{1}{T_i} (z_{b,i,\text{eq}}t + [z_{b,i,\text{eq}} - z_{b,i}(0)]T_{m,i}e^{-t/T_{m,i}}) \Big|_{t=0}^{t=T_i} \quad (3.23)$$

$$= z_{b,i,\text{eq}} + [z_{b,i,\text{eq}} - z_{b,i}(0)] \frac{T_{m,i}}{T_i} (e^{-T_i/T_{m,i}} - 1) \quad (3.24)$$

and over all periods to

$$\bar{z}_b = \frac{\sum z_{b,i,\text{eq}}T_i}{\sum T_i} + \frac{\sum (z_{b,i,\text{eq}} - z_{b,i}(0))T_{m,i}(\sigma_i - 1)}{\sum T_i} \quad (3.25)$$

If all bed level changes are removed after the flood period by means of dredging, the yearly dredging amount can finally be estimated by ignoring any excess depth. After all, the maximum bed level change at the end of the flood season can with $z_{b,1}(0) = 0$ and [Equation \(3.15\)](#) to [Equation \(3.26\)](#) be expressed as the maximum dredging depth z_{mdd}

$$z_{\text{mdd}} = z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2\sigma_3 + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3 + z_{b,3,\text{eq}}(1 - \sigma_3) \quad (3.26)$$

Because this estimated doesn't take into account the sediment supply by the river, [Equation \(3.26\)](#) can overestimate the maintenance dredging required. [Equation \(3.26\)](#) is therefore not included in the D-FAST Morphological Impact analysis.

3.5 Estimate of the spatial distribution of the bed level changes

Equation (3.19) gives the maximum and Equation (3.20) gives the minimum bed level change at the upstream end of the measure. Moving downstream for that point, the bed level change consists of a minimum bed level change $z_{b,1,eq}$ plus the part of the flood deposit that moves downstream during low flow conditions. During a flood the downstream migrating sedimentation volume may temporarily even cause bed level changes larger than $z_{b,2,eq}$ but this is rather unlikely. For convenience, it's therefore assumed that the maximum and minimum bed level change given by Equation (3.19) and Equation (3.20) are valid for each individual point in the main channel within the impacted area.

This approximation implies that first the values of $z_{b,1,eq}$, $z_{b,2,eq}$ and $z_{b,3,eq}$ can be determined for every computational cell of the simulation in the main channel. Subsequently the minimum (at the end of the low flow period) and maximum bed level change (at the end of the flood period) can be estimated given the approximated values for σ_1 , σ_2 and σ_3 and Equation (3.20) and Equation (3.19) respectively.

3.6 Time scales for bed level change

The magnitude of the maximum bed level change at the end of the flood period and the minimum bed level change at the end of the low flow period both depend on the morphological time scales $T_{m,i}$ [day] which define the rate of response of the bed levels. Using Equation (3.11) the time scale $T_{m,i}$ can also be written as $T_{m,i} = L/w_i$ with w_i the bed celerity, i.e. the propagation speed of bed level changes, and L the distance measure along the flow direction over which the bed level changes are accumulated. As mentioned before, the length L corresponds to the distance over which flow leaves the main channel and the flow pattern in the main channel adjusts to the reduced discharge. Obviously, this distance varies in reality over the channel width and it depends on the discharge condition considered. For consistent use of the rule-of-thumb, it's assumed that the length L corresponds to twice the main channel width B_{mc} .

The second parameter in the definition of the morphological time scale is the bed celerity. Based on statistics of width-averaged bed level observations averaged per km chainage year-averaged values have been determined (RIZA, 2005) for the Dutch rivers. These values are presented in Table 3.2 and Table 3.3 for Rhine branches and Meuse respectively.

In order to translate these empirical year averaged values to discrete values per discharge block the following approximation is used for free flowing Rhine branches. For the Bovenrijn discharges which are predominantly larger than 4000 m³/s (during on average 8 % of the year) a "high flow bed celerity" w_h of 10 m/dag (3.65 km/yr) is used.

For discharge blocks which are predominantly below 4000 m³/s a "low flow bed celerity" w_l is used which is derived from the year-averaged bed celerity \bar{c} as

$$w_l = \frac{\bar{c} - 0.082 \cdot 365}{0.918} \quad (3.27)$$

However, this approximation Equation (3.27) is only valid for the free flowing Rhine branches, hence it's for instance not valid for the Nederrijn where at low discharges the barriers are closed (Figure 3.8).

Figure 3.8 shows that the barriers in the Nederrijn are opened at a discharge of 1500 m³/s in the Bovenrijn at Lobith (this value is exceeded during 57 % of the year) and that the branch

traject	km-raai	voortplantingssnelheid [km/jaar]	
		1950-1973	1974-1999
Bovenrijn	859-867	0,97	1,12
Boven-Waal	868-886	0,98	1,04
Midden-Waal	887-915	1,09	1,13
Beneden-Waal	916-951	1,15	1,10
Pannerdensch Kanaal	868-879	0,79	0,97
Nederrijn, stuwpannd Driel	880-891	0,97	0,77
Nederrijn, stuwpannd Amerongen	892-922	1,36	1,17
Lek, stuwpannd Hagestein	923-947	1,16	1,03
Lek	948-989	1,12	0,96
Boven-IJssel	880-930	1,61	1,50
Midden-IJssel	931-970	1,28	1,16
Beneden-IJssel	970-1000	0,94	1,06

Table 3.4: Overview of average bed celerities (based on km-averaged bed levels including the effects of dredging) by RIZA (2005).

traject	Km-raai	voortplantingssnelheid [km/jaar]	
		voor 1950	na 1950
Grensmaas (km 16-69)	16-69	0,001	0,001
Linne-Roermond (km 69-80)	69-80	0,26	0,14
Roermond-Belfeld (km 81-100)	81-100	0,23	0,26
Belfeld Sambeek (km 101-146)	101-146	0,28	0,26
Sambeek-Grave (km 147-175)	147-175	0,37	0,11
Grave-Lith (km 176-200)	176-200	1,99	0,28
Lith-Ammerzoden (km 201-227)	201-227	0,76	0,14

Table 3.5: Overview of the reach averaged bed celerities (based on km-averaged bed levels including the effects of dredging) by Sieben (2008).

Traject	Km	Voortplantingssnelheid [km/a]
Beneden Waal& Boven Merwede	934-961	1,08
Beneden Merwede	962-977	0,75
Nieuwe Merwede	962-980	0,84

Table 3.6: Overview of the reach averaged bed celerities (based on km-averaged bed levels for the period 1975-2000 including the effects of dredging) by RIZA WSR (2007).

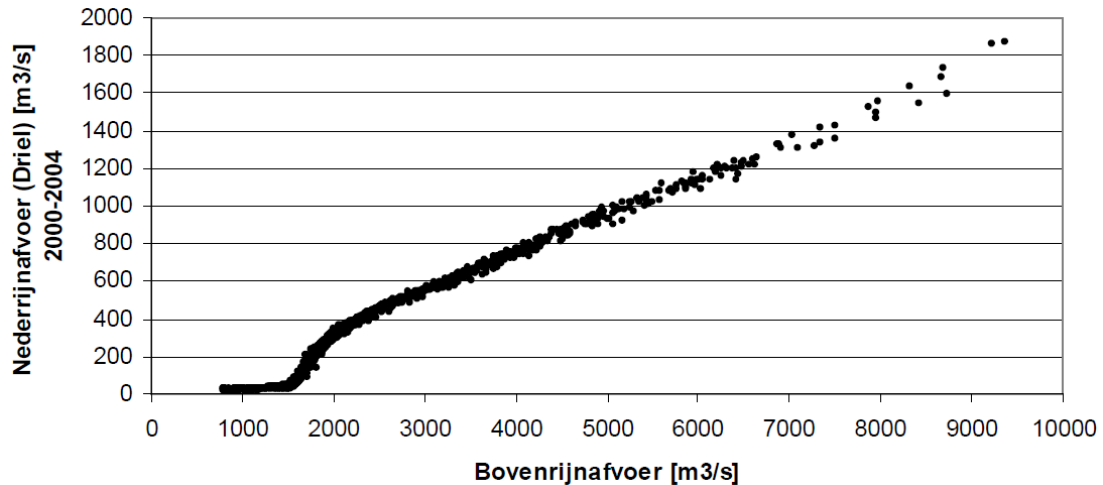


Figure 3.8: Nederrijn discharges at Driel-boven based on Donar database for the period 2000-2004).

is approximately free flowing for discharges above 2200 m³/s in the Bovenrijn at Lobith (exceeded during 33 % of the year). It's therefore assumed that the year-averaged bed celerity related to the low and high flow values as $\bar{c} = 0.082w_h + (0.918 - 0.33)w_l$ such that for $w_h = 3,65$ km/yr we obtain

$$w_l = \frac{\bar{c} - 0.082 \cdot 3.65}{0.918 - 0.33} \quad (3.28)$$

For the Meuse the we apply the following approximation. It's assumed that the Meuse barriers are open for on average 10 days per year (3 % of the time) such that the bed celerity can be estimated as

$$w_h = \frac{\bar{c}}{0,03} \quad (3.29)$$

Finally, due to the gradation the river bed of the Grensmaas will only become mobile at discharges above 1000 m³/s which occurs on average about 4 days a year. The bed celerity is thus estimated as

$$w_h = \frac{\bar{c}}{0,01} \quad (3.30)$$

Based on the approximations Equation (3.27) to Equation (3.30) and the year-averaged bed celerity values in Table 3.4 to Table 3.6 we obtain estimates for the bed celerities during high and low flow conditions.

traject	Km-raai	Voortplantingssnelheid [km/jaar]		
		jaargemiddeld \bar{W}	Bovenrijnafvoer > 4.000 m ³ /s W_h	Bovenrijnafvoer < 4.000 m ³ /s W_l
Bovenrijn	859-867	1.12	3,65	0,89
Boven-Waal	868-886	1.04	3,65	0,81
Midden-Waal	887-915	1.13	3,65	0,90
Beneden-Waal	916-951	1.1	3,65	0,87
Beneden-Waal & Boven Merwede	934-961	1.08	3,65	0,85
Beneden Merwede	962-977	0.75	3,65	0,49
Nieuwe Merwede	962-980	0.84	3,65	0,59
Pannerdensch Kanaal	868-879	0.97	3,65	0,73
Nederrijn. stuwpand Driel	880-891	0.77	3,65	0,80
Nederrijn. stuwpand Amerongen	892-922	1.17	3,65	1,48
Lek. stuwpand Hagestein	923-947	1.03	3,65	1,24
Lek	948-989	0.96	3,65	1,12
Boven-IJssel	880-930	1.5	3,65	1,31
Midden-IJssel	931-970	1.16	3,65	0,94
Beneden-IJssel	970-1000	1.06	3,65	0,83

Table 3.7: Representative bed celerities during high- and low-flow conditions Rhine branches.

Traject	Km-raai	voortplantingssnelheid [km/jaar]		
		na 1950	afvoer bij Borgharen < 1000 m ³ /s	afvoer bij Borgharen > 1000 m ³ /s
Grensmaas (km 16-69)	16-69	0,001	0,00	0,1
Linne-Roermond (km 69-80)	69-80	0,14	0,00	4,67
Roermond-Belfeld (km 81-100)	81-100	0,26	0,00	8,67
Belfeld Sambeek (km 101-146)	101-146	0,26	0,00	8,67
Sambeek-Grave (km 147-175)	147-175	0,11	0,00	3,67
Grave-Lith (km 176-200)	176-200	0,28	0,00	9,33
Lith-Ammerzoden (km 201-227)	201-227	0,14	0,00	4,67

Table 3.8: Representative bed celerities during high- and low-flow conditions Meuse.

4 Steps in the analysis

To apply the rule-of-thumb one should carry out the following five steps. D-FAST Morphological Impact can perform steps 2 and 4 for you (except for the computation of z_{mdd}).

- 1 Characterize the measure to be evaluated using D-FAST Morphological Impact
 - ◇ Determine the threshold discharge Q_{thr} (at Lobith/Borgharen) at which the measure (indirectly) starts to influence the flow pattern in the main channel.
 - ◇ Determine the bankfull discharge Q_{bf} (at Lobith/Borgharen) at which the measure is fully flooded (bankfull flow)
- 2 Define the discharge blocks (block 1 "low flow", block 3 "flood" and block 2 "transitional between low and flood flows") using
 - ◇ [Table 4.1](#) for the Rhine branches
 - ◇ [Table 4.2](#) for the Meuse
- 3 Perform the (up to six) necessary hydrodynamic simulations
- 4 Compute the characteristic bed level change per grid point in the main channel
 - ◇ maximum value [m] at the end of the flood season

$$z_{b,1}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2\sigma_3 + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3 + z_{b,3,\text{eq}}(1 - \sigma_3)}{1 - \sigma_1\sigma_2\sigma_3} \quad (4.1)$$

- ◇ minimum value [m] at the end of the low flow season

$$z_{b,2}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1) + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3\sigma_1 + z_{b,3,\text{eq}}(1 - \sigma_3)\sigma_1}{1 - \sigma_1\sigma_2\sigma_3} \quad (4.2)$$

- ◇ transitional value [m] at the end of the transition block before the flood period

$$z_{b,3}(0) = \frac{z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2 + z_{b,2,\text{eq}}(1 - \sigma_2) + z_{b,3,\text{eq}}(1 - \sigma_3)\sigma_1\sigma_2}{1 - \sigma_1\sigma_2\sigma_3} \quad (4.3)$$

- ◇ year-averaged value [m]

$$z_{b,m} = T_1 z_{b,1}(0) + T_2 z_{b,2}(0) + T_3 z_{b,3}(0) \quad (4.4)$$

- ◇ the maximum dredging depth (ignoring any excess depth)

$$z_{\text{mdd}} = z_{b,1,\text{eq}}(1 - \sigma_1)\sigma_2\sigma_3 + z_{b,2,\text{eq}}(1 - \sigma_2)\sigma_3 + z_{b,3,\text{eq}}(1 - \sigma_3) \quad (4.5)$$

- 5 Visualize the characteristic bed level changes in a graph or on a map

Table 4.1: Definition of discharge blocks for the Rhine branches

		Is er een drempelafvoer Q_{dr} groter dan $1000 \text{ m}^3/\text{s}$				
		Ja, dan		Nee, dan		
		↓		↓		
Afvoer blok 1		$Q_1 = Q_{dr}$		$Q_1 = 3000 \text{ m}^3/\text{s}$		
		bereken σ_1 met Verg.Ia en $\Delta z_{s1} = 0 \text{ m}$		bereken σ_1 met Verg.Ia en Δz_{s1} met Verg.IIa		
		↓				
		Is Q_{dr} kleiner dan $3000 \text{ m}^3/\text{s}$?				
		Ja, dan		Nee, dan		
		↓		↓		
Afvoerblok 2		Is Q_{dv} kleiner dan $6000 \text{ m}^3/\text{s}$?		Is Q_{dv} kleiner dan $4000 \text{ m}^3/\text{s}$?		
		Ja, dan		Nee, dan		
		↓		↓		
		Is Q_{dv} kleiner dan $6000 \text{ m}^3/\text{s}$?		Is Q_{dv} kleiner dan $6000 \text{ m}^3/\text{s}$?		
	Ja, dan		Ja, dan		Nee, dan	
	↓		↓		↓	
	$Q_2 = \max[Q_{dv}; Q_1 + 1000]$		$Q_2 = \max[Q_{dv}; Q_{dr} + 1000]$		$Q_2 = \max[4000; Q_{dv}]$	
	bereken σ_2 met Verg.Ib en Δz_{s2} met Verg.IIb		bereken σ_2 met Verg.Ib en Δz_{s2} met Verg.IIb		$\sigma_2 = 1$ en $\Delta z_{s2} = 0 \text{ m}$	
	↓		↓		↓	
Afvoerblok 3		$Q_3 = \max[6000; Q_2 + 1000]$		$Q_3 = Q_{dv}$		
		↓		↓		
		$Q_3 = 6000 \text{ m}^3/\text{s}$		$Q_3 = 6000 \text{ m}^3/\text{s}$		
		↓		↓		
	$T_3 = 1 - T_1 - T_2$		$T_3 = 1 - T_1 - T_2$		$T_3 = 1 - T_1$	
	↓		↓		↓	
		Is Q_{dr} kleiner dan $6000 \text{ m}^3/\text{s}$?				
		Ja, dan		Nee, dan		
		↓		↓		
		$Q_3 = \max[6000; Q_{dr} + 1000]$		$Q_3 = \min[Q_{dr} + 1000; 10.000]$		
		↓		↓		
		$T_3 = 1 - T_1 - T_2$		$T_3 = 1 - T_1 - T_2$		
		Bereken σ_3 met Verg.Ic en Δz_{s3} met Verg.IIc bij Q_3				

$$\sigma_1 = e^{-\frac{w_l}{2B_n} T_1} \quad (4.6)$$

with $T_1 = e^{\left(\frac{800-Q_{bar}}{1280}\right)} - e^{\left(\frac{800-Q_1}{1280}\right)}$ and w_l from Table 3.7 (with $Q_{bar} = 1500 \text{ m}^3/\text{s}$ for Nederrijn and Lek and $Q_{stuw} = 800 \text{ m}^3/\text{s}$ for the other branches)

$$\sigma_2 = e^{-\frac{w_h}{2B_n} T_2} \quad (4.7)$$

$$\sigma_3 = e^{-\frac{w_h}{2B_n} T_3} \quad (4.8)$$

with $T_2 = e^{\left(\frac{800-Q_1}{1280}\right)} - e^{\left(\frac{800-Q_2}{1280}\right)}$ and w_h from Table 3.7.

$$\Delta z_{b,1,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_1 \quad (4.9)$$

$$\Delta z_{b,2,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_2 \quad (4.10)$$

$$\Delta z_{b,3,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_3 \quad (4.11)$$

based on reference water depths h_o and velocities u_o and modified velocities u_n from the simulations.

Table 4.2: Definition of discharge blocks for the Meuse

		Is er een drempelafvoer Q_{dr} groter dan $1000 \text{ m}^3/\text{s}$?							
		Ja, dan				Nee, dan			
Afvoer blok 1		$Q_1 = Q_{dr}$				$Q_1 = 1250 \text{ m}^3/\text{s}$			
		bereken σ_1 met Verg.Ia en $\Delta z_{e1} = 0 \text{ m}$				bereken σ_1 met Verg.Ia en Δz_{e1} met Verg.IIa			
		Is Q_{dr} kleiner dan $1250 \text{ m}^3/\text{s}$?							
		Ja, dan		Nee, dan					
Afvoerblok 2		Is Q_{bv} kleiner dan $2000 \text{ m}^3/\text{s}$?		Is Q_{dr} kleiner dan $1500 \text{ m}^3/\text{s}$?		Is Q_{bv} kleiner dan $2000 \text{ m}^3/\text{s}$?			
		Ja, dan	Nee, dan	Ja, dan	Nee, dan	Ja, dan	Nee, dan		
		$Q_2 = \max[Q_{bv}; Q_{dr} + 250]$	$Q_2 = 1500 \text{ m}^3/\text{s}$	$Q_2 = \max[Q_{bv}; Q_{dr} + 250]$		$Q_2 = \max[Q_{bv}; 1500]$	$Q_2 = \min[1500; Q_{bv} - 250]$		
		bereken σ_2 met Verg.Ib en Δz_{e2} met Verg.IIb		bereken σ_2 met Verg.Ib en Δz_{e2} met Verg.IIb		$\sigma_2 = 1$ en $\Delta z_{e2} = 0 \text{ m}$		bereken σ_2 met Verg.Ib en Δz_{e2} met Verg.IIb	
				Is Q_{dr} kleiner dan $2000 \text{ m}^3/\text{s}$?					
Afvoerblok 3		$Q_3 = \max[2000; Q_2 + 250]$	$Q_3 = Q_{bv}$	$Q_3 = 2000 \text{ m}^3/\text{s}$	Ja, dan	Nee, dan	$Q_3 = 2000 \text{ m}^3/\text{s}$	$Q_3 = Q_{bv}$	
					$Q_3 = \max[2000; Q_{dr} + 200]$	$Q_3 = \min[Q_{dr} + 200; 3000]$			
		$T_3 = 1 - T_1 - T_2$		$T_3 = 1 - T_1 - T_2$	$T_3 = 1 - T_1$		$T_3 = 1 - T_1 - T_2$		
		Bereken σ_3 met Verg.Ic en Δz_{e3} met Verg.IIc bij Q_3							

$$\sigma_1 = e^{-\frac{w_l}{2B_n} T_1} \quad (4.12)$$

with $T_1 = e\left(-\frac{Q_{bar}}{300}\right) - e\left(-\frac{Q_1}{300}\right)$; $Q_{bar} = 100 \text{ m}^3/\text{s}$ and w_l from Table 3.8.

$$\sigma_2 = e^{-\frac{w_h}{2B_n} T_2} \quad (4.13)$$

$$\sigma_3 = e^{-\frac{w_h}{2B_n} T_3} \text{ with } w_h \text{ from Table 4.2} \quad (4.14)$$

with $T_2 = e\left(-\frac{Q_1}{300}\right) - e\left(-\frac{Q_2}{300}\right)$ and w_h from Table 3.8.

$$\Delta z_{b,1,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_1 \quad (4.15)$$

$$\Delta z_{b,2,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_2 \quad (4.16)$$

$$\Delta z_{b,3,eq} = -h_o \frac{u_n - u_o}{u_o} \text{ for } Q_3 \quad (4.17)$$

based on reference water depths h_o and velocities u_o and modified velocities u_n from the simulations.

The premisses are: the flow in the main channel is well developed at $Q = 1000 \text{ m}^3/\text{s}$, and at $Q = 2000 \text{ m}^3/\text{s}$ the flows in main channel and floodplain are both well developed.

5 Examples

This chapter describes three examples of how D-FAST Morphological Impact could be used.

5.1 Example 1: secondary channel along the Waal

For this (manually analyzed) case the effect of the secondary channel was analyzed by means of the results of a 1D SOBEK model instead of 2D WAQUA or D-Flow FM simulation results. The secondary channel is located along the Waal river at chainage 900-905 km. The secondary channel was represented in the 1D Rijntakken model as a local lateral extraction of river discharge. The extraction was 3 % of the total river discharge up to 4000 m³/s beyond that the discharge increases linearly up to 10 % at 7000 m³/s and higher discharges. The effect on the main channel discharge is shown for a number of characteristic cross-sectional profiles in Figure 5.1. The changes in the *main channel* discharge caused by the secondary channel do not simply follow from the relationship between the secondary channel discharge and the *total* river discharge. After all, the secondary channel also lowers the water level which introduces a non-linear effect in particular in the lower range of the flood discharges. As a result the *main channel* discharge does not decrease proportionally to the extra flow area added by the secondary channel (e.g. at the profile at km 900.5 at Bovenrijn discharges between 7000 and 8000 m³/s).

Step 1) Characterize the measure

The secondary channel removes 3 % of the total discharge for all discharges below 4000 m³/s in the Bovenrijn. Above that value the withdrawal increases linearly up to 10 % at 7000 m³/s. There is no threshold discharge for the secondary channel: it is active at all discharges. The secondary channel reaches bankfull at a river discharge of 4000 m³/s.

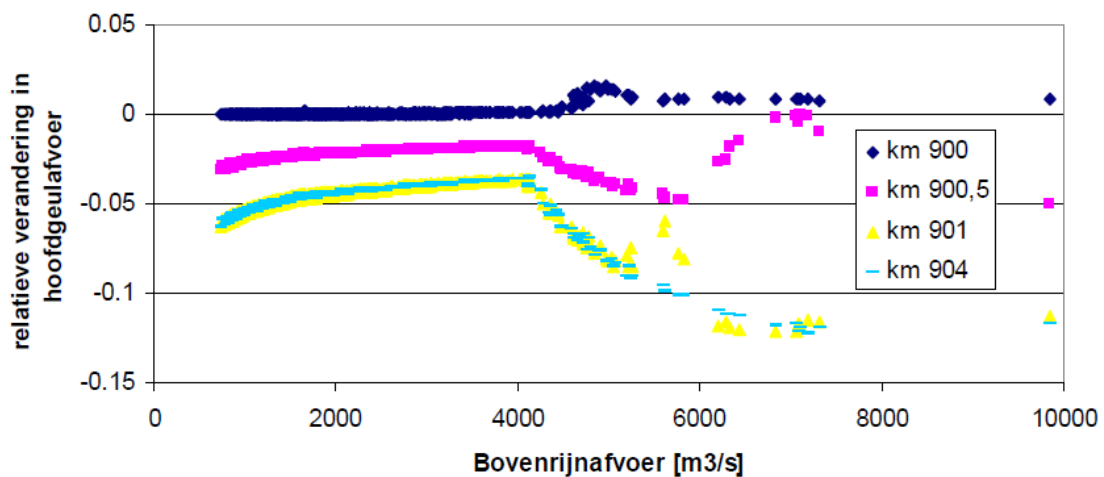


Figure 5.1: Influence of a secondary channel on the main channel discharge of the Waal

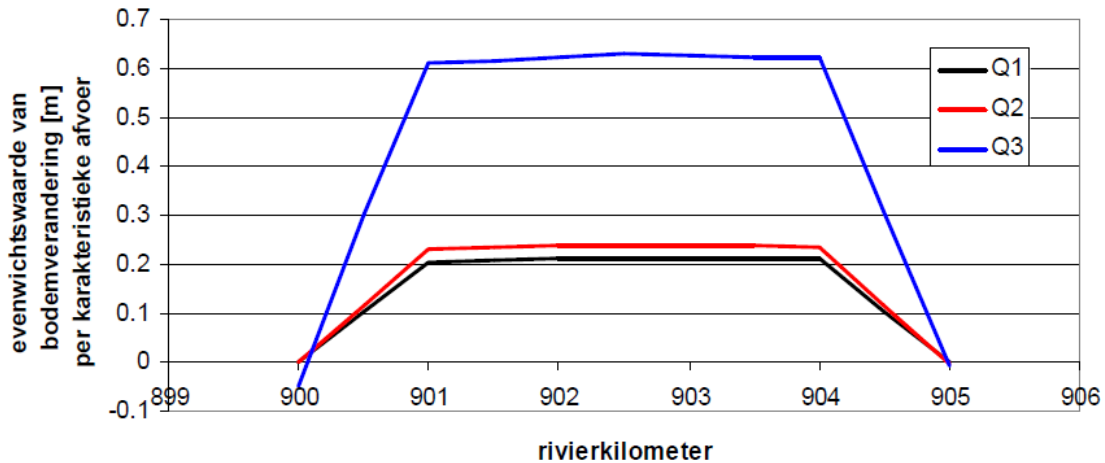


Figure 5.2: Equilibrium bed level changes in the main channel of the Waal at the site of the secondary channel.

Step 2) Define the discharge blocks

Because there is no threshold discharge the discharge $Q_1 = 3000 \text{ m}^3/\text{s}$ is used for the first (low flow) block. For the second block (transitional discharges) applies that the secondary channel reaches bankfull at $4000 \text{ m}^3/\text{s}$, so $Q_2 = 4000 \text{ m}^3/\text{s}$. The discharge Q_3 of the third block (flood) is in agreement with Table 4.1 equal to $6000 \text{ m}^3/\text{s}$. These values can be used to compute the relative duration of each block as

- ◇ $Q_1 = 3000 \text{ m}^3/\text{s}$ implies $T_1 = 1 - e^{\frac{800-3000}{1280}} = 0.84$
- ◇ $Q_2 = 4000 \text{ m}^3/\text{s}$ implies $T_2 = e^{\frac{800-3000}{1280}} - e^{\frac{800-4000}{1280}} = 0.09$
- ◇ $Q_3 = 6000 \text{ m}^3/\text{s}$ implies $T_3 = 1 - T_1 - T_2 = 0.07$

Step 3) Equilibrium bed level changes

For each of the three characteristic discharges the equilibrium bed level changes were determined for each relevant cross-sectional profile based on the SOBEK results as

$$\Delta z_{b,i,\text{eq}} = -h_o \frac{Q_{\text{main channel},n} - Q_{\text{main channel},o}}{Q_{\text{main channel},o}} \quad (5.1)$$



Note: Usually the results of a 2D model are used for each individual computational point in the main channel. However, for this application based on SOBEK results the total main channel discharge and the average main channel depth were used which thus only verifies the impact along a single stream path.

The resulting equilibrium values are shown in Figure 5.2.

Step 4) Time scales for relaxation

The main channel width (normal width between groyne heads) at the site of the secondary channel is 260 m. The bed celerity for low discharges is 900 m/yr; for high discharges this increases to 3650 m/yr. Consequently, for each block we can compute

$$\sigma_1 = e^{-\frac{w_l}{2B_n}T_1} = e^{-\frac{900}{2 \cdot 260}0.84} = 0.18 \quad (5.2)$$

$$\sigma_2 = e^{-\frac{w_l}{2B_n}T_2} = e^{-\frac{3650}{2 \cdot 260}0.09} = 0.73 \quad (5.3)$$

$$\sigma_3 = e^{-\frac{w_l}{2B_n}T_3} = e^{-\frac{3650}{2 \cdot 260}0.07} = 0.78 \quad (5.4)$$

Step 5) Computation of the characteristic bed level changes

Based on the equilibrium values determined in step 3 and the relaxation factors of step 4 the characteristic bed level changes can be computed using

$$z_{b,1}(0) = \frac{z_{b,1,eq}(1 - \sigma_1)\sigma_2\sigma_3 + z_{b,2,eq}(1 - \sigma_2)\sigma_3 + z_{b,3,eq}(1 - \sigma_3)}{(1 - \sigma_1\sigma_2\sigma_3)} \quad (5.5)$$

$$z_{b,2}(0) = \frac{z_{b,1,eq}(1 - \sigma_1) + z_{b,2,eq}(1 - \sigma_2)\sigma_3\sigma_1 + z_{b,3,eq}(1 - \sigma_3)\sigma_1}{1 - \sigma_1\sigma_2\sigma_3} \quad (5.6)$$

To illustrate, the third characteristic bed level change has also been determined by means of

$$z_{b,3}(0) = \frac{z_{b,1,eq}(1 - \sigma_1)\sigma_2 + z_{b,2,eq}(1 - \sigma_2) + z_{b,3,eq}(1 - \sigma_3)\sigma_1\sigma_2}{1 - \sigma_1\sigma_2\sigma_3} \quad (5.7)$$

For instance for cross-sectional profile km 901 we obtain $\Delta z_{b,1,eq} = 0.20$ m; $\Delta z_{b,2,eq} = 0.23$ m; $\Delta z_{b,3,eq} = 0.61$ m. Substitution of these values into the aforementioned equations gives for km 901

$$z_{b,1}(0) = \frac{0.20 \cdot (1 - 0.18) \cdot 0.73 \cdot 0.78 + 0.23 \cdot (1 - 0.73) \cdot 0.78 + 0.61 \cdot (1 - 0.78)}{1 - 0.18 \cdot 0.73 \cdot 0.78} = 0.31 \quad (5.8)$$

$$z_{b,2}(0) = \frac{0.20 \cdot (1 - 0.18) + 0.23 \cdot (1 - 0.73) \cdot 0.78 \cdot 0.18 + 0.61 \cdot (1 - 0.78) \cdot 0.18}{1 - 0.18 \cdot 0.73 \cdot 0.78} = 0.22 \quad (5.9)$$

$$z_{b,3}(0) = \frac{0.20 \cdot (1 - 0.18) \cdot 0.73 + 0.23 \cdot (1 - 0.73) + 0.61 \cdot (1 - 0.78) \cdot 0.18 \cdot 0.73}{1 - 0.18 \cdot 0.73 \cdot 0.78} = 0.22 \quad (5.10)$$

Step 6) Visualizing the results

The alongstream profile of the characteristic bed level changes is shown together with the results obtained from SOBEK in Figure 5.3. The $z_{b,1}(0)$ value (the characteristic maximum bed level change at the end of the flood period) corresponds in this case well with the bed level change that is not exceeded during 98 % of the time. the $z_{b,2}(0)$ value (the characteristic minimum bed level change at the end of the low flow period) corresponds in this case well with the bed level change which is not exceeded during 50 % of the time. The $z_{b,3}(0)$ value is in this particular case almost equal to $z_{b,2}(0)$ and it thus exceeds the simulated value that corresponds to the value not exceeded during 2 % of the time.

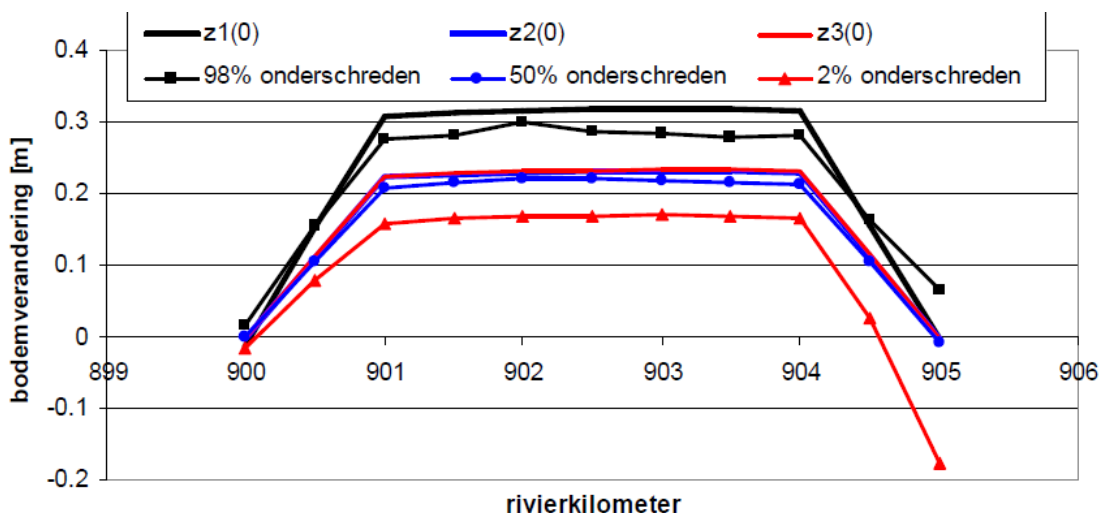


Figure 5.3: Estimated and simulated bed level changes at the secondary channel along the Waal.

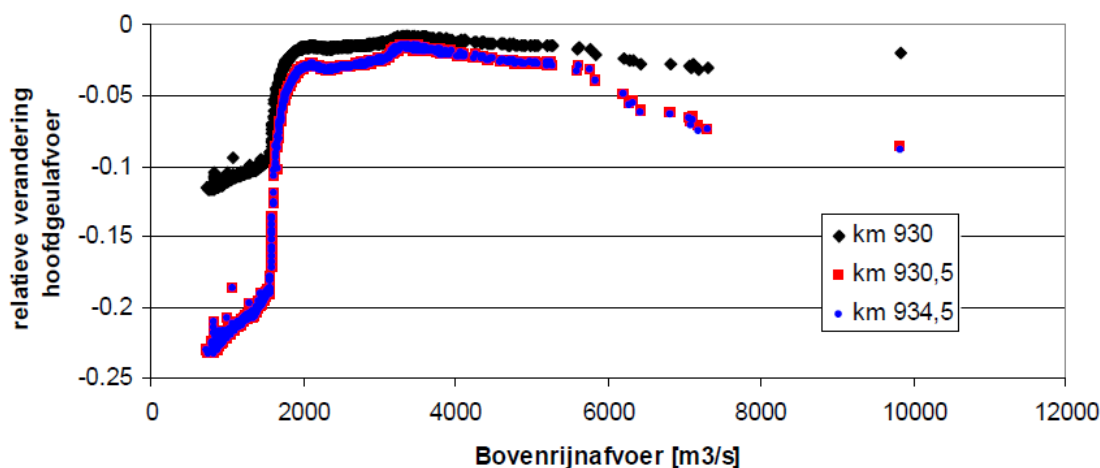


Figure 5.4: Influence of the secondary channel on the main channel discharge for the Lek

5.2 Example 2: secondary channel along the Lek

The second case also concerns a secondary channel; however, this time a secondary channel along the Lek between km 930 and km 935. Also this secondary channel has been schematized as a local lateral extraction of flow from the overall river. This extraction corresponds again to 3 % of the total discharge for values up to 4000 m³/s and increases linearly beyond to that 10 % at 7000 m³/s and higher discharges. The effect on the main channel discharge is shown for a number of representative cross-sections in Figure 5.4.

Step 1) Characterize the measure

The secondary channel extracts 3 % of the total discharge for Bovenrijn discharges up to 4000 m³/s. Above that value the withdrawal increases linearly up to 10 % at 7000 m³/s. As in the first case there is no threshold discharge since the secondary channel is active for all discharges. The reaches bankfull at a Bovenrijn discharge of 4000 m³/s.

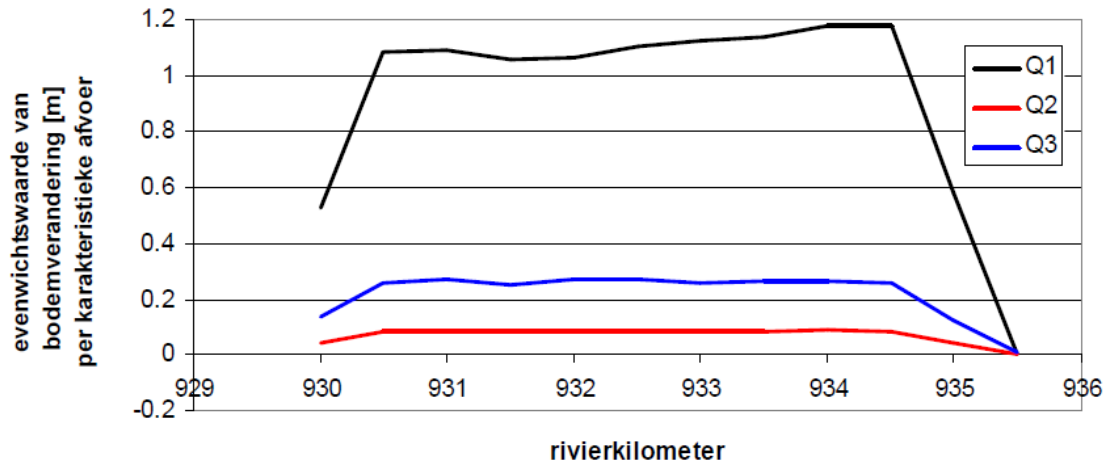


Figure 5.5: Equilibrium bed level changes in the main channel of the Lek at the site of the secondary channel.

Step 2) Definition of the discharge blocks

Because there is no threshold discharge the discharge $Q_1 = 1500 \text{ m}^3/\text{s}$ is used for the first (low flow) block. For the second block (transitional discharges) applies that the secondary channel reaches bankfull at $4000 \text{ m}^3/\text{s}$, so $Q_2 = 4000 \text{ m}^3/\text{s}$. The discharge Q_3 of the third block (flood) is in agreement with Table 4.1 equal to $6000 \text{ m}^3/\text{s}$. These values can be used to compute the relative duration of each block as

- ◇ $Q_1 = 1500 \text{ m}^3/\text{s}$ implies $T_1 = 1 - e^{\frac{800-1500}{1280}} = 0.42$
- ◇ $Q_2 = 4000 \text{ m}^3/\text{s}$ implies $T_2 = e^{\frac{800-1500}{1280}} - e^{\frac{800-4000}{1280}} = 0.50$
- ◇ $Q_3 = 6000 \text{ m}^3/\text{s}$ implies $T_3 = 1 - T_1 - T_2 = 0.08$

Step 3) Equilibrium bed level changes

For each of the three characteristic discharges the equilibrium bed level changes were determined for each relevant cross-sectional profile based on the SOBEK results as

$$\Delta z_{b,i,eq} = -h_o \frac{Q_{\text{main channel},n} - Q_{\text{main channel},o}}{Q_{\text{main channel},o}} \quad (5.11)$$

Note: Usually the results of a 2D model are used for each individual computational point in the main channel. However, for this application based on SOBEK results the total main channel discharge and the average main channel depth were used which thus only verifies the impact along a single stream path.

The resulting equilibrium values are shown in Figure 5.5.



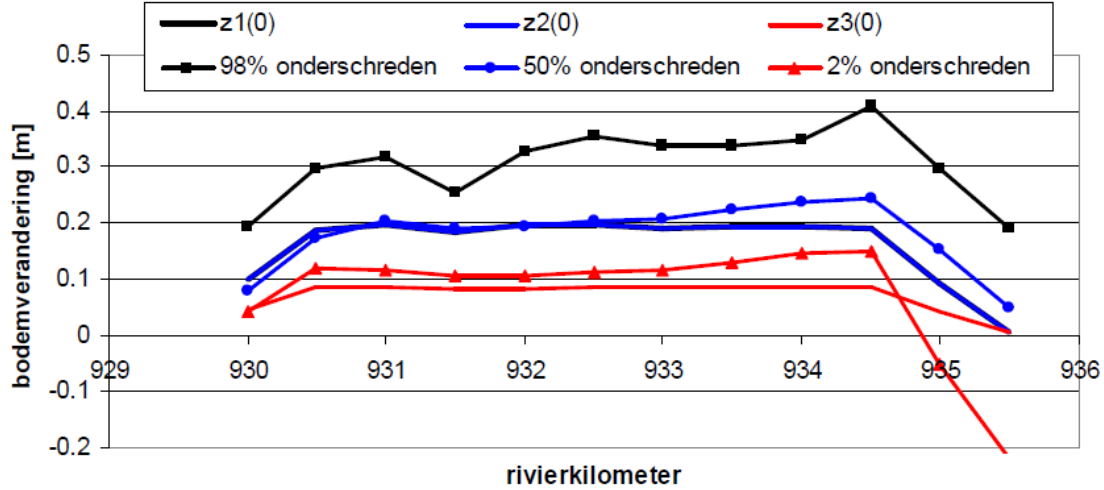


Figure 5.6: Estimated and simulated bed level changes at the secondary channel along the Lek.

Step 4) Time scales for relaxation

The main channel width (normal width between groyne heads) at the site of the secondary channel is 140 m. The bed celerity for low discharges is 0 m/yr; for high discharges this increases to 3120 m/yr. Consequently, for each block we can compute

$$\sigma_1 = e^{-\frac{w_l}{2B_n} T_1} = e^{-\frac{0}{2 \cdot 140} 0.42} = 1.00 \quad (5.12)$$

$$\sigma_2 = e^{-\frac{w_l}{2B_n} T_2} = e^{-\frac{3120}{2 \cdot 140} 0.50} = 0.004 \quad (5.13)$$

$$\sigma_3 = e^{-\frac{w_l}{2B_n} T_3} = e^{-\frac{3120}{2 \cdot 140} 0.08} = 0.40 \quad (5.14)$$

Step 5) Computation of the characteristic bed level changes

Based on the equilibrium values determined in step 3 and the relaxation factors of step 4 the characteristic bed level changes can be computed. For instance for cross-sectional profile km 930.5 we obtain $\Delta z_{b,1,eq} = 1.08$ m; $\Delta z_{b,2,eq} = 0.08$ m; $\Delta z_{b,3,eq} = 0.26$ m. Substitution of these values into the appropriate equations gives for km 930.5

$$z_{b,1}(0) = \frac{1.08 \cdot (1-1.00) \cdot 0.004 \cdot 0.40 + 0.08 \cdot (1-0.004) \cdot 0.40 + 0.26 \cdot (1-0.40)}{1-1.00 \cdot 0.004 \cdot 0.40} = 0.20 \quad (5.15)$$

$$z_{b,2}(0) = \frac{1.08 \cdot (1-1.00) + 0.08 \cdot (1-0.004) \cdot 0.40 \cdot 1.00 + 0.26 \cdot (1-0.40) \cdot 1.00}{1-1.00 \cdot 0.004 \cdot 0.40} = 0.20 \quad (5.16)$$

$$z_{b,3}(0) = \frac{1.08 \cdot (1-1.00) \cdot 0.004 + 0.08 \cdot (1-0.004) + 0.26 \cdot (1-0.40) \cdot 1.00 \cdot 0.004}{1-1.00 \cdot 0.004 \cdot 0.40} = 0.08 \quad (5.17)$$

Step 6) Visualizing the results

The alongstream profile of the characteristic bed level changes is shown together with the results obtained from SOBEK in Figure 5.6. The $z_{b,1}(0)$ value (the characteristic maximum bed level change at the end of the flood period) corresponds in this case to the $z_{b,2}(0)$ value (the characteristic minimum bed level change at the end of the low flow period). Both values correspond in this case well with the bed level change which is not exceeded during 50 % of the time. The $z_{b,3}(0)$ value corresponds in this particular case to the value not exceeded during 2 % of the time.

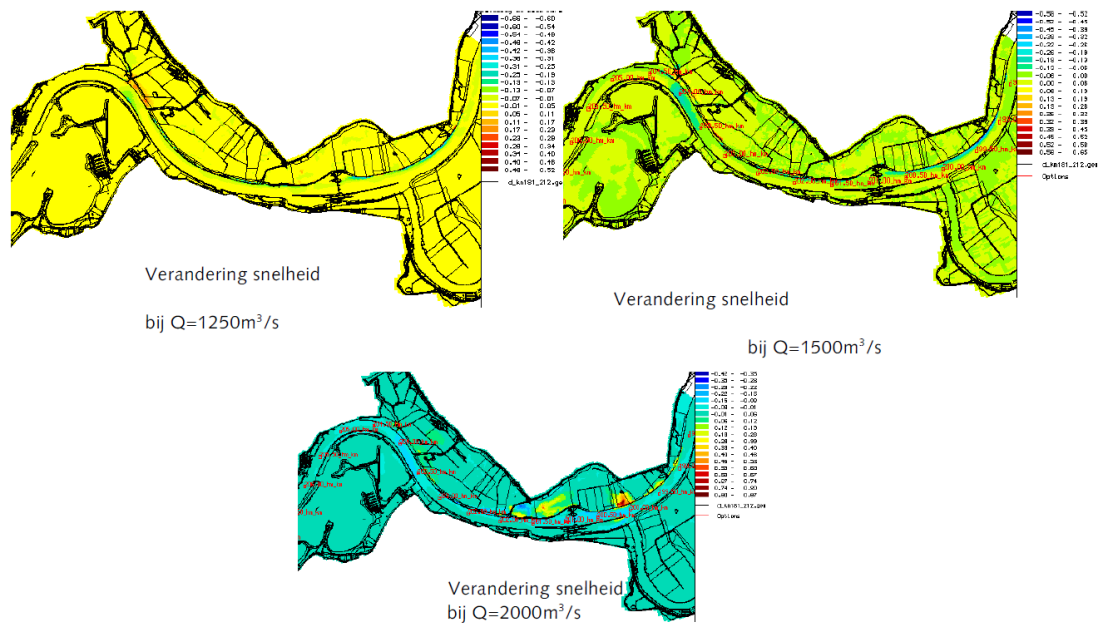


Figure 5.7: Overview of the velocity changes due to the measure

5.3 Example 3: an application to the Maas

This example shows an analysis that was carried out using the original WAQMORF tool, but results of the latest D-FAST Morphological Impact program are consistent so it's still relevant. The analysis was based on results obtained using the WAQUA model of "Over de Maas" of (Hydraulics, 2007). The simulation results were provided by Ed Lemaire (DLB).

The test consisted of the following steps

- 1 The tool D-FAST Morphological Impact was used to determine the — for the morphology — representative discharges. This step returned the discharges $1250\text{ m}^3/\text{s}$, $1500\text{ m}^3/\text{s}$ and $2000\text{ m}^3/\text{s}$ at Borgharen.
- 2 WAQUA simulations were carried for both the reference situation and situation with the measure implemented. The water depths and flow velocities were exported using WAQVIEW to the export files supported by D-FAST Morphological Impact.
- 3 The export files were used as input for a second run of D-FAST Morphological Impact to estimate i) the mean annual bed level change, ii) the maximum bed level change (at the end of the flood season) and iii) the minimum bed level change (at the end of the low flow season)

The biggest local bed level changes are located in the bend immediately downstream of the measure. The figures show the mean annual bed level changes in cm for three different critical velocities for the initiation of motion. This parameter turns out to have little effect in this particular case. The impact of the plan on river maintenance can be determined based on the available space in the navigation channel.

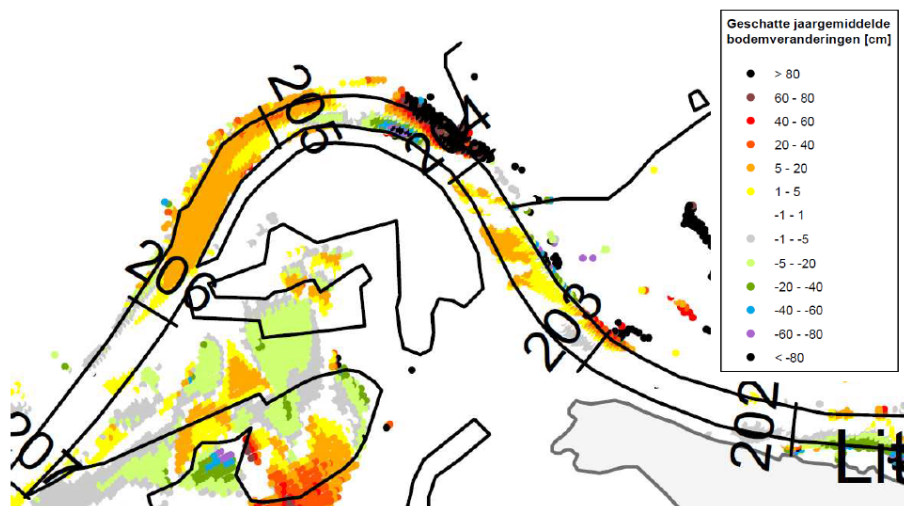


Figure 5.8: Estimated bed level changes (velocity threshold $u_{crit} = 0.01$ m/s).



Figure 5.9: Estimated mean annual bed level changes (velocity threshold $u_{crit} = 0.10$ m/s).



Figure 5.10: Estimated mean annual bed level changes (velocity threshold $u_{crit} = 0.30$ m/s).

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A File formats

The software distinguishes 6 files:

- ◇ The *rivers configuration file* defines the branches and reaches, and all parameter settings specific for the overall system, per branch or per reach.
- ◇ The *dialog text file* defines all strings to be used in the interaction with the users (GUI, report, or error messages).
- ◇ The *analysis configuration file* defines the settings that are relevant for a specific execution of the algorithm, i.e. for a specific branch, reach and measure.
- ◇ The *simulation result files* define the spatial variations in the velocities and water depths as needed by the algorithm.
- ◇ The *report file* contains a logging of the settings and lumped results for the analysis.
- ◇ The *spatial output file* contains the estimate of the spatial variation in the sedimentation and erosion patterns that will result from the measure (minimum, mean and maximum).

Each file type is addressed separately in the following subsections.

A.1 rivers configuration file

The rivers configuration file follows the common ini-file format. 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`.

Besides the `[General]` block version 1.0 files should only contain data blocks for the river branches (in Dutch: takken). The names of those blocks will be used as branch names. For instance, a block `[My branch]` will be processed as a branch called "My branch". The order of the branches will correspond to the order of the blocks in the file. The branch block defines the reaches (in Dutch: stukken) to be distinguished as well as the branch or reach specific parameter settings. The `[General]` block may contain default values for the Further details follow below.

Block	Keyword	Description
General	Version	Version number. Must be 1.0
BranchName<i>	Reach<j>	Name of reach <j> within branch <i>
BranchName<i>	QLocation	Location at which discharges for branch <i> are defined
*	QStagnant	Discharge [m ³ /s] below which main channel flow can be assumed stagnant
*	QMin	Minimum discharge [m ³ /s] at which measure becomes active
*	QFit	Two discharges [m ³ /s] used for representing the exceedance curve
*	QLevels	Four characteristic discharges [m ³ /s] used by algorithm
*	dQ	Two discharge adjustments [m ³ /s] used by algorithm
*	NWidth	Normal width [m] of main channel
*	PRLow	Low flow propagation rate [km/yr]
*	PRHigh	High flow propagation rate [km/yr]
*	UCrit	Critical (minimum) velocity [m/s] for sediment transport

The second value of `QLevels` corresponds to the typical bankfull discharge. All keywords listed for block `*` may occur either in the `[General]` block or in one of the branch specific blocks where they may optionally be concatenated with the reach number `<j>`. Those keywords may thus occur in three flavours:

- 1 Plain keyword in block `[General]`: global default value valid for all branches
- 2 Plain keyword in branch specific block: default value for that branch (overrides any global default)
- 3 Keyword followed by reach number `<j>` in branch specific block: value valid for that reach on that branch.

Example

The following excerpt of the default `Dutch_rivers.ini` configuration file shows the `[General]` as well as the first part of the `[Bovenrijn & Waal]` block for the first branch. It includes a global value of 0.3 for `UCrit` and 100 for `QMin`. The other parameters are specified at branch level and mostly uniform for the whole branch. Only `NWidth` and `PRLow` vary depending on the reach selected.

```
[General]
  Version      = 1.0

  UCrit       = 0.3
  QMin        = 1000

[Bovenrijn & Waal]
  QLocation    = Lobith
  QStagnant    = 800
  QFit         = 800 1280
  QLevels      = 3000 4000 6000 10000
  dQ           = 1000 1000
```

```

PRHigh      = 3.65

Reach1      = Bovenrijn                km  859-867
NWidth1     = 340
PRLow1     = 0.89

Reach2      = Boven-Waal              km  868-886
NWidth2     = 260
PRLow2     = 0.81

... continued ...

```

A.2 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 in particular block that start with `gui_` or `filename_`. Some data blocks may contain one or more named placeholders, e.g. `version`, used for inserting values by means of the Python `format()` method.

Example

The following excerpt of the default `messages.NL.cfg` dialog text file shows the string definition for 5 identifiers, namely " (the identifier for an empty line), 'header', 'confirm', 'confirm_or' and 'confirm_or_restart'. The header string contains one placeholder, namely `version` for the the version number.

```

[]

[header]
Dit programma is de "WAQUA vuistregel" voor het schatten
van lokale morfologische effecten door een lokale ingreep
(zie RWS-WD memo WAQUA vuistregel 20-10-08).

Het is een inschatting van evenwichtsbodemveranderingen
in het zomerbed die als gevolg van een ingreep en zonder
aangepast beheer na lange tijd ontstaan.

Dit betreft het effect op de bodem in [m]:

    jaargemiddeld zonder baggeren
    maximaal (na hoogwater) zonder baggeren
    minimaal (na laagwater) zonder baggeren

Met deze bodemveranderingen kunnen knelpunten worden
gesignaleerd. De resultaten zijn niet direkt geschikt
voor het bepalen van de invloed op vaargeulonderhoud!

De jaarlijkse sedimentvracht door de rivier bepaalt de
termijn waarbinnen dit evenwichtseffect kan ontwikkelen.'

Dit is versie {version}.

[confirm]
Bevestig met "j" ...

```

```
[confirm_or]
Bevestig met "j", anders antwoord met "n" ...

[confirm_or_restart]
Bevestig met "j", of begin opnieuw met "n" ...

... continued ...
```

A.3 analysis configuration file

The analysis configuration file follows the common ini-file format. 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.

Version 1.0 files must contain in the [General] block also the keywords `Branch` and `Reach` to identify the branch (in Dutch: tak) and reach (in Dutch: stuk) in which the measure is located. The specified names may be shortened, but they should uniquely identify the branch and reach amongst the names of the other branches and reaches. Optionally, the same block may also contain `Qmin`, `QBankfull` and `UCrit` values representative for this particular measure if they differ from those typical for the selected reach. These items are sufficient for a basic analysis. For a full spatial analysis the user needs to specify the names of the D-Flow FM map-files containing the results of the simulations without measure (reference) and with measure for the selected discharges Q1, Q2, and Q3.

Block	Keyword	Description
General	Version	Version number. Must be 1.0
General	Mode	WAQUA export or D-Flow FM map (the latter is the default)
General	Branch	Name of the selected branch
General	Reach	Name of the selected reach
General	QMin	Minimum discharge [m ³ /s] at which measure becomes active
General	QBankfull	Discharge [m ³ /s] at which measure reaches bankfull
General	UCrit	Critical (minimum) velocity [m/s] for sediment transport
Q1	Discharge	Discharge [m ³ /s] of the low flow simulation
Q1	Reference	Name of D-Flow FM map-file to be used for reference condition at Q1
Q1	WithMeasure	Name of D-Flow FM map-file that includes the measure at Q1
Q2	Discharge	Discharge [m ³ /s] of the transitional regime
Q2	Reference	Name of D-Flow FM map-file to be used for reference condition at Q2
Q2	WithMeasure	Name of D-Flow FM map-file that includes the measure at Q2
Q3	Discharge	Discharge [m ³ /s] of the high flow simulation
Q3	Reference	Name of D-Flow FM map-file to be used for reference condition at Q3
Q3	WithMeasure	Name of D-Flow FM map-file that includes the measure at Q3

The file names may be specified using relative or absolute paths. The `Reference` and `WithMeasure` keywords are **not** used when the `Mode` equals `WAQUA export`; in that case the file name are standardized as `xyz_<quantity>-zeta.00<1/2>.Q<i>`.

Example

This example shows a complete analysis configuration file for a measure in the first branch/reach of the default `Dutch_rivers.cfg` configuration. It reports the default settings. Only the `Version`, `Branch`, `Reach`, `Reference` and `WithMeasure` keywords are required for the full analysis.

```
[General]
Version      = 1.0
Mode         = D-Flow FM map
Branch       = Bovenrijn & Waal
Reach        = Bovenrijn                km 859-867
Qmin         = 1000.0
Qbankfull    = 4000.0
Ucrit        = 0.3

[Q1]
Discharge    = 1000.0
```

```

Reference = Measure42/Q1/Reference/DFM_OUTPUT_Q1/Q1_map.nc
WithMeasure = Measure42/Q1/Updated/DFM_OUTPUT_Q1/Q1_map.nc

[Q2]
Discharge = 4000.0
Reference = Measure42/Q2/Reference/DFM_OUTPUT_Q2/Q2_map.nc
WithMeasure = Measure42/Q2/Updated/DFM_OUTPUT_Q2/Q2_map.nc

[Q3]
Discharge = 6000.0
Reference = Measure42/Q3/Reference/DFM_OUTPUT_Q3/Q3_map.nc
WithMeasure = Measure42/Q3/Updated/DFM_OUTPUT_Q3/Q3_map.nc

```

A.4 simulation result files

The WAQUA program writes the simulation results in a proprietary SDS file format. The content of these result files can't be accessed directly from Python, so they need to be exported to a more accessible file format. The previous WAQMORF program also required that the user extracted the cell centred velocity magnitude and water depth values from the the WAQUA SDS-output files write them to simple ASCII files with 6 columns specifying the x-coordinates, y-coordinates, the value of the quantity (labeled as z-coordinate), m-index, n-index, and cell number. Only the "z" values and the m- and n-indices are used by the program. The names of those files has been hardcoded, they should read `xyz_<quantity>-zeta.00<1/2>.Q<i>` with the quantity name equal to 'velocity' or 'waterdepth', a 1 for the reference simulation and a 2 for the simulation with the measure implemented, and i the number of the discharge level. D-FAST Morphological Impact supports these same files; an example of such file are given below. In case of an anlysis based on D-Flow FM simulations, D-FAST Morphological Impact reads the results directly from the UGRID netCDF map-files. These files may contain multiple time steps; the final time steps will be used for the analysis. The mesh geometry is transferred from one of the simulation files to the D-FAST Morphological Impact results file.

Example

```

x, y, z, m, n, id
197940.645, 431152.719, 0.0000, 2, 1, 11
197874.004, 431430.516, 0.0000, 3, 1, 12
197801.719, 431717.008, 0.0000, 4, 1, 13
197727.047, 431985.375, 0.0000, 5, 1, 14
197658.695, 432196.953, 0.0000, 6, 1, 15
197610.234, 432323.859, 0.0000, 7, 1, 16
197581.203, 432391.383, 0.0000, 8, 1, 17
197559.625, 432439.234, 0.0000, 9, 1, 18
197542.594, 432476.234, 0.0000, 10, 1, 19
197528.668, 432506.070, 0.0000, 11, 1, 20
197515.137, 432535.016, 0.0000, 12, 1, 21
197505.176, 432556.258, 0.6156, 13, 1, 22
197496.215, 432575.305, 0.8334, 14, 1, 23
197485.773, 432597.516, 0.9794, 15, 1, 24
197475.344, 432619.711, 1.0762, 16, 1, 25
197465.578, 432640.484, 1.1305, 17, 1, 26
197456.320, 432660.203, 1.1674, 18, 1, 27
197447.242, 432679.563, 1.2085, 19, 1, 28
197438.004, 432699.258, 1.2506, 20, 1, 29
197428.273, 432720.000, 1.2913, 21, 1, 30
197417.879, 432742.133, 1.3212, 22, 1, 31

```

... continued ...

A.5 report file

D-FAST Morphological Impact will write a report of the analysis. This report file is a simple text file consistent with the earlier reports written by WAQMORF. The length and content of the report vary depending on the availability of the simulation result files and the language selected.

A.6 spatial output file

The WAQMORF program wrote the spatial output in SIMONA BOX-file format which could be visualize when combined with the curvilinear grid of the original simulation. D-FAST Morphological Impact still generates such files when run based on WAQUA results.

D-FAST Morphological Impact generates one UGRID netCDF file containing the spatial results of the analysis. The mesh information is copied from the D-Flow FM map file and the three data fields (erosion and sedimentation patterns for mean, minimum, and maximum impact) follow standardized conventions for data stored at cell centres (*face-values*) on an unstructured mesh. As a result the data may be visualized using a number of visualization tools such as QUICKPLOT and QGIS.



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