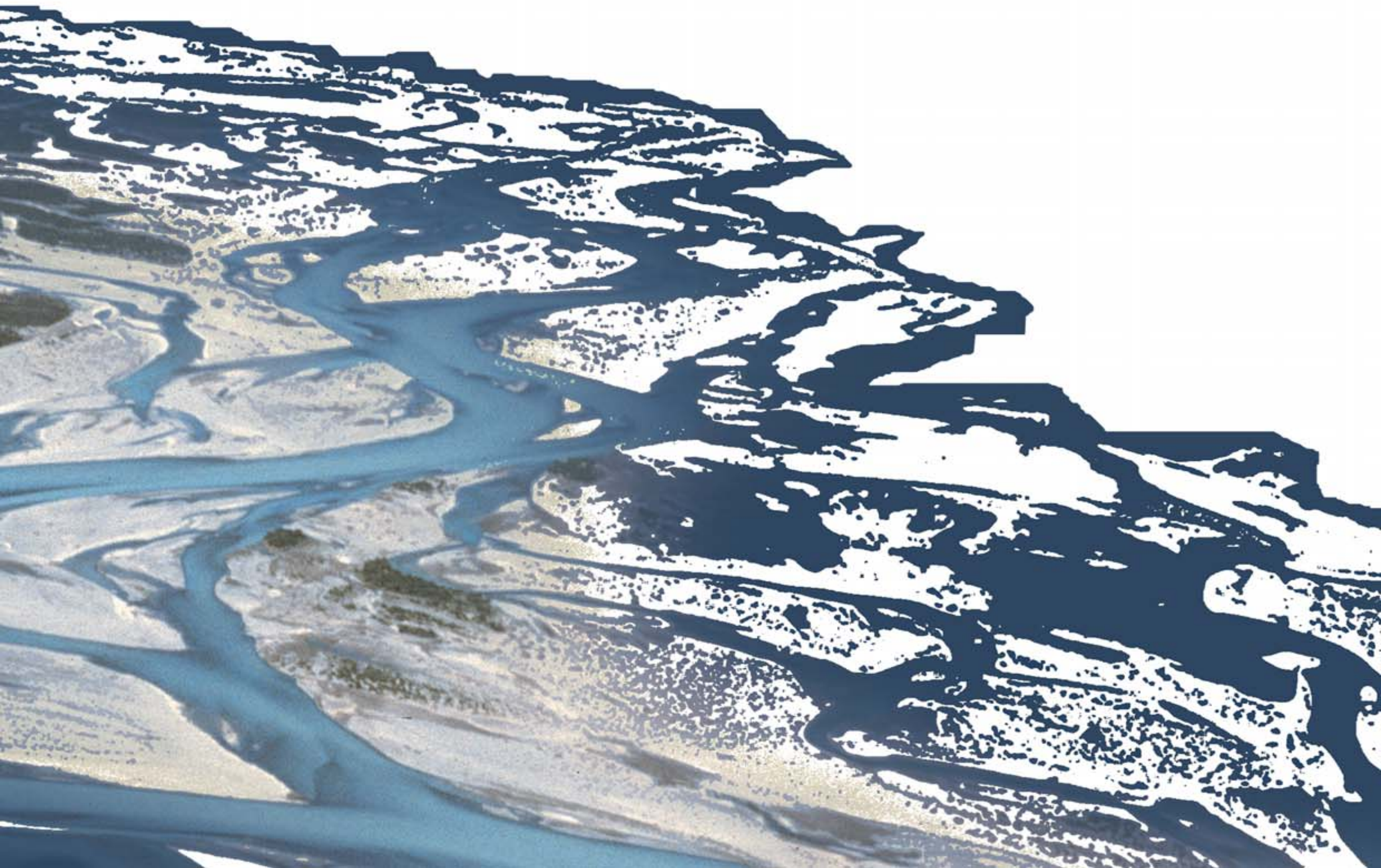
BASEMENT

BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZRAD SIMULATION

SYSTEM MANUALS

VERSION 3.0
September 2019



Preface

Preface to Versions 1.0 – 1.3

The development of computer programs for solving demanding hydraulic or hydrological problems has an almost thirty-year tradition at VAW. Many projects have been carried out with the application of "home-made" numerical codes and were successfully finished. The according software development and its applications were primarily promoted by the individual initiative of scientific associates of VAW and financed by federal instances or the private sector. Most often, the programs were tailored for a specific application and adapted to fulfil costumer needs. Consequently, the software grew in functionality but with little documentation. Due to limited temporal and personal resources to absolve an according project, a single point of knowledge concerning the details of the software was inevitable in most of the cases.

In 2002, the applied numerics group of VAW was invited by the Swiss federal office for water and geology (BWG, nowadays Swiss Federal Office for the Environment FOEN) to offer for participation in the trans-disciplinary "Rhone-Thur" project. With the idea to build up a new software tool based on the knowledge gained by former numerical codes - while eliminating their shortcomings and expanding their functionality - a proposal was submitted. The bidding being successful a partnership in terms of co-financing was established. By the end of 2002, a newly formed team took up the work to build the so-called "BASic EnvironMENT for simulation of environmental flow and natural hazard simulation – BASEMENT".

From the beginning, the objectives for the new project were ambitious: developing a software system from scratch, containing all the experience of many years as well as state-of-the-art numerics with general applicability and providing the ability to simulate sediment transport. Additionally, professional documentation is a must. As to meet all these demands, a part wise reengineering of existing codes (Floris, 2dmb) has been carried out, while merging it with modern and new numerical approaches. From a software-technical point of view, an object-oriented approach has been chosen, with the aim to provide reusability, reliability, robustness, extensibility and maintainability of the software to be developed.

After four years of designing, implementing and testing, the software system BASEMENT has reached a state to go public. The documentation at hand confirms the invested diligence to create a transparent software system of high quality. The software, in terms of an executable computer program, and its documentation are available free of charge. It can be used by anyone who wants to run numerical simulations of rivers and sediment transport – either for training or for commercial purposes.

The further development of the software tends to new approaches for sediment transport simulation, carried out within the scope of scientific studies on one hand side. On the other hand, effectiveness and composite modelling are the goals. On either side, a reliable software system BASEMENT will have to meet expectations of the practical engineer and the scientist at the same time.

Minor

em. Prof. Dr.-Ing. H.-E. Minor
Member of the steering committee of Rhone-Thur Project 2002-2007
Director of VAW, 1998-2008

October, 2006

Preface to Versions 1.4

The work since the first release of the software in October 2006 was exciting and challenging. To go public is paired with interests and demands of users – although user support for the software never was intended. But interchange with users is definitely one of the most crucial factors of successful software development. Feedback from academic or professional users conveys a different point of view and enables the development team to achieve costumer proximity as well as to consolidate experience. Accordingly, the project team tried to meet the demands as effectively as possible. In version 1.3 of BASEMENT, which was released in April 2007, there were some errors fixed, a few new features added and the documentation was completed. Since then, many things have changed: on the personnel, on the project as well as on the software technical level.

In summer 2007 one of our main software developers, Dr. Davood Farshi, left VAW and changed to an international hydraulic consultant. Dr. Farshi supported our team from 2002 to 2007 as a profound numeric specialist and was mainly involved in the development of BASEplane. At his own request, he is still engaged in the development of BASEMENT as external advisor and tester. Dr. Farshi's position in the project team was reoccupied by Christian Volz, an environmental engineer from southern Germany. Mr. Volz has broad experience in numerical modelling as well as object-oriented programming.

On the project level the framework slightly changed. The initial scope within BASEMENT was developed, the "Rhone-Thur" project, has been finalized by the end of 2007. The sequel is called "Integrales Flussgebietsmanagement". It has the same co-financer as its predecessor, namely the Swiss federal office for the environment (FOEN), and basically the same participating institutions (EAWAG, WSL, LCH(EPFL) and VAW(ETHZ)). The funding runs until the end of 2011. Due to the retirement of Prof. Dr.-Ing. H.-E. Minor in summer 2008, our laboratory is solely represented in the project committee by Dr. R. Fäh at the moment.

The emphases of the new proposal for the further development of BASEMENT are advanced topics of hydraulics and sediment transport, such as secondary currents and lateral erosion. Furthermore, the efficiency of the software should be increased by the implementation of appropriate parallelisation and coupling approaches.

Since the last minor release a long time passed, which was mainly consumed by a general revision of the software. After five years of development a diligent consolidation was expedient. In addition, the coincidence of a new team member offered an unbiased reflection of the source code. All in all it was very worthwhile.

Last but not least, there are numerous bugs fixed and some new features in the current version. Mainly the efficiency of the software has been improved. The first stage of parallelisation is completed. The current implementation of the code includes the OpenMP interface which allows for parallel execution of the basic computation loops. In other words, the software is now able to exploit the power of current multi-core processors with a convincing speedup. Furthermore, the revision of some data structures and output routines as well as the application of an optimised compiler led to a reduction in execution time.

Concerning sediment transport, the one-dimensional model BASEchain now supports the modelling of fine material, either as suspended or bed load. Also the advanced models for boundary conditions are worth mentioning. On the one hand, it is now possible to model domain boundaries with momentum and on the other hand, special boundary conditions inside the computational region, such as a weir or a gate, are implemented. The fact, that the version 1.4 of BASEMENT is also available for the Linux operating system the first time, rounds off the new additions and features of the software package at hand.

Summarised one may say that the release 1.4 of BASEMENT is a major release due to all the different kinds of changes, but it's still a minor release concerning the new features – let's call it a "major minor" release. We are looking forward to Version 2.0 of BASEMENT, which is planned for next year.

D. Vetsch
Project Supervisor

October, 2008

Preface to Version 2.0

Four years ago, in spring 2006, the first version of the software system BASEMENT was completed and ready for internal use. In autumn of the same year, the first official version 1.1 of the software was released and made available as free download on the project website www.basement.ethz.ch. Since then, the functionality of the program has been enhanced and the international user community has grown gradually. Over the last years, BASEMENT has become a reliable tool for professional investigations, especially within the scope of flood prevention, and for scientific studies. Furthermore, the software is part and parcel of the lecture “Numerical Models in Hydraulic Engineering” to ensure education of young engineers in the field of hydrodynamic numerical simulation. The lecture is held on a regular basis by VAW staff for master students of civil and environmental engineering at ETH Zurich.

In February 2009, I have become the successor of Prof. em. Dr.-Ing. H.-E. Minor as Director of the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich. In the meantime, I have joined the project committee “Integrales Flussgebietsmanagement”as a further representative of VAW besides Dr. R. Faeh.

Furthermore, there are some changes concerning the personnel of the project team of BASEMENT to mention. Lukas Vonwiller joined the team last autumn after having obtained his master’s degree at ETH Zurich. Within the scope of his master thesis at the VAW, he studied the hydrodynamics and ecological impact of floods at the river Flaz using BASEMENT. Some of his experiences with the application of BASEMENT and selected results are documented in the new tutorial on 2-D simulations in the user manual UIV. His current duties are the application and testing of the software in terms of project work. We were also very lucky being able to engage Dr. Ratko Veprek as a distinguished software engineer for a limited period of time. His contributions to the software, such as flow control of river systems, computational efficiency and the graphical user interface, just to name a few, are of great value. Unfortunately he will leave us by the day of the release to take on a post doctoral position abroad.

According to the announcement in the preface to version 1.4, the second major version of BASEMENT is released with little delay but with all the more important improvements and substantial new features. First of all, the new version 2.0 of the program comes with a graphical user interface (GUI), which allows running or stopping simulations and tracking the progress. Furthermore, the model setup and configuration, i.e. the assembling of the command file, is completely integrated into the GUI. The user is guided through the setup and any input is validated directly. In addition, the integrated help function, which is based on the command file reference, provides detailed information on the meaning of input parameters. This gives way to a clearer model setup compared to the rather fault-prone manual text editing, which is still available and also accessible through the GUI. Another main feature of the new GUI is the editing of the topography for BASEchain. Besides the GUI based setup, interpolation and thinning out of model cross sections, a graphical viewer helps the user to check the configuration and subdivision. For this reason, the new version of BASEMENT comes with its own topography file format for BASEchain. The new format has a clear structure similar to the style of the command file.

Moreover, the visualisation of actual results during a simulation with BASEviz has been improved and is now more interactive, i.e. the simulation can be paused, continued or the variable shown can be switched. Other improvements concern computational efficiency and sediment transport, especially gravitational bed load transport. Please refer to the release notes in the section “introduction and installation” of this manual for further details about new features and bug fixes.

The software system BASEMENT in its current version 2.0 has reached the point to be termed as a state of the art numerical modelling tool for flow and sediment transport in rivers. The incorporated well established or new numerical approaches, software technical features like parallelization or the coupling of sub domains, advanced features for sediment transport and flow control are making it a reliable tool for professional as well as scientific applications. With the new GUI another hurdle has been cleared and a new era of the software in terms of usability has begun. We are looking forward to the further development as well as upcoming releases of BASEMENT and we are curious about how the software will establish itself in the future.

Prof. Dr. R. Boes
Committee Member of Project “Integrales Flussgebietsmanagement”
Director of VAW

May, 2010

Preface to Version 2.8

End of an era

More than 11 years ago, the first official version 1.1 of the software system BASEMENT was released and has been made available as free download on the project website www.basement.ethz.ch. Since then, the functionality of the program has been enhanced and the Swiss as well as the international user community has grown gradually. Over the last years, BASEMENT has become a reliable tool for professional studies, especially within the scope of flood prevention and morphodynamics, and for research at universities. Furthermore, the software is part and parcel of different lectures at ETH Zurich to ensure education of young engineers in the field of hydro- and morphodynamic numerical modelling. The lectures are held on a regular basis by VAW staff for master students of civil and environmental engineering at ETH Zurich.

With version 2.8, an era of BASEMENT development comes to an end. During the last 2 years, the software has been rewritten from scratch to make it more efficient and to allow for using new technologies like general purpose graphics possessing units (GPGPUs). After successful testing of the prototype, version 3.0 is almost ready and will be released in the upcoming months. Therefore version 2.8 will be the last of its kind (i.e. no version 2.9 but maintenance updates and bug fixes will be released as versions 2.8.x). However, version 3.0 will not have all the features of version 2.8 right from the start. Thus version 2.8 remains the working horse for many applications and will be long-term supported.

The current version contains important improvements and substantial new features. First of all, the software environment (i.e. third party libraries) was upgraded to most recent versions and to 64bit to avoid compatibility problems with new hardware and operating system versions such as MS Windows 10 and Ubuntu 18. In doing so, the stability of the GUI on high-DPI devices was improved. Furthermore, a vegetation model was added to BASEplane that affects flow resistance and erodibility related to growth. Several improvements related to morphodynamics were made, e.g. updated and new transport formulae and internal sediment boundary conditions.

We hope to maintain good user experience and wish you effective simulations.

In the name of the project team
Dr. D. Vetsch
Project Director

May, 2018

Preface to Version 3.0

Beginning of a new software era

Computing performance has always been a challenging issue with respect to the development of the BASEMENT software. Since the first official release of the software in 2006, several approaches have been tested and implemented. For instance, parallelization features were included in version 1.4 (2008) using OpenMP, which allowed the use of nowadays common multi-core processors (CPUs). Additionally, the “cycle-step” was released with version 2.2 (2011) for accelerating morphodynamic simulations in particular. All attempts to improve the efficiency of the software were carried out with the requirement to maintain model accuracy and stability - this principle holds to this day.

However, growing complexity due to increasing number of model features led to technical constraints that posed limits to potential performance gain and to the adaption of corresponding software-technical concepts. Especially the progresses in the field of general-purpose computation on graphic processing units (GPGPU), the availability of corresponding hardware at affordable price and the availability of the Oxford Parallel Domain Specific Language OP2 for unstructured meshes, have led to the decision to rewrite the BASEMENT software from scratch. The resulting new major version 3.0 has three main pillars that contribute to improved computing performance: pure first-order finite volume discretization, strong scaling of multi-core CPU simulations and GPGPU acceleration for large computational meshes. This results in four to more than 90 times faster simulations compared to the previous version 2.8.

Version 3.0 comes with a new user interface for model setup and simulation including a workflow with separated tasks that enables customizable simulations. For now, the features of version 3.0 are still limited to 2-D hydro- and morphodynamics and bed-load transport with uniform sediment. The roadmap for further development of the BASEMENT software includes the enhancement of version 3.0 towards the simulation capabilities of version 2.8 and further maintenance of version 2.8 at least for the next five years. In doing so, mixed sediment transport, suspended load transport and the revision of the 1-D model will be implemented with high priority.

The development of the new software would not have been possible without the support of the Swiss Federal Office for the Environment (FOEN) and the backing of the BASEMENT advisory board. The FOEN has been financially supporting the BASEMENT project since 2002, first in the scope of the framework “Hydraulic Engineering and Ecology” and since 2014, as an independent project, which is greatly appreciated.

In the name of the project team
Dr. D. Vetsch, Project Director
Prof. Dr. R. Boes, Director VAW

September, 2019

Preamble

VERSION 3.0.2

March 2020

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See https://www.basement.ethz.ch/people

Commissioned and co-financed by

Swiss Federal Office for the Environment (FOEN)

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Citation Advice

For System Manuals:

Vetsch D., Siviglia A., Bacigaluppi P., Bürgler M., Caponi F., Conde D., Gerke E., Kammerer S., Koch A., Peter S., Vanzo D., Vonwiller L., Weberndorfer M. 2020. System Manuals of BASEMENT, Version 3.0. Laboratory of Hydraulics, Glaciology and Hydrology (VAW). ETH Zurich. Available from https://www.basement.ethz.ch. [date of access].

For Website:

BASEMENT – Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation, 2020. https://www.basement.ethz.ch

For Software:

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BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZRAD SIMULATION

INTRODUCTION & INSTALLATION

VERSION 3.0
September 2019

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1

Summary of Contents

1.1 Introduction

BASEMENT version 3.0 is a freeware simulation tool for hydro- and morphodynamic modelling developed at the Laboratory of Hydraulics, Hydrology and Glaziology (VAW) of the ETH Zurich. The software provides a precise and powerful tool for the simulation of river hydro- and morphodynamics. BASEMENT system manual provides information about BASEMENT version 3.0 and guides the user through the process of using BASMENT version 3.0.

1.2 Content of System Manuals

The documentation is composed of four parts, the Introduction & Installation, the User Manual, the Reference Manual and the Tutorials & Test Cases.

1.2.1 Introduction & Installation

This part aims at introducing BASEMENT version 3.0 to the user by presenting the novelties and changes of the released version. First, the installation procedure is explained for Windows and Linux operating systems. Then, the differences between BASEMENT version 2.x and version 3.x are described in the migration guide for the users already familiars with BASEMENT. The release notes summarize the changes introduced by BASEMENT version 3.0 and the summary of features provides an overview of the available functionalities of BASEMENT version 3.0.

1.2.2 User Manual

The user manual provides information about the simulation environment of BASEMENT version 3.0. The modelling procedure presents the three-stage process, namely the pre-processing, the numerical simulation and post-processing. The numerical simulation is carefully described in the simulation workflow section. The graphical user interface (GUI) provides a user-friendly tool to assist the user during the numerical simulation process.

1.2.3 Reference Manual

The reference manual provides information about the mathematical models and numerical approximations implemented in BASEMENT version 3.0.

1.2.4 Tutorials and Test Cases

This part is composed of three tutorials and two test cases. The tutorials guide the user throught the pre-processing, the numerical simulation and post-processing stages of BASEMENT version 3.0 by taking a section of the river Flaz in Graubünden as example for the numerical simulation. The test cases aim at testing the performance and acuracy of the simulations performed with BASEMENT version 3.0 by standardized test cases, namely the circular dam break and the conical dune.

2

Setup and First Start

2.1 Setup and First Start

2.1.1 System operator requirements

2.1.1.1 Microsoft Windows

BASEMENT version 3.0 has been tested for MS Windows 10. For the latest news concerning new features and current changes, please visit the webpage https://www.basement.ethz.ch.

2.1.1.2 Linux

BASEMENT is available for the following Linux (x86-64) systems:

- Ubuntu 16.04 (LTS), alias “Xenial Xerus”:
  - Kernel version 4.4
  - GNU C Library (glibc) version 2.23
  - VTK-version: 5.10
  - GPU driver version:
    - Kepler architecture and later: at least 418.39
    - Tesla architecture: in [384.111, 385.00) or in [410.72, 411.00)
- Ubuntu 18.04 (LTS), alias “Bionic Beaver”:
  - Kernel version 4.15
  - GNU C Library (glibc) version 2.27
  - VTK-version: 6.3
  - GPU driver version:

  - ∗ Kepler architecture and later: at least 418.39
  - ∗ Tesla architecture: in [384.111, 385.00) or in [410.72, 411.00)

The binaries were compiled and tested on both Linux systems. Binaries without GUI should run on debian-based linux systems.

2.1.1.3 Hardware Configuration

We recommend the following hardware configurations:

2.1.1.3.1 CPU multi-core processors (x86/x86-64)

- Intel (Xeon, 12 to 18 Cores, dual socket)
- 1 GB per core
- Minimum of 2.8 GHz

2.1.1.3.2 Graphical Processing Units (GPUs)

Please note that the GPU-support of BASEMENT version 3.0 is **only** possible for CUDA-enabled (Compute Unified Device Architecture) GPUs produced by NVIDIA. BASEMENT version 3.0 has been specifically tested with GPUs listed in 2.1.

Table 2.1 *GPU hardware used for the numerical simulations*

Card	Tesla K20	Tesla P100	GTX 1080 Ti	GTX 1070 Ti	GTX 1050 Ti	Quadro P620
Memory [GB]	5	12	11	8	4	2
Architecture	Kepler	Pascal	Pascal	Pascal	Pascal	Pascal
Bandwidth[GB/s]	208	549	484	256	112	80
CUDA cores	2496	3584	3584	2432	768	512

2.1.2 Installing under Windows

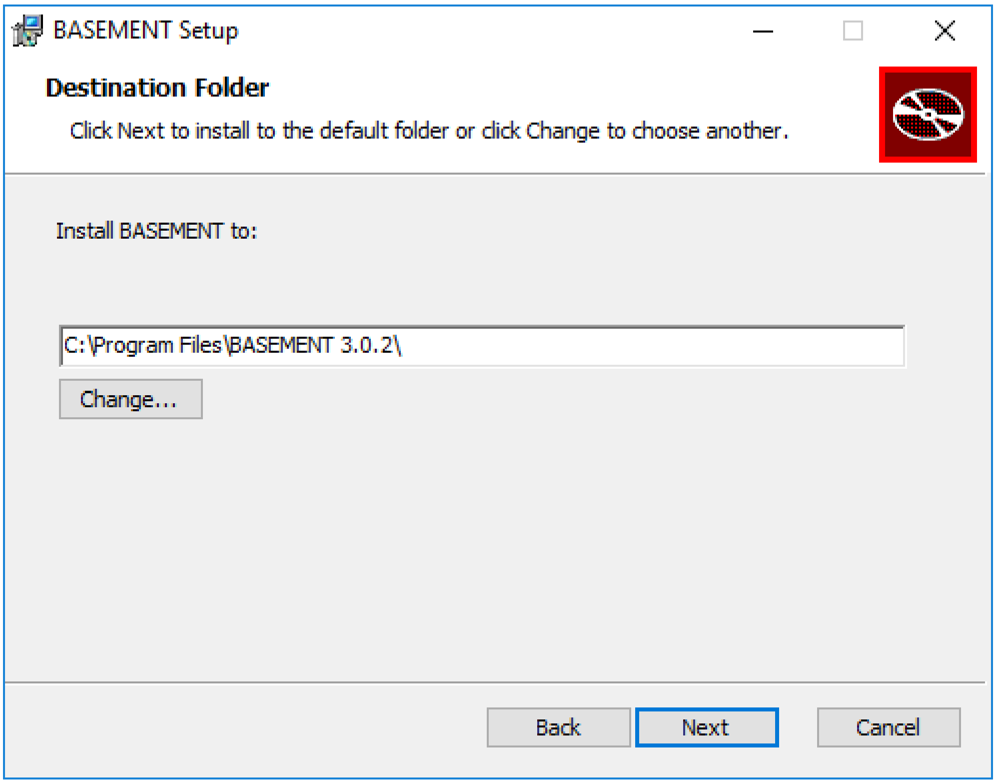
BASEMENT version 3.0 is available for Microsoft Windows Windows 10 operating system.

2.1.2.1 Getting the binaries

First of all, you need to get a copy of the latest software package. Therefore go to the project webpage https://basement.ethz.ch and download the latest version (BASEMENT version 3.x) free of charge.

2.1.2.2 Installation procedure under Windows 10

Please note, that existing installations are not automatically detected by the installer. Therefore, uninstall any previous BASEMENT version before installing a more recent



Destination Folder

Click Next to install to the default folder or click Change to choose another.

Install BASEMENT to:

C:\Program Files\BASEMENT 3.0.2\

Figure 2.1 *Select the installation folder.*

version e.g. using the link in the start menu. After downloading the version 3.x from the project webpage, start the installation by double-clicking on the BASEMENT installer.

Step 1: Accepting the license agreement

Please read the License Agreement carefully and click on the 'I accept' button if you accept the terms and conditions and proceed with the installation.

Step 2: Select the installation folder

After accepting the License agreement, you can choose where to install the binaries. The recommended location is "C:\Program Files\BASEMENT 3.0.2" (Figure 2.1). You are free to choose any other directory.

Step 3 and 4: Confirming and finishing the installation

Clicking 'Install' will start the installation process. After all files are copied, a final window informs about the success of the installation. Click 'Finish' to close the installer.

Step 5: Start BASEMENT

You can start the program by opening the Start Menu, navigating to the Start Menu folder of BASEMENT and clicking on the program icon of BASEMENT version 3.x (Figure 2.2). To create a Desktop shortcut, simply drag the program icon to your Desktop. Clicking on the BASEMENT icon runs the program as a standalone application including a simple graphical user interface (to run BASEMENT in batch mode see the section Run the programm in the User Manual documentation part).

The graphical user interface should appear as in Figure 2.3.

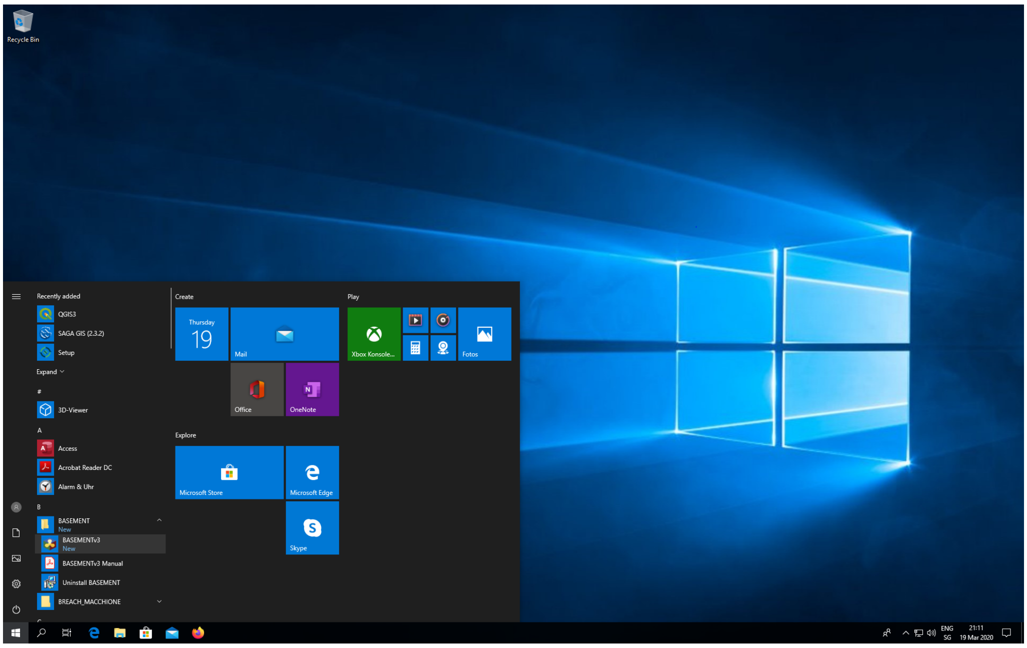


Figure 2.2 *Start BASEMENT over the icon in the Start Menu folder.*

Scenario Directory: Please choose a directory for the configuration and result files.

BASEMENT

BAsic Simulation EnvironMENT
for Computation of Environmental Flow
and Natural Hazard Simulation

Version 3.0.2 / March 2020

(C) 2020 ETH Zurich / Laboratory of hydraulics, hydrology and glaciology (VAW)

www.basement.ethz.ch

Figure 2.3 *The graphical user interface.*

2.1.3 Installing under Linux

2.1.3.1 Getting the binaries

You need to get a copy of the actual distribution as described in the Windows installation section. You can download the most recent version from the projects webpage https://basement.ethz.ch.

2.1.3.2 Installation procedure

Step 1: Preparation of the installation

Extract the downloaded package and change to the directory containing the installation script. Make the installation script executable by running (replace * by the BASEMENT and Ubuntu version number):

```
$ chmod +x BASEMENT_v*_linux64_ubuntu*.sh
```

To run the setup enter

```
$ ./BASEMENT_v*_linux64_ubuntu*.sh
```

and follow the instructions. You have to read and accept the license text.

The BASEMENT Debian package file (*.deb) is extracted.

Step 2: Install the Debian package

Administrative rights are required to install the package using dpkg. Therefore prefix the command with “sudo” (replace *** by the version number):

```
$ sudo dpkg -i BASEMENT-***.deb
```

The Debian package automatically detects if your configuration misses one of the required packages. In such a case you can either use

```
$ sudo apt-get -f install
```

to install all missing packages automatically or, in case you want to install dependencies manually, you can perform

```
$ sudo apt-get install MISSING_PACKAGE
```

to install the missing packages from the repository. Replace MISSING_PACKAGE with the missing package name.

Previous versions of basement are automatically detected by the installer and deleted before the installation starts.

Step 3: Run basement

If the installation of the package was successful, than the executables are copied to

/usr/bin

and the other program files are copied to

/usr/share/basement

You can now run Basement from the console by typing:

```
$ basement
```

Step 4: In case of trouble

Report your issue and get in touch with other users in the BASEMENT forum: https://people.ee.ethz.ch/~basement/forum/

2.2 Running BASEMENT

2.2.1 Windows 10

When running BASEMENT under Microsoft Windows operating system, the easiest way to start a simulation is by clicking on BASEMENT icon. After running, BASEMENT will open the graphical user interface. You have to select the scenario directory that contains all the configuration files and binaries by pressing on the folder icon, where you can load the path to the scenario directory.

The configuration is done in three steps (three .json files) that can be edited using BASEMENT graphical user interface or JSON editors. Each step is executed independently (setup, simulation and results) and the generated files are saved in the scenario directory containing the command and auxiliary files. The procedure to run numerical simulations with BASEMENT using the graphical user interface (GUI) or in batch mode is explained in the User manual.

2.2.2 Linux

BASEMENT runs as a console application without program icon. On Linux, open a console and type:

```
$ basement
```

to start the program (if no environment variables have been set, change into your ‘bin’ directory of the installation path). The GUI starting page is appearing. You have now to select or create the scenario directory in the scenario directory field. The configuration of the .json files (3 steps) is the same as for Microsoft Windows (see Section 2.2.1) and information about the use of the GUI is given in the section ‘BASEMENT Graphical User Interface’ of the User Manual. Selecting the executables and running a simulation on Linux or using batch mode works the same way as it does on Windows explained in the User Manual. *Notice:* **The command filename must not contain any spaces or special characters like ä, ö, ü, è, etc.**

3

Migration Guide Version 2.8 to 3.0

3.1 General

***Table 3.1** List of BASEMENT main features*

	Version 2.8	Version 3.0
1-D model	✓	
2-D model	✓	✓
Hydrodynamics	✓	✓
Morphodynamics:		
- Bed load	✓	✓
- Suspended load	✓	
External sub-domain	✓	
Model coupling (multi domain)	✓	
Controller	✓	
Subsurface flow	✓	
Vegetation	✓	
SMP hardware	✓	✓
GPU/HPC support		✓

3.2 Major Changes from version 2.x to 3.x

3.2.1 Workflow

Table 3.2 *Major changes in workflow*

	Version 2.8	**Version 3.0**
Configuration files	one command file with arbitrary name: *.bmc	three command files with fixed name: model.json, simulation.json and results.json
Data storage	results stored in a specified format	setup and result stored in HDF5 container (.h5)
Rerun	modify *.bmc file and run simulation	modify simulation.json and run simulation
Restart	modify *.bmc and select restart file	modify model.json and select restart file (.h5)
Executables	one executable (basement.exe) for CPU & SMP computing	separate executables for GUI, setup, results and for each simulation backend, e.g. for CPU, SMP and GPU

3.2.2 Input data

3.2.2.1 Mesh features

Table 3.3 *Main changes regarding the computational mesh*

Version 2.8	**Version 3.0**
Triangular and quadrilateral cells	Triangular cells
Dual mesh (cell vertex and cell centered)	Cell centered mesh
Variable bottom elevation over the cell	Constant bottom elevation over the cell
Computational mesh in 2dm format (SMS), including material indices (stringdefs defined separately in *.bmc file)	Computational mesh in 2dm format (SMS), including material indices and stringdefs
Domain differentiation with element_ids	Domain differentiation with regiondef

Table 3.4 *Main changes regarding the grid generation with BASEmesh*

Version 2.8	**Version 3.0**
Single procedure to generate a .2dm file with BASEmesh	Two procedures to generate a .2dm file with BASEmesh according to the mesh resolution
Elevation information stored per mesh node (node z-coordinate)	Elevation information stored per cell
Stringdefs can be saved in separate *.bmc file for further usage	Stringdefs must be included at the end of the 2dm file
Manual editing of mesh in Qgis	Not available
View of the mesh in 3D	View of the mesh in 2D

3.2.2.2 Model setup

Table 3.5 *Main changes regarding model setup*

	Version 2.8	**Version 3.0**
Command file type	run.bmc	model.json
Physical properties	gravity viscosity rho_fluid	gravity - -
Geometry	mesh file stringdef movable bed index_table -	mesh file stringdef - regiondef interpolation

Table 3.6 *Main changes in the* ***hydraulics*** *block of the domain BASEPLANE_2D*

	Version 2.8	**Version 3.0**
Parameters:		
Riemann Solver	exact, HLL and HLLC	HLLC
Fluid density	no (physical properties block)	yes
Max time step	no (timestep block)	yes
CFL	no (timestep block)	yes

	Version 2.8	**Version 3.0**
Dynamic depth solver	water depth from left and right side of the cell edge and from center of the right and left cells	water depth from center of the right and left cells
Safe mode	no	yes
Friction		
Type	Manning Strickler Chezy Yalin Darcy-Weissbach Bezzola	Manning Strickler Chezy - - Bezzola
Wall friction	yes	no
Grain size friction	yes	no
Boundary		
Type	-	**Standard**
	hydrograph	uniform_in uniform_out
	-	**Standard**
	zhydrograph	zhydrograph **Linked** zhydrograph_linked
	zero_gradient	zero_gradient_out
	weir	weir_out_constant, weir_out_dynamic **Linked** weir_linked_constant, weir_linked_dynamic
	gate	-
		Standard
	HQ_relation	hqrelation_out **Linked** 2way_hqrelation_linked, hqrelation_linked
	coupling	-
	wall	-
	-	**Internal**: wall_internal dynamic_wall_internal hqrelation_internal

	Version 2.8	**Version 3.0**
File type	hydrograph, weir, gate, hqrelation	discharge, weir elevation, hqrelation, wse
Boundary inside the computational domain	Inner boundary (weir, gate and hqrelation)	**Internal** boundary: wall, dynamic wall and h-Q relation **Linked** boundary: weir, h-Q relation
Turbulence model	yes	no
External source		
Type	source discharge	total and distributed
Sink behavior	negative source discharge values	exact, available, infinity
Initial		
Type	dry continue index_table	dry continue region_defined
Flood tracking	no	yes

Table 3.7 *Main changes in the* ***morphology*** *block of the domain BASEPLANE_2D*

	Version 2.8	**Version 3.0**
Parameter		
Active layer	yes (control_volume)	no
Porosity	porosity	sediment_porosity
Density	density	sediment_density
Starting time	- (bedload)	morphodynamic_start
morph_cycle	yes	no
morphological factor	no	yes
time scalling	no	with morphological factor

	Version 2.8	**Version 3.0**
Create new layers	yes	no
Grid perturbation (random)	distortion	-
Bedmaterial		
Grain class	Single or multi grain classes	Single grain class
Layer	Multiple layers	Single layer
Fix bed elevation	.2dm mesh or node list	over region (index)
Bedload		
Bedload transport	Simple upwind scheme	Godunov-type upwind scheme
Closure formula	mpm	MPM
	-	MPM-like (adaptable)
	engelundhansen	Engelund and Hansen
	mpmh	-
	power_law	Grass-like (adaptable)
	mpm_multi	-
	wilcockcrowe	-
	ashidamichiue	-
	parker	-
	rickenmann	-
	smartjaeggi	-
	smartjaeggi_multi	-
	wu	-
	vanrijn	-
Boundary		
- Inflow	-	**Standard**
	sediment_discharge	sedimentograph
	-	sedimentograph_warea
	-	sedimentograph_conveyance
	IOUp	equilibrium_in
	transport_capacity	transport_capacity
	-	transport_capacity_warea
	-	transport_capacity_conveyance
- Outflow	IODown	equilibrium_out
Parameters	upwind factor	-
	cell average bedload flux	cell average bedload flux (default)
Direction	lateral_bed_slope	IKEDA
	curvature_effect_static	-

	Version 2.8	**Version 3.0**
	curvature_effect_dynamic	CURVATURE
Inner boundary	yes (weir, open)	no
Incipient motion	angle_of_repose	repose_angle
	local_slope_vanrijn	van_rijn
	local_slope_chen	chen_et_al
Gravitational transport	yes	no
Source		
Type	sediment_discharge	-
	dredge	-

3.2.3 Simulation

Table 3.8 *Main changes regarding simulation parameters*

	Version 2.8	**Version 3.0**
Command file type	run.bmc	simulation.json
Simulation time	start_time	start
	total_run_time	end
	output_time_step	out
	restart_time_step	-
	console_time_step	-
	reference_time	-
Timestep	initial_time_step	init
	minimum_time_step	minimum

	Version 2.8	**Version 3.0**
Simulation outputs	wse	water_surface
	depth	water_depth
	velocity	flow_velocity
	abs_velocity	flow_velocity_abs
	abs_momentum	-
	z_element	bottom_elevation
	z_node	-
	friction	friction_chezy
	deltaz	delta_z
	tau	-
	specific_discharge	spec_discharge
	concentration	-
	susp_load	-
	susp_net_deposition_rate	-
	susp_grain_conc	-
	susp_deltaz	-
	susp_total_pickup	-
	susp_total_deposition	-
	susp_grain_pickup	-
	susp_grain_deposition	-
	theta_critical	-
	grain_size	-
	grain_bedload	-
	bedload_vec	-
	saturation	-
	sediment_sum	-
	-	flow_radius
	-	flow_curvature
	-	flood_tracking
	pore_pressure	-
	-	ns_hyd_discharge
	-	ns_mor_discharge
	external_source_discharge	-
	radius_curvature	-
	radius_curvature_abs	-
	momentum	-
	water_table	-
	biomass	-
	carrying_cap	-
	source_friction	-
	source_wall_friction	-
	source_internal_friction	-
	source_bed	-
	balance_discharge_fluxes	-
	balance_momentum_fluxes	-

3.2.4 Results

Table 3.9 *Main changes regarding the results parameters*

	Version 2.8	**Version 3.0**
Command file type	run.bmc	results.json
Format	ascii, sms, tecplot, shape, vtk	xdmf
Output Type	node_centered	-
	element_centered	element_centered
	BASEviz	-
	node_history	-
	element_history	-
	stringdef_history	nodestring
	edge_history	-
	boundary_history	nodestring
	balance	-
	avs_ucd	-
	sediment_grid	-

3.3 Case example

3.3.1 Description

This section provides helpful hints for the users already familiarised with BASEMENT. For beginners, please have a look at the User Manual and the Tutorials first. The objective of this test case is to illustrate the main changes between BASEMENT version 2.8 (v2.x) and 3.0 (v3.x). A hydraulic simulation of a simple straight trapezoidal channel illustrates the changes and differences between the two versions. The geometry of the channel is specified in Table 3.10.

Table 3.10 *Geometry of trapezoidal channel*

Type	**Value**	**Unit**
Length	500	m
Bed width	20	m
Bank slope	1/3	-
Bank height	4	m
Bank crest width	2	m
Bed slope	0.2	%
Flood plain width	10	m

3.3.2 Computational mesh

The topology of the computational mesh used for BASEMENT v3.x is different than for version 2.x, see Tables 3.3 and 3.4. This section describes the differences between the two

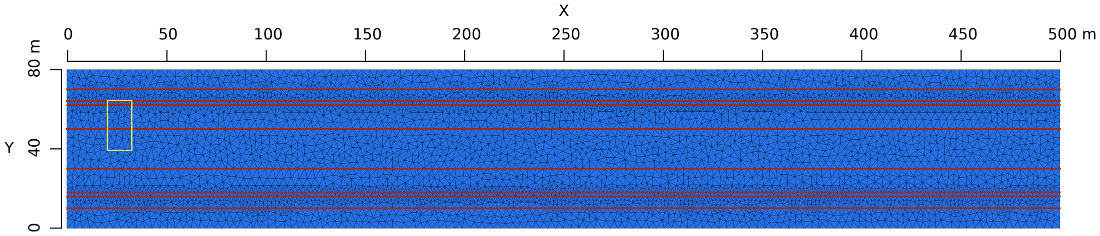


Figure 3.1 *Quality mesh used for the case example with breaklines (red)*

mesh types and provides a guideline on how to import a v2.x mesh into BASEMENT version 3.x.

3.3.2.1 Quality mesh

Table 3.11 *Quality mesh attributes*

Type	Value
Number of cells	9418
Number of vertices	4862
Minimum triangle angle	30
Cell maximum area	10
Number of breaklines	8
Regiondefs	3 (channel bed, banks and floodplains)

The quality mesh contains all the mesh attributes defined by the user, i.e. cell size, breaklines, regiondefs, minimum triangle angle and maximum cell area, but has no elevation information. The quality mesh of the simple straight trapezoidal channel (Figure 3.1) is identical for both versions, v2.x and v3.x and its attributes are listed in Table 3.11. The procedure to generate a quality mesh with QGIS using the BASEmesh plugin is explain in the Tutorial of BASEMENT v2.8 documentation.

3.3.2.2 Computational mesh

The elevation information can be provided by cross sections, height contour lines, raster data or elevation functions. The computational mesh is generated by interpolating the elevation data at specific points of the quality mesh.

The main difference between the computational mesh of BASEMENT version 3.x and version 2.x lies in the process of attributing the elevation information to the mesh cells. A small surface area (yellow rectangle, Figure 3.1) is schematically reproduced on Figure 3.2 in order to illustrate the two approaches used to create the computational mesh.

In BASEMENT version 2.x, the topographic elevation is attributed to the cell vertices (Figure 3.2 a). The quality mesh defines the location on the elevation model at which the elevation information will be assigned to create the computational mesh. It results in a continuous interpolation of the topography between the vertices, displaying a variable elevation over the cell. In contrast, for BASEMENT version 3.x, the elevation information

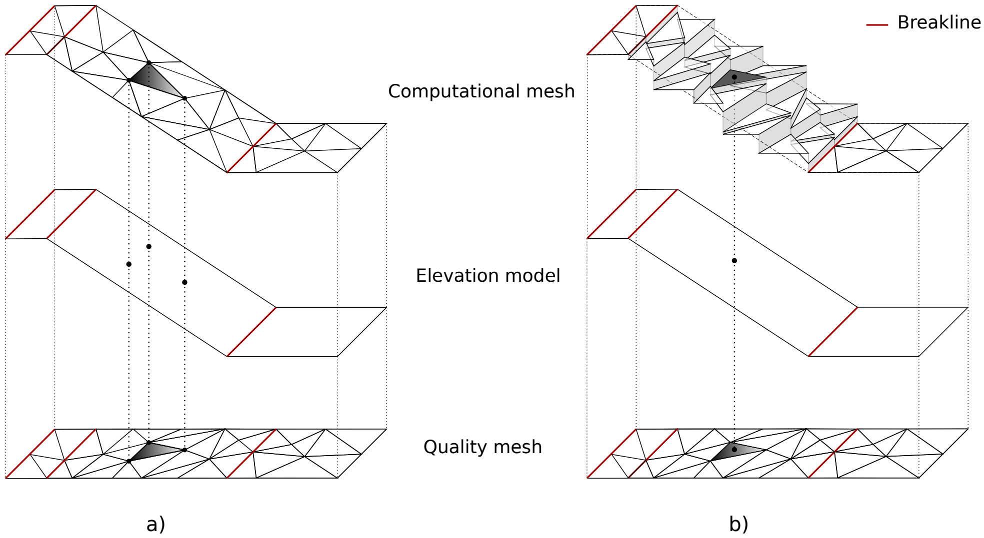


Figure 3.2 *Schematic sketch of the elevation interpolation methods with breaklines (red): a) BASEMENT version 2.x b) BASEMENT version 3.x*

is assigned to the coordinate of the cell center, resulting in a constant elevation over the cell surface (Figure 3.2 b).

Breaklines are used to shape the mesh by separating the domain into specific zones (river bed, banks and floodplains) of similar feature (e.g. friction, cell mesh density,. . .). The edges of cells adjacent to the breakline lie on the breakline. In BASEMENT version 2.x, the elevation information of the breakline is exactly similar to that of the vertices along it, which allows to represent clear changes in slope as for example between the bed and the bank. This is not the case in version 3.x, as the elevation information is not assigned to vertices anymore but to the coordinate of the cell center. Therefore, the definition of breaklines deserves some particular attention in BASEMENT version 3.x, where two or more breaklines need to be defined in order to obtain cells at desired elevation (e.g. the elevation at the bank crest has to be garanteed by two breaklines).

The computational mesh of the trapezoidal channel for the simulation with BASEMENT version 2.x is represented on Figure 3.3 and the computational mesh for the simulation with BASEMENT version 3.x on Figure 3.4. The flow direction is from top to bottom.

3.3.2.3 Import of a 2.x to a compatible 3.x computational mesh

The computational mesh of BASEMENT version 3.x can be obtained using a computational mesh of BASEMENT version 2.x. The import of a 2.x mesh to a mesh compatible with BASEMENT version 3.x consists of defining a unique elevation value to each cell from the elevation information of the 2.x mesh vertices.

First of all, the computational mesh version 2.x has to be composed of triangular elements. The QGIS plugin BASEmesh is used to generate a computational mesh for BASEMENT version 2.x, the tutorial is provided in the Tutorial of BASEMENT v2.8 documentation. The computational mesh is saved in a .2dm file and the stringdefs list is saved in a separate .txt file. In order to use the computational mesh version 2.x for simulations with BASEMENT version 3.x, the .2dm mesh file has to be modified:

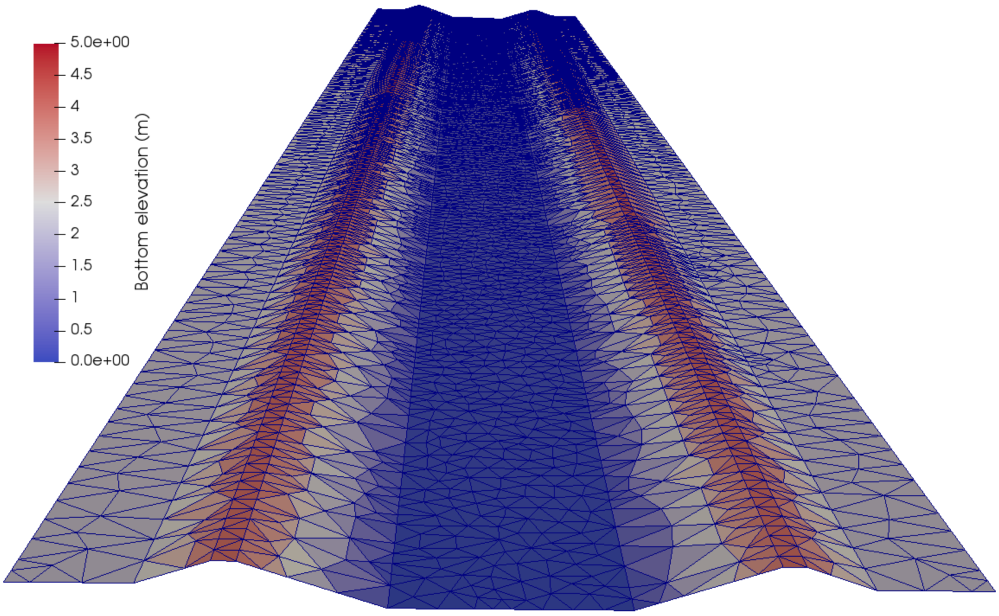


Figure 3.3 *Computational grid BASEMENT version 2.x with breaklines (view from downstream)*

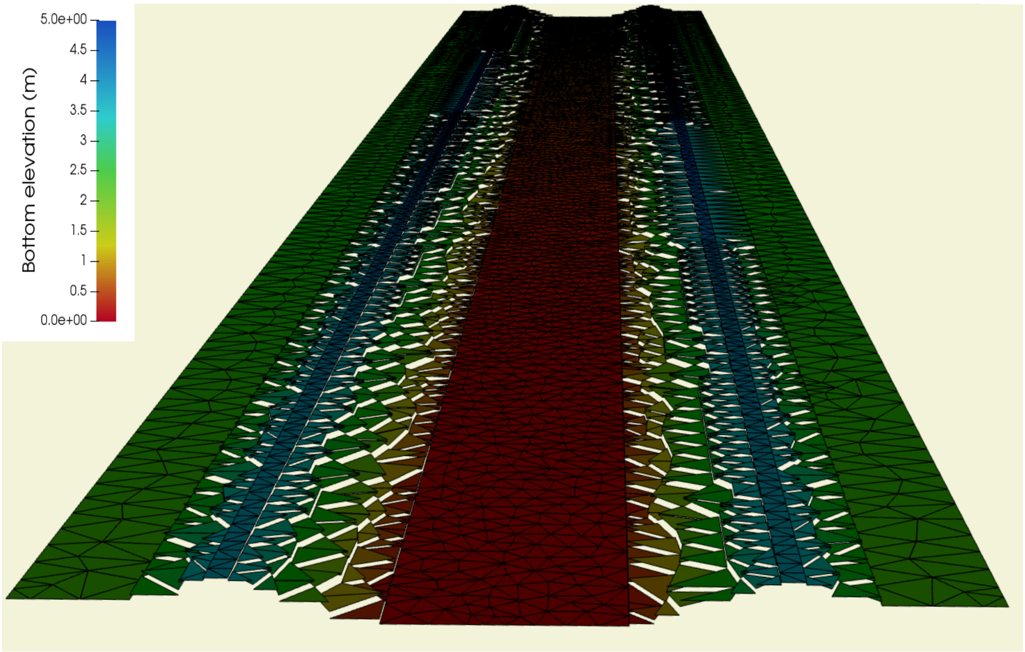
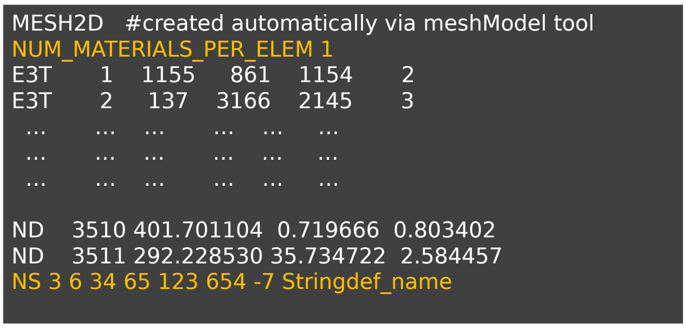


Figure 3.4 *Computational grid BASEMENT version 3.x with breaklines (view from downstream)*



```
MESH2D   #created automatically via meshModel tool
NUM_MATERIALS_PER_ELEM 1
E3T      1   1155    861    1154      2
E3T      2    137   3166   2145      3
  ...       ...   ...       ...   ...     ...
  ...       ...   ...       ...   ...     ...
  ...       ...   ...       ...   ...     ...

ND    3510 401.701104  0.719666  0.803402
ND    3511 292.228530 35.734722  2.584457
NS 3 6 34 65 123 654 -7 Stringdef_name
```

Figure 3.5 *Lines to add manually to the 2dm mesh file (orange)*

1. Add manually the line *NUM_MATERIALS_PER_ELEM 1* after the 1st line of the 2dm file and copy the stringdefs (list of nodes or nodestring) saved in the separate text file to the end of the 2dm file (see example Figure 3.5). The “Stringdef_name” must be replaced accordingly. Please Note: The number of nodes per nodestring is limited to 40. Larger nodestrings must be split up.

2. Inside the model.json file (model setup, see Section 3.3.3), give the name of the modified .2dm mesh file in the GEOMETRY block and choose between the interpolation methods:

- Mean: the average elevation of the three cell vertices is calculated
- Median: the median elevation of the three cell vertices is calculated
- Maximum: the maximum elevation value of the cell vertices is allocated to the cell.
- Minimum: the minimum elevation value of the cell vertices is allocated to the cell.
- Weighted: same as for the mean interpolation method, it calculates the average elevation of the three vertices after applying a weight factor that accounts for the cell geometry (triangle). The mean and weighted interpolation methods give the same results in case of equilateral triangle.

The interpolation method defines how the elevation information stored on the nodes of the computational mesh version 2.x is interpolated in order to generate a computational mesh compatible with BASEMENT version 3.x. The choice of the interpolation method and its relevance in the numerical simulation is let to the user.

The result of the different interpolation methods is displayed in Figure 3.6, where a cross section of the trapezoidal mesh illustrates the local differences between the mesh of BASEMENT version 2.x and the different interpolated meshes used in simulations with BASEMENT v3.x.

Moreover, Figure 3.7 represents the same cross section on the trapezoidal mesh for the same mesh resolution but with only 2 breaklines defined on each side of the bank crest. The change in slope at the levee bottom and crest is less distinct compared to Figure 3.6 and most of the interpolation methods can’t preserve the bank elevation. In the case of a numerical simulation where the exact elevation of the bank is required (e.g. to calculate the bordfull discharge), the definition of breaklines ensures the conservation of the bank elevation, independently from the chosen interpolation methods. Otherwise, the

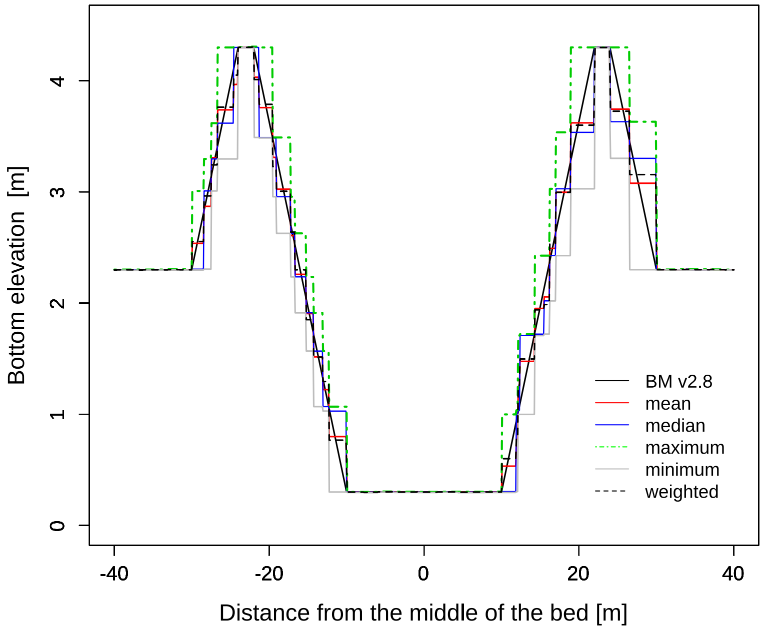


Figure 3.6 *Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at x= 150 m of the trapezoidal channel with breaklines*

interpolation methods “maximum” and “median” can be appropriate in the situation with only one breakline defined at the crest.

The regions delimited by breaklines e.g. the levees or the river bed, can be assigned to different interpolation methods over the computational mesh. Figure 3.8 illustrates the same cross section but for the trapezoidal mesh with a coarser mesh resolution and with breaklines. In this example, the bank side facing the river bed could be defined as “mean” while the other sides (facing the floodplain) could be defined as “maximum”.

3.3.3 Setup and simulation

The simulations were performed for all the interpolation methods using BASEMENT version 3.0. A simple hydraulic simulation starting from dry initial conditions and with a progressive discharge from zero to the bankfull discharge (water depth around 4 m) was running for 20000 seconds. The output data was recorded every 2000 seconds for which the steady state condition was ensured. The Strickler friction type is used with a value of 30. Standard boundaries are used with the inflow boundary of type ‘uniform_in’ and the outflow boundary defined as ‘uniform_out’. The numerical simulation is performed with the HLLC Riemann solver.

Different files are needed to setup the numerical simulation of BASEMENT version 3.0:

- Computational mesh (2dm), including stringdef specification
- Configuration files (model.json, simulation.json and results.json)
- Boundary condition data (.txt)

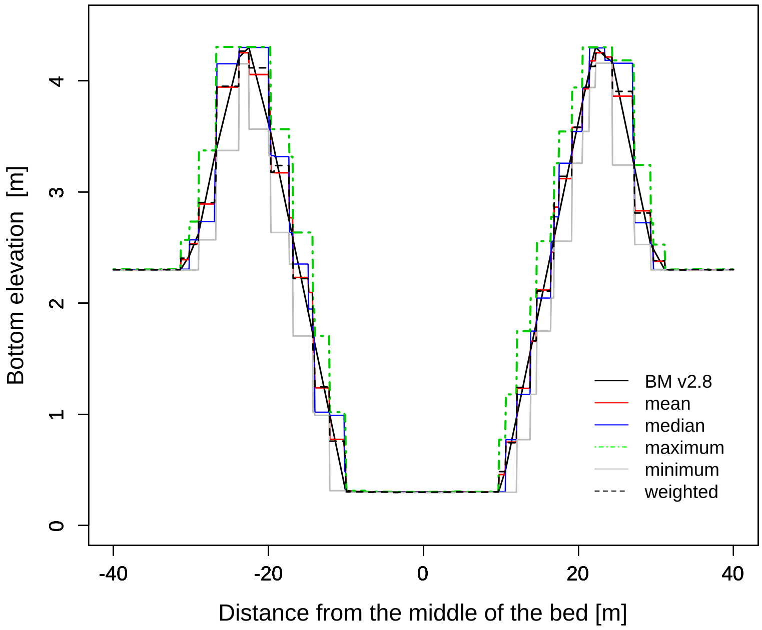


Figure 3.7 *Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at x= 150 m of the trapezoidal channel with only one breakline defined at the bank crest*

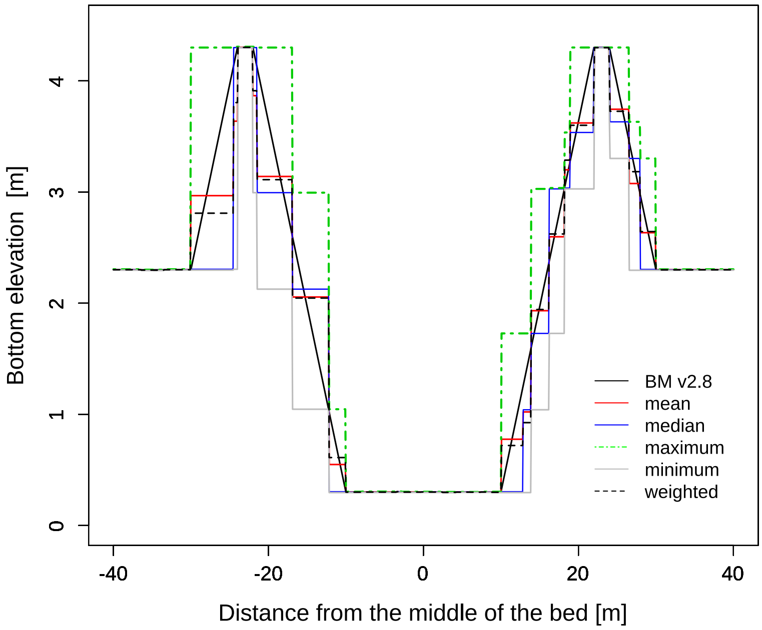


Figure 3.8 *Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at x= 150 m of the trapezoidal channel with breaklines and for a coarser mesh resolution*

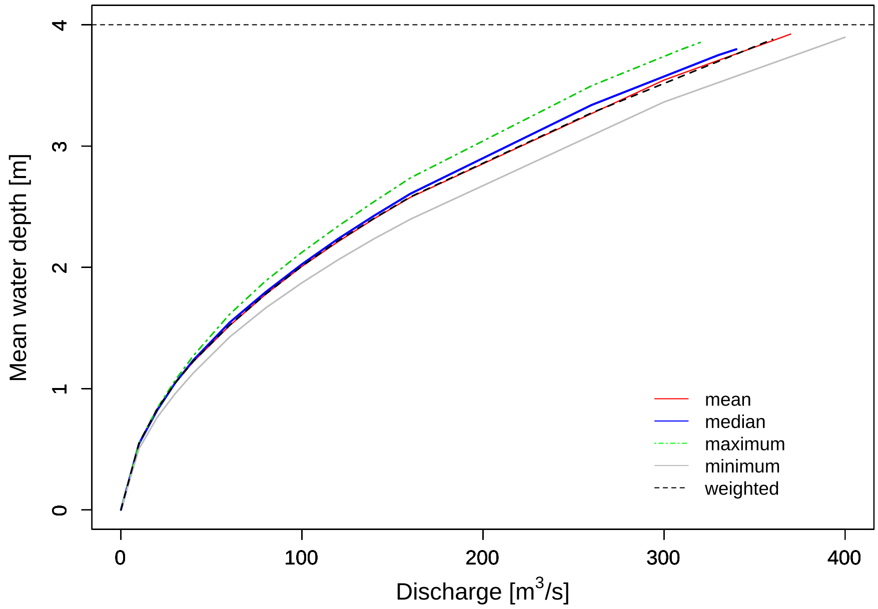


Figure 3.9 *Comparison of H-Q relations between the simulations of BASEMENT v3.0 for different interpolation types on the trapezoidal channel at x = 150 m.*

Three configuration files, model.json, simulation.json and results.json replace the command file (*.bmc) of BASEMENT version 2.x. See the User Manual for more information about their attributes. As decribed in Section 3.3.2.3, the specification of stringsdefs, i.e. the list of nodes is included in the computational mesh (.2dm) in BASEMENT version 3.x.

3.3.4 Results and discussion

In BASEMENT version 3.x, the output data are generated either on cells (cell centered) or at the boundaries (stringdefs). Various results are available (see Table 3.9 and Table 3.8).

3.3.4.1 Hydraulic results

The result of the simulations with BASEMENT version 3.0 for different interpolation methods are compared in a stage discharge rating curve (Figure 3.9). The mesh features are summarized in Tables 3.10 and 3.11.

The bankfull water depth is 4 m and is represented by the dashed horizontal line. The bankfull discharge represents the capacity maximum of the channel before water overflows the channel banks. The smaller channel capacity is reached with the interpolation type “maximum” and the maximum capacity with the interpolation type “minimum”.

3.3.4.2 Boundary conditions

In BASEMENT version 3.0, the inflow data is averaged over the boundary length and the mean value is uniformly distributed over the cell edges. This assumption simplifies the

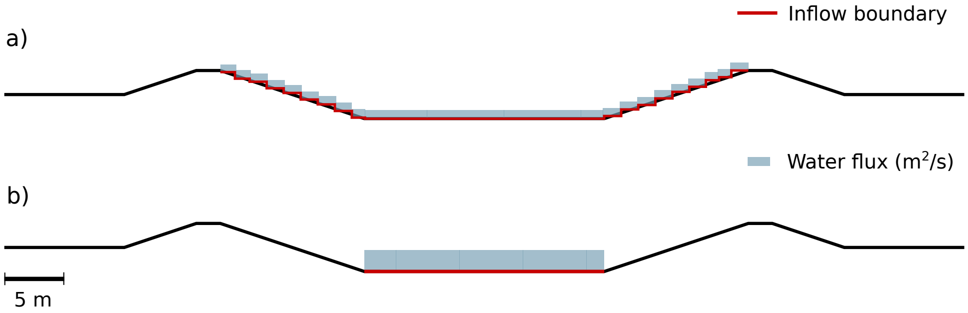


Figure 3.10 *Channel cross section and inflow boundary limit in BASEMENT version 3.0 a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit*

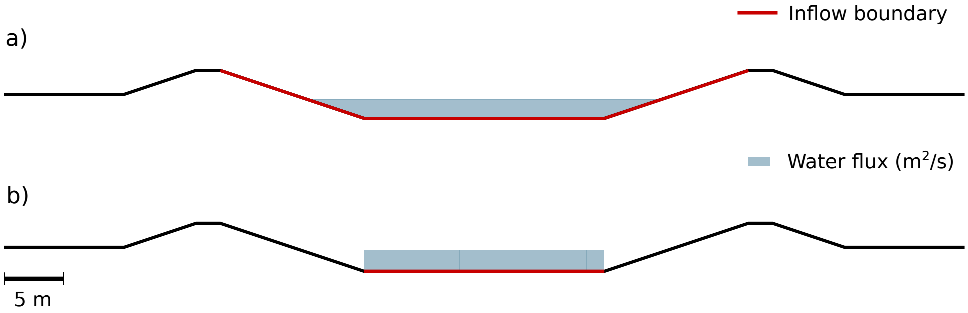


Figure 3.11 *Channel cross section and inflow boundary limit in BASEMENT version 2.8 a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit*

boundary conditions compared to BASEMENT version 2.8. Figure 3.10 and Figure 3.11 show two simplified representation of the averaged discharge value distribution on the element edges of the inflow boundary cross section for BASEMENT version 3.0 and BASEMENT version 2.8 respectively.

An inflow boundary defined between the top elevation of the two levees in BASEMENT version 3.0 (red line in Figure 3.10, a) generates an undesired converging flow from the bank towards the channel center (Q= 60 m^3/s) and small flux towards the floodplains as represented on Figure 3.12 for a discharge value Q= $200m^3/s$. An inflow boundary restricted to the channel bed width (Figure 3.10, b) will locally increase the flow velocity at the inflow boundary as the discharge increases. In this case, stable flow conditions are obtained after a distance of 20-30 meters from the inflow boundary. Figure 3.13 illustrates the location of high flow velocity by an area of low water level. The water depth at boundary conditions (inflow and outflow) depends on the stringdef length, the friction value and the boundary condition type (froude, uniform,. . .).

The boundary conditions in BASEMENT v3.0 are more sensitive to the domain geometry and boundary parameters than those in BASEMENT v2.8, therefore, the resulting values located near the boundary conditions should be interpreted with caution and enough space should be provided to reach stable flow conditions. The stringdef length is limited to a maximum of 50 nodes. In case of large computational mesh with fine resolution, the boundaries shall be split into several smaller stringdef of equal length and consequently, the discharge applied to the boundaries has to be adapted.

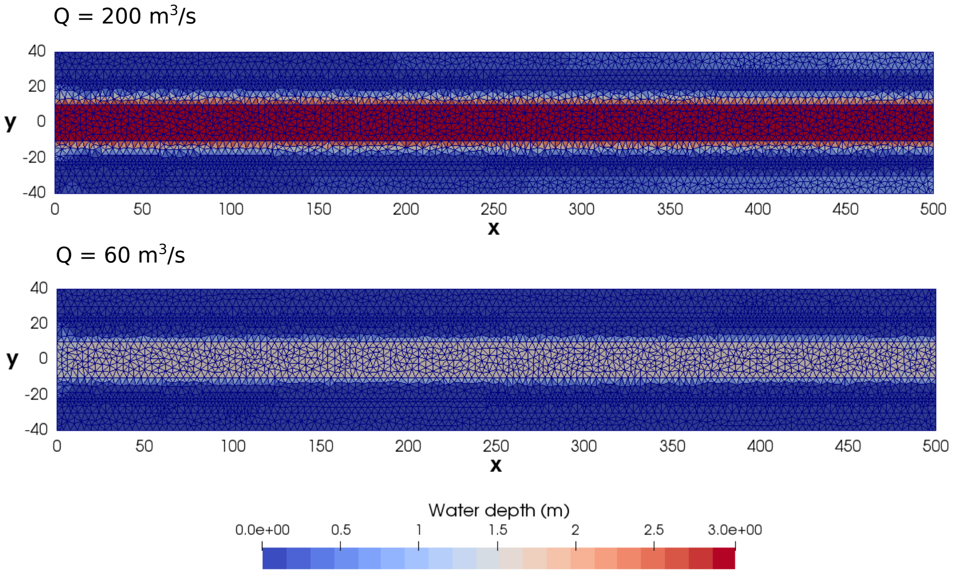


Figure 3.12 *Planar view of the simulation results using BASEMENT v3.0 of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary (x= 0.0 m) defined between the top elevation of the levees (Figure 3.10, a), inducing a converging flow from the levee towards the channel center and small fluxes towards the floodplains for higher discharge Q= 200* m^3/s

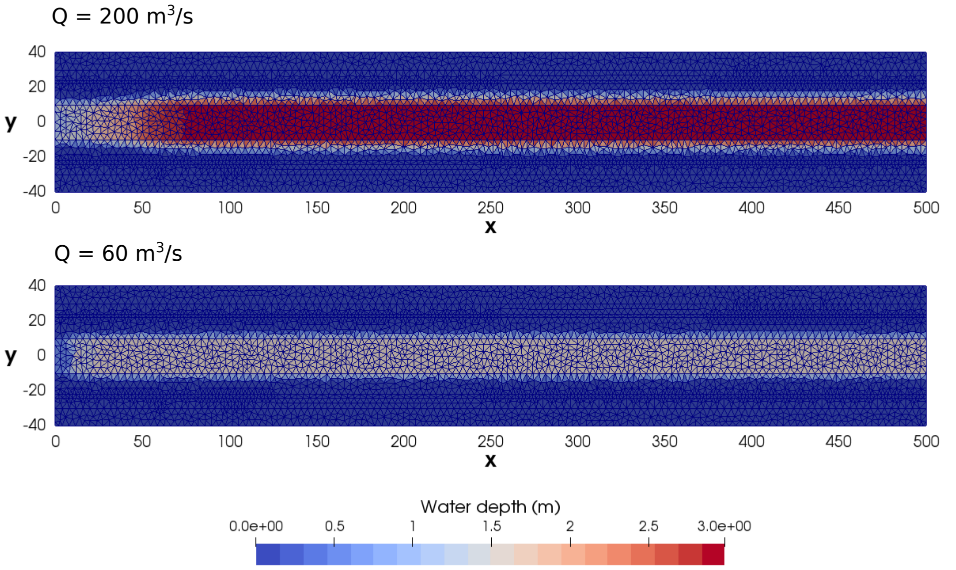


Figure 3.13 *Planar view of the simulation results using BASEMENT v3.0 of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary (x= 0.0m) restricted to the channel bed (Figure 3.10, b), inducing an increase of the flow velocity.*

3.3.4.3 Discussion

This case example of the hydraulic simulation of a trapezoidal channel pointed out the differences between BASEMENT version 2.8 and 3.0 for the topology and the boundary setup. The use of a BASEMENT v2.x mesh into BASEMENT v3.x is possible by interpolation but the simulation results may differ between the two versions due to the new topology. The simulation with BASEMENT v3.x based on the topology of version 2.x must be calibrated and must be considered as a new model. Moreover, the inflow boundary should be carefully defined in order to avoid unexpected flow behaviour at the boundary. Finally, additional breaklines might be required in order to attribute a precise elevation to the edges or to some parts of the mesh.

3.4 Performance

3.4.1 Introduction

The performance of BASEMENT versions 2.8 and 3.0 is assessed by comparing the execution time of simulations based on a common test case. The circular dam break test case is introduced here but explained more in details in the “Test case” section of this documentation. The circular dam break is a hydrodynamic simulation that reproduces the wave propagation induced by the break of a circular dam located at the center of the computational mesh. The reference solution of the circular dam break is given by Toro (2001). The simulation was performed for BASEMENT version 2.8 using a CPU backend on 1, 2, 4, 8 and 12 cores and for BASEMENT version 3.0 using the CPU backend up to 32 cores and different GPU backends on Ubuntu 16.04. The backend types are listed and described in the section “Test case”. Beside of that, five different mesh resolutions were defined for the circular dam break, with 10’000 cells (10k), 50’000 cells (50k), 100’000 cells (100k), 500’000 cells (500k) and 1’000’000 cells (1000k).

3.4.2 Speedup

The execution time of all the simulations is shown on Figure 3.14. The execution time increases with the computational mesh size. The CPU simulations performed with BASEMENT version 3.0 are executed faster than those performed with BASEMENT version 2.8. The execution speed increases even more if the simulations are performed on GPU processors with the best performance reached using sinle GPU processors.

The speedup $S = \frac{T_1}{T_N}$ is calculated as the ratio between serial and parallel execution time for a similar mesh size with T_1, the sequential execution time (Xeon 1) and T_N the execution time of the Nth different backends types.

3.4.3 Scalability

The speedup of the simulations performed with CPU are shown on Figure 3.15 for an increasing number of threads. The black line represents the ideal speedup according to the increasing number of threads.

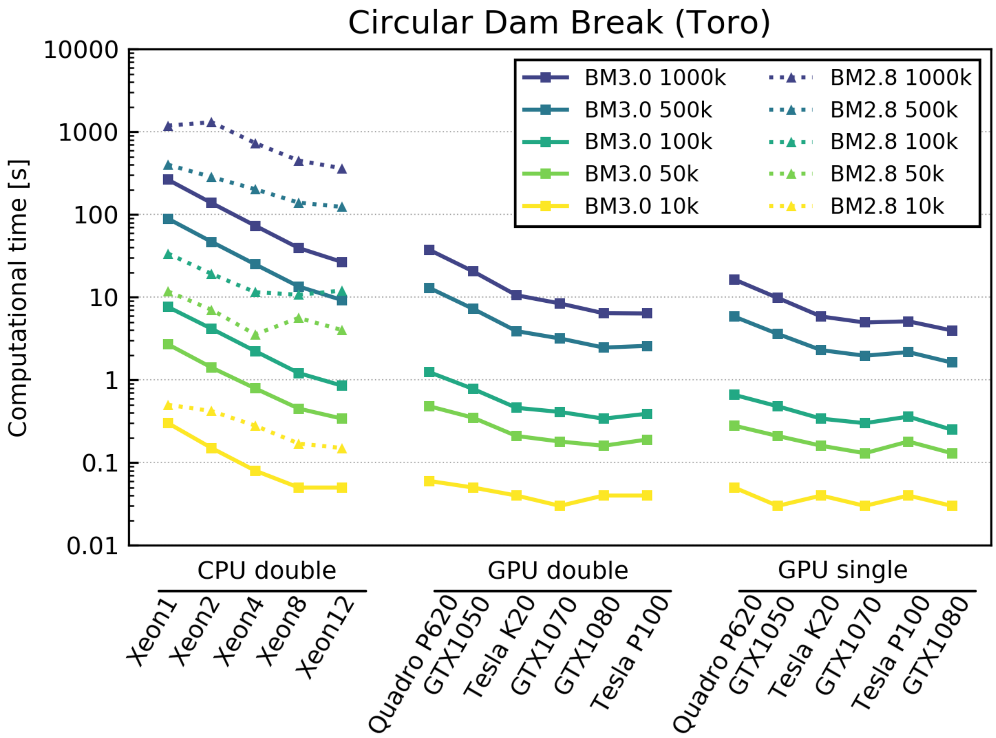


Figure 3.14 *Execution time of the circular dam break test case for different backends and mesh sizes*

The increasing number of threads for simulations performed with BASEMENT version 2.8 does not increase the speedup significally and leads to a maximal speedup (plateau) for small thread number already. The simulations performed with BASEMENT version 3.0 show a significant speedup with increasing number of threads and mesh elements. The speedup is more efficient for large meshes.

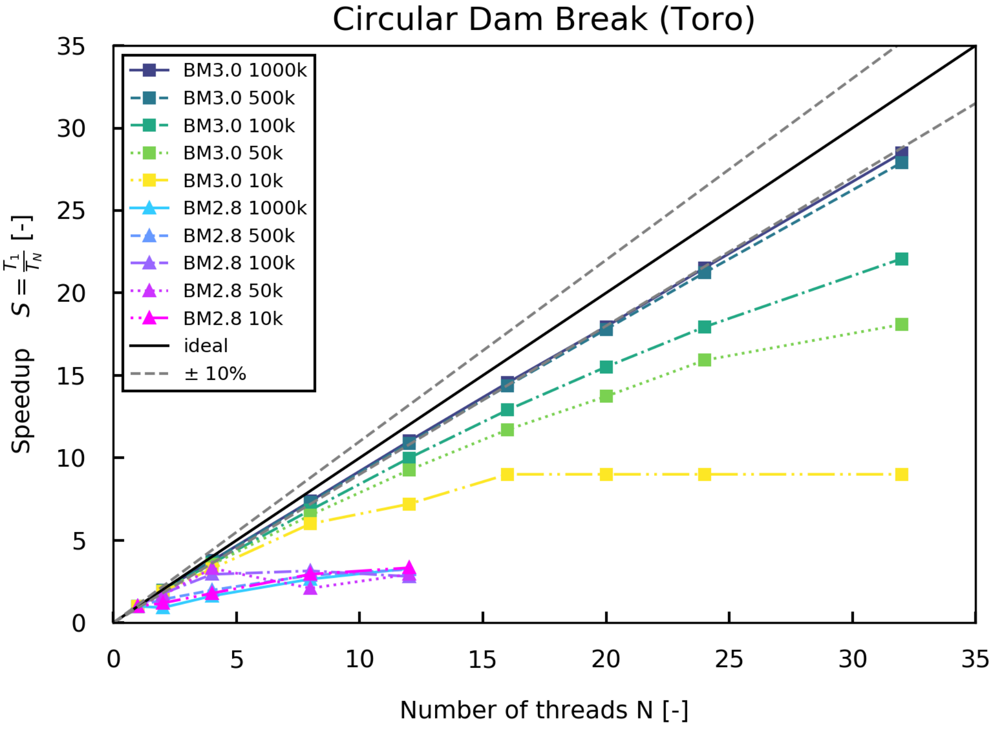


Figure 3.15 *Speedup compared to the sequential time (T_1) of the circular dam break test case performed on CPU for an increasing number of threads and different mesh sizes*

4

Release Notes

4.1 Version 3.0

4.1.1 General

- Supported operating systems: Windows 10, Linux Ubuntu 16.04 and 18.04
- Backend types: CPU, GPU (linux only), OpenMP
- New GUI (Graphic User Interface)
- New simulation workflow: numerical simulation in 3 steps (Setup, Simulation, Results) with separate executables for GUI, setup, results and for each simulation backend, e.g. for CPU, SMP and GPU
- Storage of setup and results files in HDF5 container (*.h5)
- New mesh (element centered, 1st order)
- Same mesh used for hydrodynamics and morphodynamics simulations
- Pre-processing: two procedures to generate a mesh using BASEmesh (QGIS plugin)
- Stringdef list and material indices included in the 2dm file
- json command files
- Restart and rerun
- Results in xdmf format
- The value at boundary condition is averaged over the stringdef length (hydraulics and morphology)

4.1.2 Hydraulics

- Boundary types: Wall (default), Standard, Linked (new) and Internal (new)
- Riemann Solver: HLLC, with hydrostatic reconstruction based on modified states (Duran et al., 2013)

- Sources with sink behaviours: exact, available and infinity
- Flood tracking
- Safe mode parameter

4.1.3 Morphology

- Bedload transport: HLL-type Approximate Riemann Solver (Soares-Frazão and Zech, 2011) with Godunov-type upwind scheme
- MPM-like and GRASS-like bedload formula
- Boundary conditions: Wall (default), Standard
- Geometrical (default), wetter area or conveyance weighting schemes for inflow boundary conditions 'sedimentograph' and 'transport capacity'.
- Fix bed elevation over regions (index)

4.1.4 System manuals

- Complete new manuals (Introduction and Installation, User manual, Reference Manual, Tutorials and Test cases)
- New logo
- Migration guide from version 2.x to 3.x
- Simulation workflow
- Tutorials: Flaz river for the pre-processing, setup of an hydrodynamic and morphologic simulation and post-processing
- Test cases: Circular dam break (hydraulics) and Conical dune (morphology)

4.2 Version 3.0.1

4.2.1 Bug Fixes

- The system manuals are now installed by the installers on Linux and are available in the graphical user interface (GUI).

- Correction of the structure of the file result.json in section “Tutorials and Test Cases” of the system manuals.

- Some Windows registry settings were put at incorrect locations by the Windows installer. In particular, the list of installed software provided by Windows did not include BASEMENT. This problem has been fixed.

4.3 Version 3.0.2

4.3.1 General

- BASEMENT now natively supports CUDA on Windows. This allows the use of CUDA-enabled GPUs for computation under Windows 10.
- In addition, many third party libraries and the installers have been updated. In particular, the version for Microsoft Windows uses a new installer, therefore we recommend to use the link in the start menu to uninstall previous versions of BASEMENTv3 before you update.

4.3.2 Bug Fixes

- Vector data are now loaded correctly in Paraview Versions 5.7.0 and newer.
- The setup binary does not produce an error anymore during restart simulations if the .h5 file extension is provided in the path for the restart.h5 file. The .h5 extension should explicitly be provided in the file name.
- The number of decimal places for doubles in the GUI has been increased from 3 to 6 digits.
- Minor corrections to the System Manual.

4.3.3 Known Issues

- Model setup fails if there is a dot '.' in the working directory path. For example: *"MySimulations/Sim1.1/"* does not work, while *"MySimulations/Sim1_1/"* works.
- Aborting a simulation using Ctrl+C can corrupt the HDF5 result file.
- Currently, there is a known, but not yet resolved issue in the sediment transport solver. More specifically, the flux calculation exhibits an asymmetrical behavior depending on the orientation of the flux vector with respect to the edge normal. Up to now, we have not observed a significant impact of this on the simulation of sediment transport. We will fix this issue as soon as possible and recommend to examine the plausibility of morphodynamic simulation results critically as always.

Note: Existing installations are not automatically detected by the updated installer. Therefore uninstall any previous version of BASEMENT e.g. using the link in the Start Menu before installing the newest version.

5

Summary of Features Version 3.0

5.1 Hydrodynamic features

Riemann Solver

- HLLC, with hydrostatic reconstruction based on modified states (Duran et al., 2013).

Hydraulic Initial Conditions

- Dry
- Continue
- Region defined (regiondef) for water surface elevation or water depth, u and v

Parameters

- CFL
- Minimum water depth
- Fluid density
- Maximum time step

Boundary Conditions

- WALL : inviscid, default
- STANDARD (in parenthesis user-required data):
  - INFLOW: uniform (discharge; slope), froude (discharge, froude number), hq_relation (H-Q relation), zhydrograph (water surface elevation, inflowPossible)

  - OUTFLOW: uniform (slope), zero_gradient (-), weir (weir height, constant or dynamic poleni factor), hq_relation (H-Q relation), dynamic wall (collapse time), zhydrograph (water surface elevation, inflowPossible)
- INTERNAL: dynamic wall (collapse time), internal wall (-), hq_relation (H-Q relation)
- LINKED: hq_relation (H-Q relation), 2 way hq_relation (2 H-Q relations, time lag, water surface elevation upstream and downstream), weir (weir height, constant or dynamic poleni factor), zhydrograph (water surface elevation)

Friction

- Type: implicit Runge-Kutta 2nd order integration
- Closure types:
  - Manning
  - Strickler
  - Chezy
  - Bezzola

All require a default (or index defined) friction value.

Flood

- Flood tracking (tracking time step)

Source (water volume)

- Type: total (as discharge, m3/s), distributed (as rain, mm/h)
- Sink behaviors:
  - Exact (as prescribed)
  - Available (as prescribed or less)
  - Infinity (as much as possible)

5.2 Morphodynamic features

Bedload transport

- HLL-type Approximate Riemann Solver (Soares-Frazão and Zech, 2011)

Parameters

- Morphodynamic start time
- Sediment porosity

- Sediment density

Initial conditions

- Mesh file
- Continue

Incipient motion

- van Rijn (1989) and Chen et al. (2010)
- Angle of repose

Closure formula

- MPM (coefficien = 8, exponent = 15, critical threshold = 0.047)
- MPM-like (coefficient, exponent, critical threshold are adaptable)
- GRASS-like (coefficient, exponent, critical threshold are adaptable)
- Engelund and Hansen

Direction

- Lateral bed slope effect (Ikeda, 1982)
- Curvature effect

Bedload boundary conditions

- WALL: inviscid, default
- STANDARD:
  - INFLOW: equilibrium (reference_bed_elevation), sedimentograph (sediment discharge), transport capacity (boudary factor)
  - OUTFLOW: equilibrium (reference_bed_elevation)
  - Weighting scheme for transport capacity and sedimentograph: geometrical (default), wetted area, conveyance

Bed material

- Grain class
- Fixed bed

6

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BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZRAD SIMULATION

USER MANUAL

VERSION 3.0
September 2019

BASEMENT

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1

Basic Simulation Environment

1.1 Introduction

The software system BASEMENT (BAsic-Simulation-EnvironMENT) provides a functional environment for numerical simulation of river flows with sediment transport in alpine and sub-alpine regions.

The continual development of the software system has lead to BASEMENT version 3.0, a newly developed version motivated by an increase of efficiency, while guaranteeing the stability of the numerical models. Compared to the former versions of BASEMENT, version 3.0 has a simpler spatial discretization and improved performance. In addition, the software provides a new simulation workflow and graphic user interface (GUI).

The development process is at an early stage and focuses primarily on efficient two dimensional flows modelling with bedload transport. Further development of the software system BASEMENT is expected in the future with the implementation of a 1D model and the increase of available features and application domains.

1.2 General Use

1.2.1 Problem Description

In connection with watercourses and river areas, increasingly complex problems have to be addressed. The estimation of floods, the more frequent occurrence of restoration projects or the study of naturally shaped watercourses implicate the examination of larger regions - also outside of the actual waterway - and a more manifold shape of the channels. The simple formulas for the calculation of flow behaviour used in the past showed in several cases to be insufficient to obtain the desired information. The extent of the considered areas makes the application of hydraulic models in a laboratory - usually employed for difficult cases - impossible or too expensive. So, the numerical simulation of flow behaviour is in many cases the most obvious solution. However, existing programs have still some weak points. Some are limited in their capabilities (e.g. only steady flow and no sediment transport) or may lack in user support caused in incompleteness of documentation or training of users. Furthermore, inherent numerical problems request certain expertise to be overcome. In addition, the preparation of the input data and the processing of the results to a shape, which facilitates the interpretation, are often very laborious.

The aim of the software system BASEMENT, in terms of its free availability and its accompanying scholar programs, is to enable a broader range of people to skilfully process river modelling projects in a justifiable amount of time.

1.2.2 Product Delineation and Employment Domains

1.2.2.1 Product Delineation

BASEMENT is a river engineering tool, which supports the engineer in the solution of tasks in the domain of river area modelling. The program permits reliable computations based on state of the art numerical tools, constant onward development and successive realisation of case studies.

Unlike currently used programs for the simulation of a specific flow behaviour, BASEMENT intends the arrangement of many different problem types with one single tool to gain an integrated understanding for the initial position, the solution process and its results.

1.2.2.2 Employment Domains

The aim of BASEMENT is to permit the solution of as many problems as possible in the domain of river engineering, especially in cases for which the traditional dimensioning tools are insufficient and studies including physical hydraulic models are not possible or too expensive. Typical employment domains are:

- Several problems in relation with the sediment transport of water courses, for instance the future development of deltas and alluvial fans, the long term evolution of the bottom of channels, or the aggradation of storage spaces and the consequences of their scavenging;
- River engineering enterprises, which imply the modification of the channel geometry, as this can be the case for example for revitalisations or protection measures, where the consequences of the interventions have to be evaluated;
- Identification and quantification of dangers for the development of danger maps or of protection and emergency measures, considering the flow behaviour and sediment deposition both inside and outside of the main channel, as well as erosion danger, and consequences of debris flows and dam breaks.

1.2.3 Capabilities

BASEMENT has the following fundamental capabilities:

- Simulation of flow behaviour under steady and unsteady conditions in a channel as well as its transition;

- Simulation of sediment transport (bed load) under steady and unsteady conditions in a channel with arbitrary geometry;
- Simulation of erosion and deposition;

2

Modelling procedure

2.1 General

The modelling procedure involves three stages: the pre-processing, the numerical simulation and the post-processing (Figure 2.1). A numerical project is based on a topographical region on which one or more scenarios are studied by running appropriate numerical simulations. Each scenario and all representative parameters with the required type of data should be defined in advance. The pre-processing stage consists of gathering the necessary external data in order to obtain the required input file format for the numerical simulation. The simulation generates output files that can be visualized and modified by external softwares (e.g. ParaView) in order to represent and interpret the results of the numerical simulation. The scenario directory contains all the files (input files, configuration files, output files,. . .) required to execute a numerical simulation with BASEMENT.

This section will present in details the pre- and post-processing parts, while the numerical simulation will be explained in Section 4.

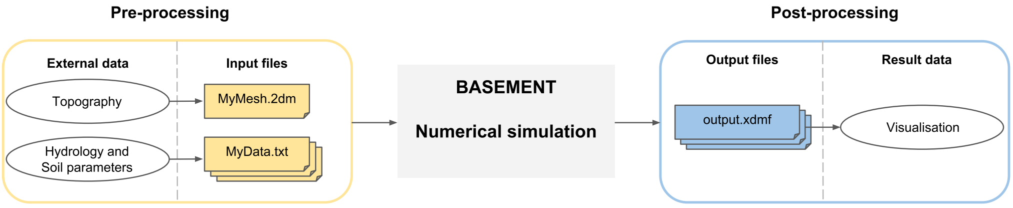


Figure 2.1 *Overview of the modelling procedure with BASEMENT*

2.2 Preprocessing

2.2.1 General

Three main types of external data need to be provided for the numerical simulation: topography, hydrology and sediment data. The pre-processing stage involves the conversion of external data into appropriate input files that are used in the numerical simulation. The topography of the investigated region has to be transformed into a computational mesh. The topographical data types are manifold and may come from a cluster of point with (x,y,z)-coordinates, cross sections, height contour lines or raster data like a digital elevation model (DEM). Beside the computational mesh, hydrological and morphological data have to be determined for the numerical simulation and therefore converted into series data, constant or dynamic value (e.g. weir activation). The hydrology is characterised by inflow discharge, friction, water level or local sources and sink. The soil parameters include the mean grain size, the porosity, sediment density, the roughness, the angle of rest and the sediment flow.

2.2.2 Computational mesh

2.2.2.1 Concept

The numerical methods used in BASEMENT are based on a discretization of the domain topography into unstructured triangular elements. These elements are the control volumes (finite volume of 1st order) for the computation of flow equations and the complex of these elements forms the computational mesh. Once the domain has been discretise into unstructured triangular elements, thus forming a quality mesh, the topographical elevation information has to be assigned to the quality mesh in order to generate the final computational mesh. The elevation information is attributed to the element center and is equally distributed over the element area. An appropriate definition of the element center coordinates is crucial for the generation of the computational mesh. It exists different methods to define the interpolation point coordinates of a triangular element, in BASEMENT, the average of the triangle node coordinates is used. The element edges define the boundary of the control volume and the connection between the neighboring elements.

One single computational mesh is used for hydro- and morphodynamic simulations and has to be of type “MyMesh.2dm” (Figure 2.1). The plugin BASEmesh for the free and open source geographic information system software Quantum GIS (QGIS) provides automated routines for mesh generation in case of a small or large meshes. The breaklines, the definition of boundaries and the generation of the quality mesh are steps of the mesh generation process using BASEmesh.

2.2.2.2 Breaklines

Breaklines affect the quality mesh outcome by preventing the meshing of elements over them during the meshing process. Breaklines enable to delineate the limits of the quality mesh as well as relevant regions like buildings or zones of local mesh refinement. These regions are characterized by marker points (Regiondefs) that allow the user to divide the computational mesh into areas of common features for the numerical simulation, e.g setting different initial friction values or definition of an external source over a specific region of the mesh.

Breaklines are important and should be carefully defined due to the computational mesh specificity of attributing one elevation information to the cell center. The risk encountered is the loss of geometrical accuracy at locations of distinct change of slope (e.g. levee crests or river side walls) or where the cells are required to have a determined and fixed elevation (riverbed, bank crest,...). In order to overcome this issue, areas of fixed or known elevation need to be delimited by breaklines as regions to ensure that the right elevation is assigned to the cell.

2.2.2.3 Boundary conditions

Boundary conditions control the water and sediment flow on the domain. They are defined on the domain as stringdef, i.e. a selected sequence of vertices and element edges of the computational mesh located either at the border or inside the computational mesh. The sequence of vertices along the stringdef gives the stringdef direction with a left and right side. The upstream flow direction is defined by the user during the setup stage of the numerical simulation and has to be set according to the stringdef definition, i.e. direction.

It exists two types of boundary conditions, the external and internal boundaries. The external boundaries are defined on the domain boundary, while the internal boundary is defined inside the domain. More informations about the type of boundaries and their features can be found in the Reference Manual.

The stringdefs are listed as nodestring at the end of the computational mesh file “MyMesh.2dm”.

Please Note: In BASEMENT version 3.x, the number of nodes per nodestring is limited to 40, i.e. larger nodestrings must be split up.

2.2.2.4 Mesh quality

The quality of the mesh is defined by the size and number of mesh elements that compose the computational mesh. Regions of high interest need some mesh refinement to get higher accuracy and regions of lower interest often have a coarser mesh. Two parameters are characterizing the mesh quality: the maximum element area and the minimum element angle.

The maximum element area is assigned to cluster of elements, i.e. specific region surrounded by breaklines and can vary among the zones. The minimum element angle is a parameter defined over the entire mesh. Smaller angles lead to less elements, while larger angles lead to more elements.

2.2.3 Hydrological and sediment data

2.2.3.1 Hydrology

The hydrology of the domain can be specified at boundary conditions in case of water fluxes or over a defined region of the computational mesh if an external source (mass) like rainfall, local source or sink is considered. The water flux can be implemented as discharge (m^3/s), h-q relation or as water surface elevation and the external source can be implemented as discharge or as rainfall precipitation (mm/h).

The type of data can be assigned as a single constant value (lake level, constant discharge,. . .) or as a time series like a hydrograph or series variable (e.g. h-q relation) or as dynamic in case of weir activation or dam collapse. In case of variable water flux (e.g. discharge hydrograph or rating curve), the hydrological data is stored in a time series data file (MyData.txt, see Figure 2.1). The simulation module will then interpolate the desired values to the actual computational time. The source data is either defined as constant or in a time series.

Initial hydraulic conditions can be defined as dry or defined by setting the values of the water surface elevation (wse), the velocity in x direction (u) and y direction (v) over the regions.

2.2.3.2 Sediment transport

The river bed is characterized by a porosity and a mean grain size diameter (m) determined from sediment or line samples. In BASEMENT version 3.0, the simulation works only for uniform sediments.

The sediment flow is defined as a specific bedload flux, which is averaged and evenly distributed over the stringdef length (sediment flow boundary). The sediment boundaries are of type standard (external boundaries). The type of data for the specific bed load flux is either set constant or defined in a time series as sedimentograph $[m^3/s]$ or in a transport capacity formula, without porosity. The reference bed elevation has to be provided at inflow and outflow boundary conditions of type equilibrium.

2.3 Simulation Workflow

The software system BASEMENT encompasses the numerical simulation, composed of numerical subsystems, executables binary files and interfaces to the infrastructural software like the pre- and post-processors. More details concerning the simulation workflow are described in Section 4.

2.4 Postprocessing

2.4.1 Output files

The output are generated on the mesh elements (cell centered) or at nodestrings and are stored in a binary file format (.h5). The output type available are summarized in Table 2.1.

Table 2.1 *Output types*

Cell centered	**Nodestring**
Water surface elevation, water depth, bottom elevation, Chézy friction, delta_z, specific discharge, flow velocity, flow curvature, flow radius, flood tracking	Hydraulic and morphodynamic discharge

2.4.2 Result visualization

The visualization of results is separated from the software system BASEMENT and can be done with independent products using a well-defined common interface. The output are available as an extensible data model format “output.xdmf” (see Figure 2.1) for the cell centered outputs or in a text format (.csv) for the nodestring output. The software ParaView enables to visualize the results stored in “output.xdmf”.

3

Grid Generation with BASEmesh

3.1 General

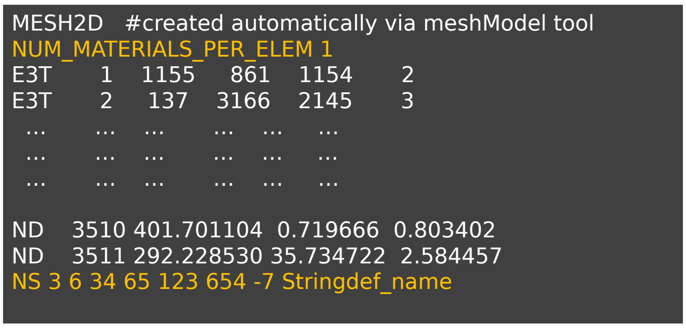
In order to provide a free and open source solution for the creation of computational meshes (Pre-Processing) and to visualize simulation results (Post-Processing) the plugin BASEmesh for the free and open source geographic information system (GIS) software QGIS was developed.

BASEmesh is a QGIS plugin developed to generate triangulated computational grids for BASEMENT based on the advanced mesh generator Triangle by Jonathan R. Shewchuk (Shewchuk, 1996) as meshing algorithm. Currently, there are two versions of BASEmesh available. BASEmesh version 1.4.4 contains all the features including a workflow to generate large meshes for BASEMENT v3.x. This version of BASEmesh is supported up to QGIS version 2.18.28. BASEmesh 1.4.5 contains the same features as version 1.4.4 but is supported and tested for QGIS version 3.10 and newer.

The generation of a computational mesh compatible with BASEMENT version 3.0 is twofold and depends on the domain size and mesh resolution. For small meshes (< 10’000 - 50’000 cells), the procedure to create a computational mesh (2dm) using BASEmesh is the same as for 2D meshes in BASEMENT version 2.8 and the tutorials can be found either in Section 3.3.5 of BASEMENT User Manual version 2.8 or in the Tutorial 1 and 2 of the Pre-Processing section in the Tutorial Manual of version 2.8 available on www.basement.ethz.ch. For larger meshes, the creation of shapefiles during the usual procedure strongly slows down the meshing process. Therefore, the pre-processing for large meshes follows the a new procedure, which avoids the shapefiles generation of of the quality mesh.

3.2 Installation

BASEmesh is at present available on a specific Plugin repository which has to be connected manually in the QGIS plugin manager. In contrast to other plugins, it is not available via the official QGIS plugin repository which is set as default in every QGIS installation.



```
MESH2D   #created automatically via meshModel tool
NUM_MATERIALS_PER_ELEM 1
E3T      1    1155    861    1154     2
E3T      2     137   3166    2145     3
 ...     ...  ...     ...  ...    ...
 ...     ...  ...     ...  ...    ...
 ...     ...  ...     ...  ...    ...

ND    3510 401.701104  0.719666  0.803402
ND    3511 292.228530 35.734722  2.584457
NS 3 6 34 65 123 654 -7 Stringdef_name
```

Figure 3.1 *Lines to add manually to the 2dm mesh file (orange)*

To install BASEmesh, follow these steps:

(1) Start QGIS

(2) Load the QGIS plugin manager by choosing *Manage and Install Plugins...* in the menu *Plugins* in the QGIS main toolbar

(3) Go to *Settings* (you should now see the connection to the official QGIS-plugin repository)

(4) Click on *Add...* and give a name, e.g. ‘BASEmesh repository’

(5) Enter the repository address: https://people.ee.ethz.ch/~basement/qgis_plugins/qgis_plugins.xml (do not copy paste this address, because it might include line breaks)

(6) Press *OK*

(7) The additional repository should now be visible (make sure that the *Status* is *connected*)

(8) Go to *All* in the menu of the plugin manager and search for ‘BASEmesh’

(9) Choose the BASEmesh plugin (if several are available, choose the one with the highest version number) and press *Install plugin*

3.3 Generation of small meshes

This section illustrates how a small computational mesh (<10’000-50’000 cells) can be generated for simulations in BASEMENT v3.0. The computational mesh is generated using the QGIS plugin BASEmesh in the exact same way as for BASEMENT version 2.8. The mesh generation process is described in detail in Section 3.3.5 of BASEMENT User Manual version 2.8 or in the Tutorial 1 and 2 of the Pre-Processing section in the Tutorial Manual of version 2.8 available on www.basement.ethz.ch. The computational mesh with the elevation information located at the mesh vertices is exported as a 2dm file and a separate stringdefs list is generated during this process. In order to use the 2dm file for simulations with BASEMENT v3.0, the stringdefs list and name have to be added manually at the end of the computational mesh (2dm) and saved under a new name (Figure 3.1). The modified 2dm file is the one used in simulation with BASEMENT v3.0.

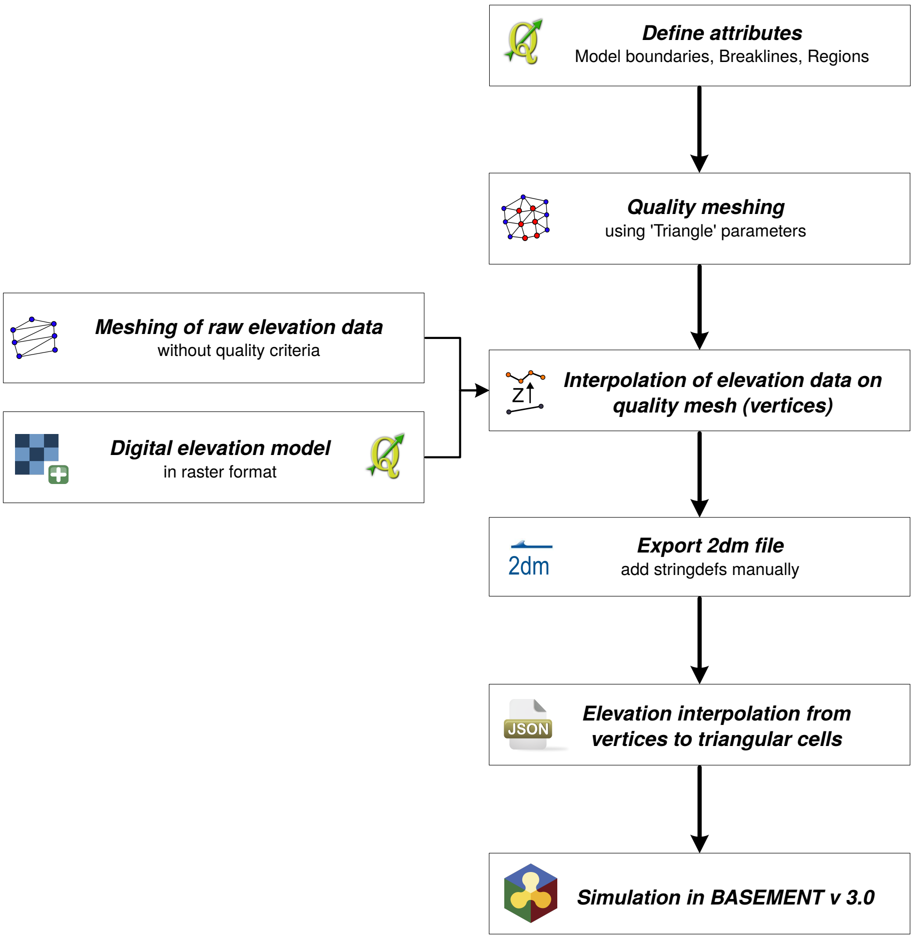
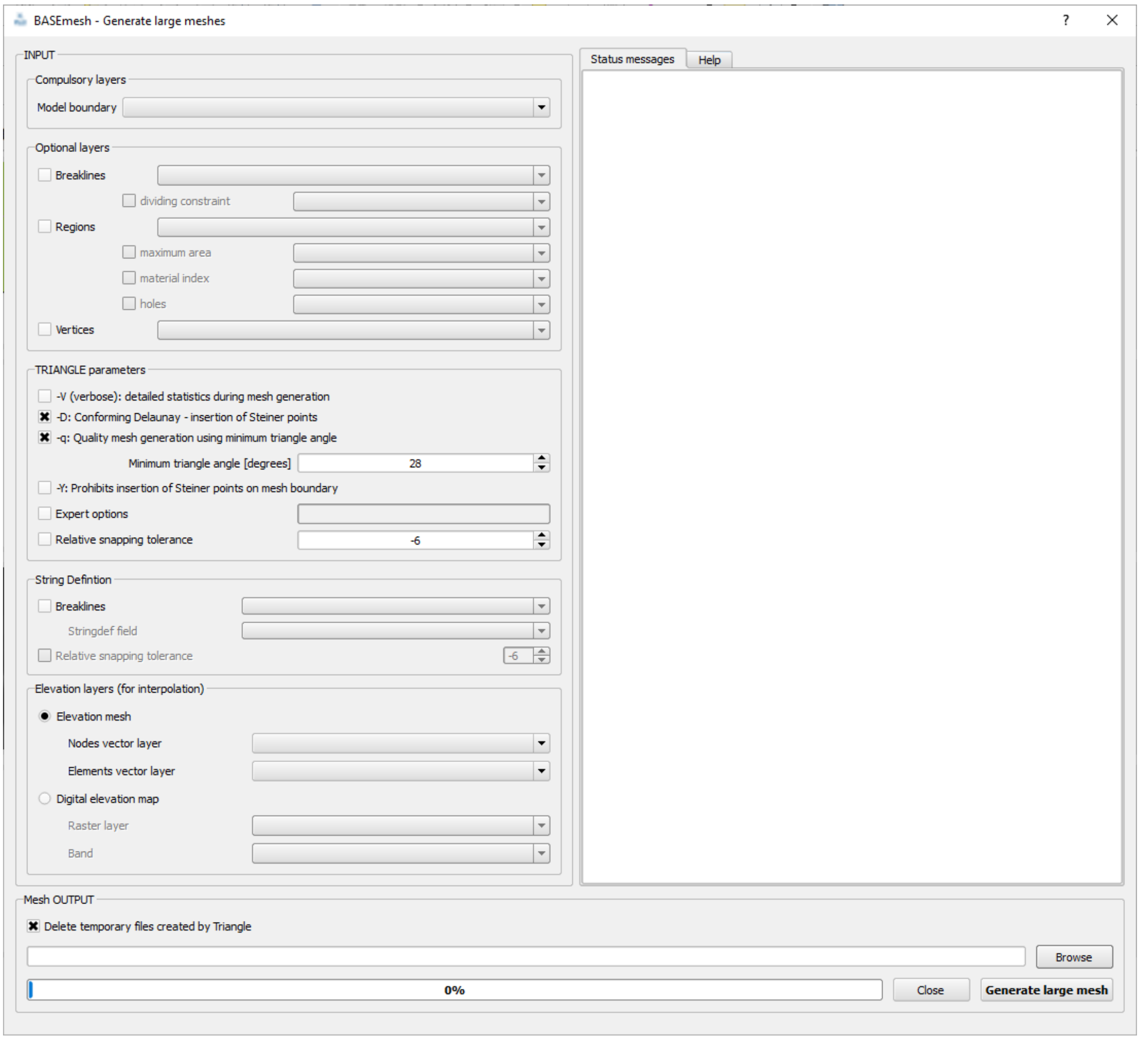


Figure 3.2 *BASEmesh workflow for small meshes and adaptations required in the 2dm and executable (.json) files for the simulation with BASEMENT v3.0*

The elevation information is saved on the mesh vertices and needs to be interpolated to obtain one uniformly distributed elevation information allocated to the corresponding cell. The interpolation method (mean, median, maximum, minimum or weighted) is selected inside the GEOMETRY block of the configuration file model.json.

```
"GEOMETRY": {
    "mesh_file": "Flaz_mesh.2dm",
    "INTERPOLATION": {
        "method": "weighted"
    }
```

More details concerning the elevation interpolation methods are given in the case example of the Migration Guide. Figure 3.2 shows the BASEmesh workflow for small meshes with the transformations required for numerical simulations with BASEMENT v3.0. The procedure for small meshes enables to use existing computational meshes of BASEMENT version 2.x (.2dm) into BASEMENT version 3.x following the two last steps of Figure 3.2.



Model boundary

☐ Breaklines

☐ dividing constraint

☐ Regions

☐ maximum area

☐ material index

☐ holes

☐ Vertices

☐ -V (verbose): detailed statistics during mesh generation

☒ -D: Conforming Delaunay - insertion of Steiner points

☒ -q: Quality mesh generation using minimum triangle angle

Minimum triangle angle [degrees] 28

☐ -Y: Prohibits insertion of Steiner points on mesh boundary

☐ Expert options

☐ Relative snapping tolerance -6

☐ Breaklines

Stringdef field

☐ Relative snapping tolerance -6

● Elevation mesh

Nodes vector layer

Elements vector layer

○ Digital elevation map

Raster layer

Band

☒ Delete temporary files created by Triangle

Figure 3.3 The generation of large meshes can be done with the new procedure in BASEmesh 1.44.

3.4 Generation of large meshes

During the quality meshing process, the BASEmesh plugin generates shape files that are significantly slowing down the procedure in case of large meshes. Therefore, a new procedure was developed to generate large computational meshes, which skips the generation of shape files. This new procedure for large mesh is available in BASEmesh versions 1.4.4 (up to QGIS version 2.18.28) and 1.4.5 (from QGIS version 3.10 and newer) under the button "XL Mesh" and combines the steps of quality meshing, elevation interpolation, nodestring definition and mesh export. The graphical user interface of the "XL Mesh" procedure is illustrated in Figure 3.3. The resulting meshes are directly compatible with BASEMENT version 3.x.

The general procedure to obtain the .2dm mesh file remains mostly the same. Be aware that all the attributes (elevation data, breaklines, points defining the regions, stringdefs,. . .) should be defined before starting the large mesh generation.

The computational mesh is generated with Jonathan Richard Shewchuk's excellent unstructured 2D-mesh generator TRIANGLE (Shewchuk, 1996) and requires the specification of all geometric information about the computational domain:

- *Model boundary*: extent of the computational domain.
- *Breaklines*: distinct interruptions of the surface slope (dyke crest, river side walls, . . .) which shall be preserved in the computational mesh.
- *Regions*: distinct regions of the mesh surrounded by breaklines, which can be characterized by a material index (matID) and maximum triangle area, or can be specified as a hole in the mesh.
- *Holes*: parts within the mesh which are excluded from modelling (e.g. buildings). These parts are defined by special points (layer region_points) surrounded by breaklines.
- *Vertices*: enforced geometric points in the mesh (e.g. measurement points).

Further, the mesh quality can be influenced by the "TRIANGLE parameters". It is important to keep in mind, that the quality of the computational mesh influences the results of your numerical analysis, e.g. stability, computation time, accuracy, etc. Parameters of major importance are:

- *Maximum area* constraints: definition of the mesh density using *maximum area* contraints for the triangular mesh elements. The *maximum area* is defined as attribut in the layer region_points and holds for a specific *Region* surrounded by breaklines.
- *Dividing constraints*: With this attribut in the layer *Breaklines* one can enforce a certain number of mesh elements along a breakline. This is of major importance for the use of inner boundaries in BASEMENT, where an equal number of mesh elements at the uptream and downstream interface is required.
- *Minimum triangle angle*: no elements with angles smaller than the minimum angle specified are generated (smaller angles lead to less elements, while larger angles lead to more elements).
- *Relative snapping tolerance*: defines, how far two point coordinates may be located apart to still be considered at the same location. The default value is 10E-6. Increasing this tolerance can help to avoid problems due to improper snapping of vertices (line or polygon features) and points in OGIS.

In BASEMENT a list of node IDs is defined as *stringdef* or *nodestring.* They can be defined on the basis of breaklines with a *stringdef* attribute and can be used to define a boundary condition or an output along these nodes. The IDs correspond to the node IDs of the computational mesh. In comparison to the Stringdef tool, the defined stringdefs are added at the end of the .2dm mesh file with the tag "NS" for Nodestring and are **not** written in a separate file. Please Note: In BASEMENT version 3.x, the number of nodes per nodestring is limited to 40, i.e. larger nodestrings must be split up.

Finally, topographical information contained in the elevation model be be interpolated on the computational mesh, i.e. an elevation value is assigned to each node of the computational grid. As a result, the final computational mesh is obtained, which is then exported and can be used for simulations. The elevation data serving as input can be provided in two different elevation model types:

1. *Elevation mesh* triangulated from pointwise elevation data (TIN). The routine identifies the coordinates of each quality mesh node and determines any underlying elevation mesh element. Two methods are used for data interpolation:

   a) If an underlying elevation mesh element is found, the elevation of the quality mesh node is interpolated at its x-y-coordinates. This is the normal case, since the elevation mesh usually covers the whole computational domain. Nodes interpolated with this method are marked by a 1 in the element - field of the node attribute table. If the quality mesh node is located at the exact coordinates of an elevation mesh node, its height value is preserved exactly.

   b) If no underlying elevation mesh element is found, the quality node elevation is set to that of the nearest node of the elevation mesh. This is the case if quality mesh nodes lie outside the domain covered by the elevation mesh or when holes are present in the elevation mesh. It may lead to incorrect quality mesh ndoe elevations. Hence, it is recommended to choose a bigger domain for elevation meshing than for quality meshing. Nodes interpolated this way are marked by a 0 in the element - field of the result attribute table and are named ‘with special treatment’ in the QGIS status messages.

2. *Digital elevation map* as raster data which contains the topography as DTM. The raster elevation data is directly mapped on the computational mesh nodes without interpolation. If no corresponding raster cell is found, the elevation is set to ‘-9999’.

Be aware that the interpolation process can be time consuming.

The mesh is automatically exported in the .2dm format in the specified directory. During the meshing process temporary files are generated. These can be automatically deleted by checking the box “Delete temprary files created by Triangle”.

4

Simulation workflow

4.1 General

The simulation workflow of the software system BASEMENT (light grey rectangular background on Figure 4.1) is composed of three parts: the pre-simulation, the simulation and the post-simulation. Each part contains an executable (red rectangles) and a command file (.json). The command files are in standardized file format of type JavaScript Object Notation (.json) with an independent language and syntaxe. Binary files (green cylinders) of HDF5 type (Hierarchical Data Format version 5, www.hdfgroup.org) work like containers that can store large amount of data and thus allow the division of the numerical simulation in three parts. The input and output data files are located outside of the simulation environment (Figure 4.1).

The pre-simulation consists on setting up the model for the simulation. The hydro- and morphodynamic parameters are defined inside the command file model.json. The setup executable combines the computational mesh (MyMesh.2dm), external required data (MyData.txt) and the command file (model.json), validates the model and stores it inside the binary setup.h5.

The simulation part runs the simulation on a selected backend type. It combines the

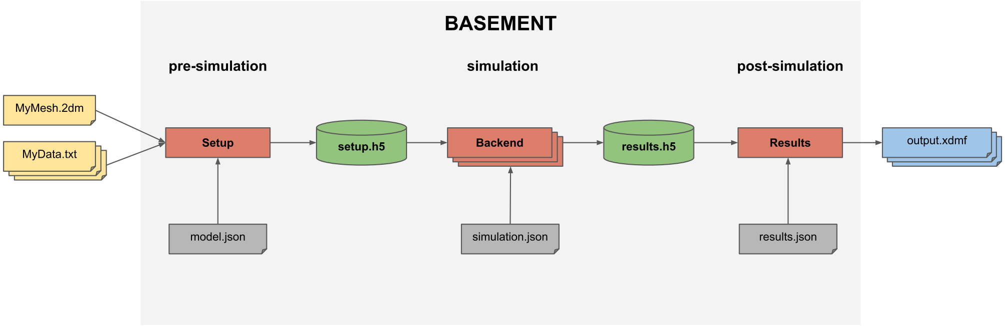


Figure 4.1 *BASEMENT simulation workflow*

model (setup.h5) stored in the first container with the command file simulation.json, where the simulation parameters are defined (e.g. execution time, output). The results of the simulation are stored in the second container (results.h5).

The post-simulation part transforms the simulation result file into output data that can be processed by the user. The type of output format (e.g xdmf) is specified inside the command file results.json. The post-simulation process is based on python scripts.

4.2 Pre-simulation

4.2.1 Command files

The first command file model.json defines the parameters required to run a numerical simulation on the generated computational mesh. The domain is available for 2D-simulations only and comprises two main components, the geometry and hydraulics blocks. The morphology block is also available and can be added for simulations with bed load transport.

The geometry block gives information on the computational mesh used for the 2D-simulation. The name of the computational mesh and its location in the folder have to be specified. If a computational mesh of BASEMENT version 2.x is used, the elevation interpolation method has to be defined. The stringdefs are listed by their name and the upstream flow direction should be indicated as either left or right (see the Numerical Approximation section in the Reference Manual). The regiondefs are also listed by name with the area index as parameter.

The hydraulics block contains the information about the initial conditions (dry, continue, index), the parameters (CFL, minimum water depth,. . .), the boundary conditions, friction values, external sources and flood tracking. The boundary conditions are defined by giving the corresponding stringdef name and the required type (standard, linked or internal). The friction type is assigned to the different domains (regiondef), as for external sources and flood tracking if required.

The morphology block contains all information for setting a morphological simulation with uniform bedload transport. The bed material, the bedload transport formula, initial conditions and parameters like porosity and sediment density are required. Standard bedload boundary conditions characterize sediment inflow and outflow. The curvature and lateral bed slope effects could be activated in order to influence the bedload transport direction.

The command file model.json does not give any information about the duration of the simulation or the type of output. These are implemented in the next command files.

4.2.2 Model setup

The setup executable gathers the different input files and generates the run file for the simulation stored in binary format (setup.h5). It validates the model before starting the simulation.

4.3 Simulation

4.3.1 Command file

The command file simulation.json contains information about the simulation time, the type of output (see Table 2.1) and optionally the minimum and maximum time step allowed. The user can define the start time, the output timestep and the end of the numerical simulation. The water surface, the water depth, the flow velocity or the change in bed elevation are examples of specific output that can be defined inside the command file. The output is generally defined on the mesh elements except for the discharge, calculated at flow boundaries.

The command file simulation.json is coupled to the setup file stored inside the first container (setup.h5) in order to run the numerical simulation on a selected backend type. The results are stored as “results.h5” inside the second container.

4.3.2 Model backend

The backend type can be selected between central processor unit (CPU), graphics processor unit (GPU) or a combination of GPU and CPU. The CPU provides sequential or multi-threading (OpenMP) backends. The backend types that support the numerical simulation are:

- seq: sequential execution on the CPU
- omp: multi-threading using OpenMP technology
- cuda: GPU
- cudaC: GPU with some kernels running sequentially on the CPU
- cudaO: GPU with some kernels running in parallel (OpenMP) on the CPU

All the backends execute the numerical simulations in double precision (default) and can be changed to single precision. For simulation running on CPU, the number of cores has to be given as argument.

4.4 Post-simulation

The post-simulation converts the simulation results stored in the second container (results.h5) into a defined output format. The name and the output format are specified inside the command file results.json. At the moment, only the .xdmf file type is available (Figure 4.1). The output.xdmf file can be modified by the user using the software ParaView to present the simulation results in a proper way.

A python script is available for extracting the stringdefs results (discharge) stored in the results.h5 binary and converts them in a text format (.csv).

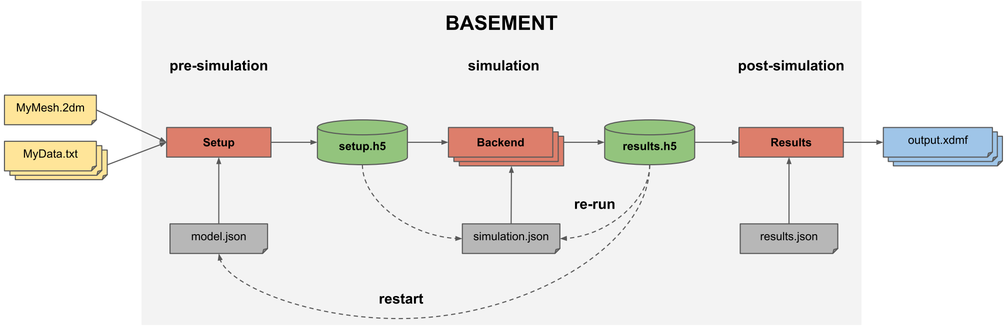


Figure 4.2 *BASEMENT simulation workflow with restart and re-run processes*

4.5 Re-run Simulation

The concept of rerun is to execute the same setup file (setup.h5) by fetching the initial conditions from the result file (results.h5) without parsing the command file model.json. It allows to continue a simulation from given results, thus obtaining a longer simulation without starting from the beginning. Other parameters can be modified like setting different output time step or adding/removing an output type. The rerun is activated by setting a start time larger than zero and the initial conditions are taken from the result file (results.h5) that should be copied inside the setup file.

4.6 Restart Simulation

Restarting a simulation (Figure 4.2) means to modify the parameters of the command file model.json, while fetching initial conditions from an existing result file (results.h5). It allows, for example to run two different simulations one after the other, e.g. by adding bed load transport after a purely hydraulic simulation that reached steady state.

The block containing the initial conditions (model.json) is set as continue and the existing result file name with the time at which the new simulation start is specified inside the command file. The command file simulation.json indicates the desired end of the simulation and the output time step. The starting time is still required and should be set to 0.0.

5

Graphical User Interface (GUI)

5.1 Graphical user interface

5.1.1 General

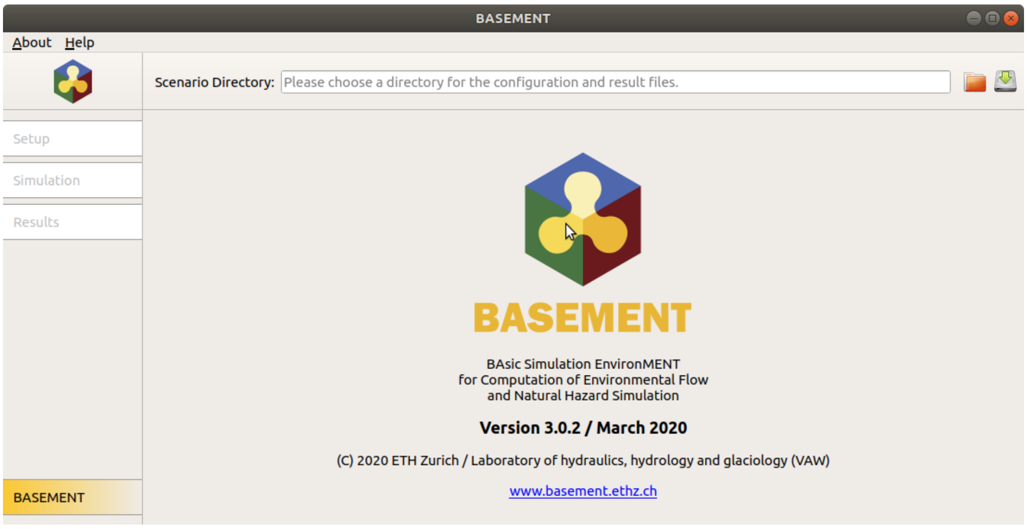
The BASEMENT graphical user interface assists the user with model configuration, numerical simulation and result export. For this purpose, the application provides a convenient way to edit the JSON configuration files and to select and run the backend executables.

5.1.2 First steps

Once started, the BASEMENT user interface application displays the welcome screen (see Figure 5.1). Notice that all the tabs except for 'BASEMENT' are deactivated. The first and most important step when using the application is to select the scenario directory. This directory will contain all the configuration and output files that the application reads and writes. To select a scenario directory, click the button with the "Open" icon and select a folder using the folder selection dialog.

5.1.2.1 Scenario directory

A scenario directory can only be opened by a single instance of the application at a time. A temporary 'scenario_directory.lock' file is created in the scenario directory to enforce this constraint. This file signals that the directory is locked until the application is closed. If the scenario directory does not exist (this is checked regularly by the application) then an error icon is displayed in the scenario directory text field.



Scenario Directory: Please choose a directory for the configuration and result files.

BASEMENT

BAsic Simulation EnvironMENT
for Computation of Environmental Flow
and Natural Hazard Simulation

Version 3.0.2 / March 2020

(C) 2020 ETH Zurich / Laboratory of hydraulics, hydrology and glaciology (VAW)

www.basement.ethz.ch

Figure 5.1 *Welcome Screen*

5.1.2.2 Load and save

The JSON configuration files stored in a directory are loaded when it is selected as a new scenario directory. All currently unsaved changes are discarded after the user accepts the corresponding warning. To save the three JSON configuration files for setup, simulation, and results into the current scenario directory click the button with the “Save” icon.

The tab ‘Setup’ is activated and selected as soon as a valid scenario directory has been chosen.

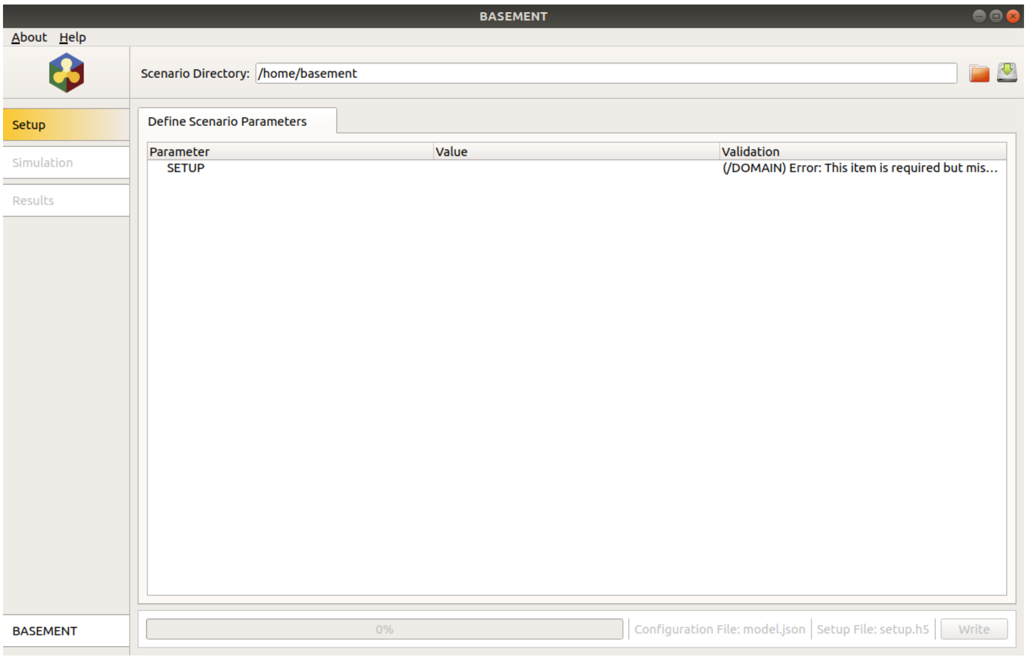
5.1.3 Setup

The setup screen (Figure 5.2) is designed for scenario parameter definition. The main part, the JSON editor, contains three columns: ‘Parameter’, ‘Value’, and ‘Validation’. The name of a JSON item (a parameter or a group of parameters) is displayed in the column ‘Parameter’, its value is displayed in the column ‘Value’ and the corresponding validation messages are shown in the ‘Validation’ column. Note that the button ‘Write’ is deactivated as long as the validation fails due to invalid parameters. Initially, only the item ‘Setup’ is present.

5.1.3.1 Adding and deleting items

To add a subitem to a parameter group (i.e. a JSON array or a JSON array), right-click on the item to open a context menu as shown in Figure 5.3. Select the item that you want to add for JSON objects or click the generic ‘Add item’ for JSON arrays. Once selected, the new subitem and all required sub-subitems are created automatically with default values (if available). Press Ctrl+Shift+A to expand all parameter groups quickly.

To delete a JSON item, use the context menu and select ‘Delete item’. Deleting parameter groups deletes the group and all contained items (after displaying a warning).



Scenario Directory: /home/basement

Parameter	Value	Validation
SETUP		(/DOMAIN) Error: This item is required but mis...

Figure 5.2 *Setup Screen*

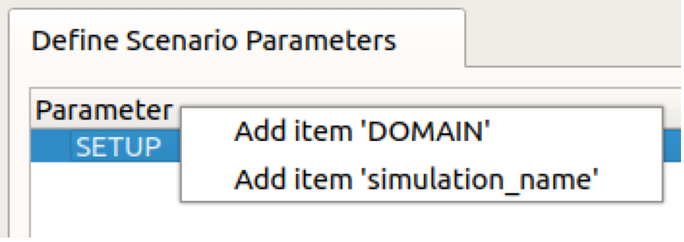
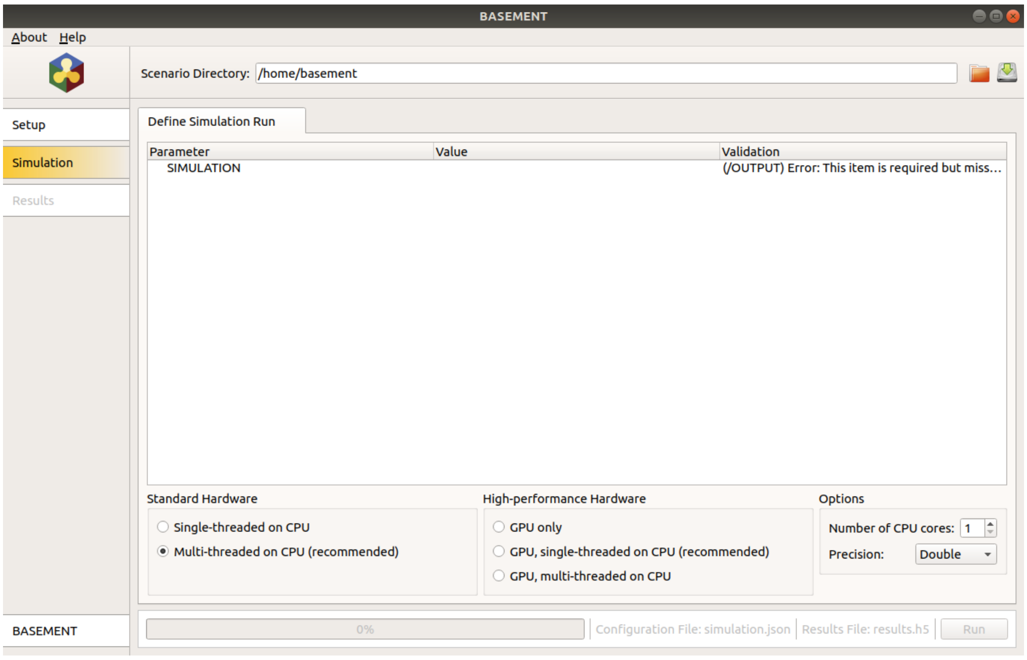


Figure 5.3 *Adding JSON Items*

Figure 5.4 *File Name Editor*



Scenario Directory: /home/basement

SIMULATION — (/OUTPUT) Error: This item is required but miss...

Standard Hardware:
- ○ Single-threaded on CPU
- ● Multi-threaded on CPU (recommended)

High-performance Hardware:
- ○ GPU only
- ○ GPU, single-threaded on CPU (recommended)
- ○ GPU, multi-threaded on CPU

Options:
Number of CPU cores: 1
Precision: Double

Configuration File: simulation.json | Results File: results.h5

Figure 5.5 *Simulation Screen*

5.1.3.2 Help and parameter values

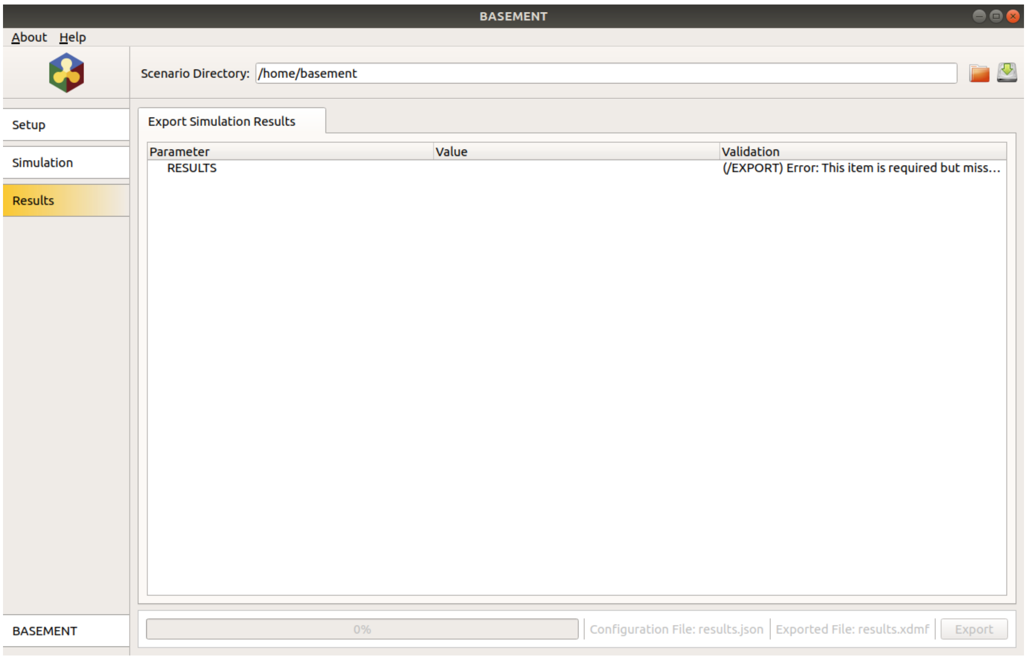
If you want to see the help for a parameter, mouse-over the parameter name and a tooltip with a parameter description appears. Double-clicking a parameter value opens a type-specific editor. In particular, you can click the “Open” icon to select a file for parameters that expect a file name (see Figure 5.4).

5.1.3.3 Run BASEMENT setup

Click the ‘Write’ button to write the JSON file and to run the setup executable in the background when you are done with configuring the scenario parameters (the names of the written files are displayed next to this button). A closable console tab is opened. This tab contains two views: ‘Console Output’ and ‘Error Output’. The first view contains information about the status from the running BASEMENT setup process. The second view, ‘Error Output’, contains error messages from this process. If everything went well, all the files are successfully written and the ‘Simulation’ tab is activated.

5.1.4 Simulation

The simulation screen (Figure 5.5) is enabled if the file ‘setup.h5’ exists in the scenario directory. Use this screen to edit and review the parameters required to run the numerical simulation. The JSON editor works just like the editor in ‘Setup’, but of course the available parameters are different and only the item ‘Simulation’ is present initially.



Scenario Directory: /home/basement

Parameter	Value	Validation
RESULTS		(/EXPORT) Error: This item is required but miss...

Configuration File: results.json

Exported File: results.xdmf

Figure 5.6 Results Screen

5.1.4.1 Selecting the simulation backend

The simulation screen also provides a way to select the simulation executable and command line flags: Choose the number of CPU cores that shall be used for the simulation, whether you want to compute on the GPU and the precision of the simulation using the controls on the lower end of the screen. Clearly, the number of CPU cores can only be set for multithreaded simulation backends.

5.1.4.2 Run simulation

When all the parameters are defined and valid, click the button ‘Run’ to launch the numerical simulation. Again, this will save the JSON configuration file and start the simulation backend in the background (the names of the files that are written are displayed next to the button). Track the progress of the simulation using the progress bar or click ‘Abort’ to abort. If everything went well, all the files are successfully written and the ‘Results’ tab is activated.

5.1.5 Results

The results tab (Figure 5.6) is enabled if the file ‘results.h5’ exists in the scenario directory. It can be used to define the export parameters. Again, the JSON editor works just like the editor in ‘Setup’. Initially, only the item ‘Results’ is present.

When all the parameters are defined and valid, click the button ‘Export’ to save the JSON configuration file and generate the output. If everything went well, the exported file (and an auxiliary results file in the case of export to ‘xdmf’) is successfully written to the scenario directory and is available for post-processing.

6

Run the program

6.1 Running BASEMENT

6.1.1 Graphical user interface (GUI)

The installation and executing of the BASEMENT software is described in the part Setup and First Start of the “Introduction and Installation” of this manual. Further details concerning the GUI of BASEMENT are explained in Section 5.1.

6.1.2 Batch mode under Linux

Executing a simulation with BASEMENT normally opens the graphical user interface (GUI) and requires some input from the user, e.g. to select the model data and to confirm warnings generated by the program at the start and during run-time. But BASEMENT can optionally be started without any graphical interaction and without user input. This feature is especially useful if one or several models shall be run automatically via batch or script file. Be aware that executing in batch mode requires special attention, since significant warnings may be suppressed without being noticed! It is recommended to study the generated ‘log-file’ after the simulation to check the program output for warnings which may have been generated during run time.

Executing in batch mode can be specified at the program start of BASEMENT using command line arguments. The execution of BASEMENT is split in three steps, the setup, the simulation and the results having their own backend and parameters.

6.1.2.1 Setup

The setup parameters of the numerical model are defined in the json file (“model.json”). The setup is executed from the command prompt (console) using the following line:

```
$ ./BMv3_BASEplane_setup -f model.json -o mySim_run.h5
```

The arguments of the setup can be obtained in the command prompt (console) with the help flag '-h'. Table 6.1 shows the setup arguments.

```
$ ./BMv3_BASEplane_setup -h
```

Table 6.1 *Command line flags and arguments for the setup*

Setup flag	Definition and arguments
-h , –help	display help information
-g , –graph	plot the tree as graph
-p , –process	level of processing (int)
-a , –archive	restore the archive (string)
-n , –nthreads	number of threads (int)
-l , –log	level of debug messages (int)
-f , –file	(required) the configuration file name
-o , –output	(required) the output name (.h5)

6.1.2.2 Simulation

The execution of the simulation depends on the backend type. There are five different backend types that can be run with single precision by adding "_single" to the backend name.

Write the following lines to execute the simulation file ("simulation.json") in batch mode using the command line on a sequential backend:

```
$ ./BMv3_BASEplane_seq -f simulation.json -r mySim_run.h5
  -o mySim_run_results.h5 -p
```

And using a single precision:

```
$ ./BMv3_BASEplane_seq_single -f simulation.json -r mySim_run.h5
  -o mySim_run_results.h5 -p
```

Please note: Using single precision can lead to less accurate results!

The available backends are listed below with all having the possiblity of running on single precision:

```
$ ./BMv3_BASEplane_seq

$ ./BMv3_BASEplane_omp

$ ./BMv3_BASEplane_cuda

$ ./BMv3_BASEplane_cudaC

$ ./BMv3_BASEplane_cudaO
```

The backend "_omp" stands for parallel execution with OpenMP and the number of thread should be specified. The backend "_cuda" stands for GPU simulation. The backend "_cudaC" executes the simulation using a coupled GPU and sequential processor and finally "_cudaO" uses a coupled GPU and parallel processor.

The command line arguments of the simulation are shown in Table 6.2.

Table 6.2 *Command line flags and arguments for the simulation*

Setup flag	Definition and arguments
-h , –help	display help information
-p , –progress	print simulation progress
-r , –runfile	(required) h5 file name with model definition
-a , –archive	restore the archive (string)
-n , –nthreads	number of threads (int)
-l , –log	level of debug messages (int)
-f , –file	(required) the configuration file name
-o , –output	(required) the output name (.h5)

6.1.2.3 Results

The last backend converts the simulation results in output, therefore, the result file ("results.json") is executed as follow:

```
$ ./BMv3_BASEplane_results -f results.json -r mySim_run_results.h5
  -o mySim_output
```

The command line arguments for the output generation are listed in Table 6.3

Table 6.3 *Command line flags and arguments for the results*

Setup flag	Definition and arguments
-r , –results	(required) h5 file name with simulation results
-a , –archive	restore the archive (string)
-n , –nthreads	number of threads (int)
-l , –log	level of debug messages (int)
-f , –file	(required) the configuration file name
-o , –output	(required) the output name

The command line argument can be supported in any order.

Note that the 'xdmf' output file format contains a reference to the simulation results instead of copying the data. Also, an auxiliary results file (named 'output_aux.h5' if the output name is 'output') is generated when exporting this file format. This has the advantage of using less storage space, but it also means that the three files (i.e. the simulation results file, the auxiliary results file, and the generated output file) are required to display the results. When opening such an output file, the file with the simulation results will be read from the path specified using the '–results' command line parameter. Therefore provide a relative path to the simulation results file if you want to be able to move these files to different locations together.

Of particular interest is the possibility to run BASEMENT in the batch mode without the GUI to be started. Under Linux this can be done with a shell script. In a shell script, the three steps as well as several simulations can be run consecutively (for example over the weekend). To generate a shell script just create an empty text file and replace the ending '.txt' by '.sh'. In this file several command lines can be defined as for example:

```
# Project 1
./BMv3_BASEplane_setup -f /home/MyUser/Project_1/model.json
      -o /home/MyUser/Project_1/mySim_run.h5

./BMv3_BASEplane_seq -f /home/MyUser/Project_1/simulation.json
      -r /home/MyUser/Project_1/mySim_run.h5
      -o /home/MyUser/Project_1/mySim_run_results.h5

./BMv3_BASEplane_results -f /home/MyUser/Project_1/results.json
      -r /home/MyUser/Project_1/mySim_run_results.h5
      -o /home/MyUser/Project_1/mySim_output

# Project 2
./BMv3_BASEplane_setup -f /home/MyUser/Project_2/model.json
      -o /home/MyUser/Project_2/mySim_run.h5

./BMv3_BASEplane_cuda -f /home/MyUser/Project_2/simulation.json
      -r /home/MyUser/Project_2/mySim_run.h5
      -o /home/MyUser/Project_2/mySim_run_results.h5

./BMv3_BASEplane_results -f /home/MyUser/Project_2/results.json
      -r /home/MyUser/Project_2/mySim_run_results.h5
      -o /home/MyUser/Project_2/mySim_output
```

To make the shell script executable open to console in the same directory of the shell script and run

```
chmod +x myShellScript.sh
```

Then run the shell script in the console with

```
./myShellScript.sh
```

6.1.3 Batch mode under Windows

Running BASEMENT 3.x in with a graphical user interface under Microsoft Windows can be done with the same work flow as described in Section 6.1.2. The syntax of the PowerShell is slightly different from that of the console. Further, the different backends of the BASEMENT software package have to be called with the full path of the installation folder. Note: Folder paths with whitespaces must be written in quotation marks (“”).

For example in the case you installed BASEMENT 3.x in under the path “C:\Program Files (x86)\BASEMENTv3.0” and your simulation scenario is stored on drive “F:\” in the folder “Project_1”, then you should run the simulation with the following three commands:

```
C:\"Program Files\BASEMENT 3.0.2"\bin\BMv3_BASEplane_setup.exe
      -f F:\Project_1\model.json
      -o F:\Project_1\mySim_run.h5

C:\"Program Files\BASEMENT 3.0.2"\bin\BMv3_BASEplane_seq.exe
      -f F:\Project_1\simulation.json
      -r F:\Project_1\mySim_run.h5
      -o F:\Project_1\mySim_run_results.h5 -p

C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_results.exe
      -f F:\Project_1\results.json
      -r F:\Project_1\mySim_run_results.h5
      -o F:\Project_1\mySim_output
```

Of particular interest is the possibility to run BASEMENT in the batch mode without the GUI to be started. Under Microsoft Windows this can be done with a batch file. In a batch file, the three steps of the simulation workflow as well as several simulations can be run consecutively (for example over the weekend). To generate a batch file file just create an empty text file and replace the ending ‘.txt’ by ‘.bat’. In this file several command lines can be defined as for example:

```
"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_setup.exe
      -f F:\Project_1\model.json
      -o F:\Project_1\mySim_run.h5

"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_seq.exe
      -f F:\Project_1\simulation.json
      -r F:\Project_1\mySim_run.h5
      -o F:\Project_1\mySim_run_results.h5 -p

"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_results.exe
      -f F:\Project_1\results.json
      -r F:\Project_1\mySim_run_results.h5
      -o F:\Project_1\mySim_output


"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_setup.exe
      -f F:\Project_2\model.json
      -o F:\Project_2\mySim_run.h5

"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_omp.exe
      -f F:\Project_2\simulation.json
      -r F:\Project_2\mySim_run.h5
      -o F:\Project_2\mySim_run_results.h5 -p -n 6
```

```
"C:\"Program Files\BASEMENT3.0.2"\bin\BMv3_BASEplane_results.exe
     -f F:\Project_2\results.json
     -r F:\Project_2\mySim_run_results.h5
     -o F:\Project_2\mySim_output
```

Then run the batch file by double clicking on it.

7

References

Shewchuk, J.R. (1996). Triangle: Engineering a 2D Quality Mesh Generator and Delaunay Triangulator. *Applied computational geometry: Towards geometric engineering*, *Lecture notes in computer science*, Lin, M.C. and Manocha, D. eds., No. 1148: 203–222. *Springer-Verlag*,

BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZRAD SIMULATION

REFERENCE MANUAL

VERSION 3.0
September 2019

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1

Mathematical Models

1.1 Hydrodynamics

1.1.1 Introduction

Mathematical models of the so-called *shallow water* type govern a wide variety of physical phenomena. Especially the one-dimensional (1D) de Saint-Venant equations (SVE) or two-dimensional (2D) shallow water equations (SWE) are of practical interest with regard to water flows with a free surface under the influence of gravity. Applications of the models include e.g.:

- River hydrodynamics
- Propagation of flood waves
- Dam break waves
- Flooding and inundation
- Ecological assessment based on flow quantities

The 2D SWE are based on the following set of hypotheses:

- the water is assumed to be incompressible; i.e. the water density ρ is constant
- the vertical acceleration of the water particles are assumed to be small compared to the longitudinal component of the acceleration. As a consequence the pressure distribution is hydrostatic;
- the bottom slope is small enough for the longitudinal coordinate to coincide with the horizontal axis;
- the flow regime is turbulent. As a consequence the head loss, mainly due to friction against the bottom, is proportional to the square of the flow velocity.

1.1.2 Governing Equations

The governing equations are obtained under shallow water conditions imposing mass conservation for the fluid and solid phases and the momentum principle to a flow in an open channel with a fixed bottom.

Introducing a Cartesian reference system (x, y, z) in which the z axis is vertical and the $x - y$ plane is horizontal with respect to gravity g , the system of governing equations can be written as

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = S_h \\ \frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{h} + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{bx} + S_{fx}\right) = 0 \\ \frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_y q_x}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q_y^2}{h} + \frac{1}{2}gh^2\right) + gh(S_{by} + S_{fy}) = 0 \ , \end{cases} \tag{1.1}$$

where:

h	$[m]$	water depth
g	$[m/s^2]$	gravity acceleration
u (v)	$[m/s]$	depth averaged velocity in x (y) direction
q_x (q_y)	$[m^2/s]$	discharge per unit width in x (y) direction
S_h	$[m/s]$	lateral inflow/outflow discharge per unit width
S_{fx} (S_{fy})	$[-]$	friction terms in x (y) direction .

The bed slope source terms

$$S_{bx}, S_{by}$$

are evaluated as follows:

$$S_{bx} = -\frac{\partial z_B}{\partial x} \quad ; \quad S_{by} = -\frac{\partial z_B}{\partial y} \tag{1.2}$$

1.1.3 Closure relations

In order to solve system (eq. 1.1) we need to specify the closure relations for the friction terms S_{fx}, S_{fy} and the value of lateral inflow/outflow discharge per unit width S_h.

1.1.3.1 Friction terms

The governing equations (eq. 1.1) have been derived under the hypothesis of turbulent flow, hence the friction terms can be assumed proportional to the square of the depth-averaged velocity and can be written as:

Several formulae are available for S_f. All these formulae use hypothesis (H3) of a turbulent flow regime, hence the assumption that the slope of the energy line is proportional to the square of the flow velocity u. The most frequently used laws are

Adopting a quadratic friction law, the friction term is proportional to the square of the depth-averaged velocity and can be written as:

$$S_{fx} = \frac{u|\vec{u}|}{gc_f^2 h} \quad ; \quad S_{fy} = \frac{v|\vec{u}|}{gc_f^2 h} \tag{1.3}$$

where g is the gravity acceleration, u and v are the depth averaged velocities in x and y direction, $|\vec{u}| = \sqrt{u^2 + v^2}$ is the magnitude of the velocity vector and c_f is the dimensionless friction coefficient.

Several formulae are available for the dimensionless friction coefficient c_f. Here it is quantified using both a power or a logarithmic for which are described in the next sections.

1.1.3.1.1 Power Law

The Manning-Strickler power law is widely used in practice and it requires that either the Strickler's k_{str} $[m^{1/3}/s]$ or the Manning's n coefficients ($k_{str} = n^{-1}$) is specified.

In this case the dimensionless friction coefficient c_f is calculated as

$$c_f = \frac{k_{str} h^{1/6}}{\sqrt{g}} \tag{1.4}$$

1.1.3.1.2 Logarithmic Law

The following approaches are implemented to determine the friction coefficient c_f:

Chézy:

$$\begin{array}{lll} c_f = 5.75 \log\left(12\dfrac{R}{K_s}\right) & \text{for} & R > K_s \\ c_f = 5.75 \log(12) & \text{for} & R < K_s\ , \end{array} \tag{1.5}$$

where K_s $[m]$ is the bed roughness height which is commonly taken to be proportional to a representative sediment size d_x. For rivers, K_s can be assumed $K_s = n_k d_{90}$ where $n_k = 2 \div 3$.

Bezzola:

In this closure relation, proposed by Bezzola (2002), c_f is given as a function of the roughness sublayer height y_R $[m]$ (usually for rivers $y_R \approx 1.0 d_{90}$ is a good approximation). This approach is also valid for small values of the relative submergence h/y_r Bezzola (2002).

$$\begin{cases} c_f = 2.5\sqrt{1 - \dfrac{y_R}{h}}\ \ln\left(10.9\dfrac{R}{y_R}\right), & \text{for} \quad \dfrac{h}{y_R} > 2 \\ c_f = 1.25\sqrt{\dfrac{h}{y_R}}\ \ln\left(10.9\dfrac{R}{y_R}\right), & \text{for} \quad 0.5 \le \dfrac{h}{y_R} \le 2 \\ c_f = 1.5, & \text{for} \quad \dfrac{h}{y_R} < 0.5 \end{cases} \tag{1.6}$$

1.1.3.2 Lateral inflow/outflow

S_h is used to represent additional sources of water like rainfall and springs or water abstraction (sink) and are allocated on a set of elements defined by regions. The external

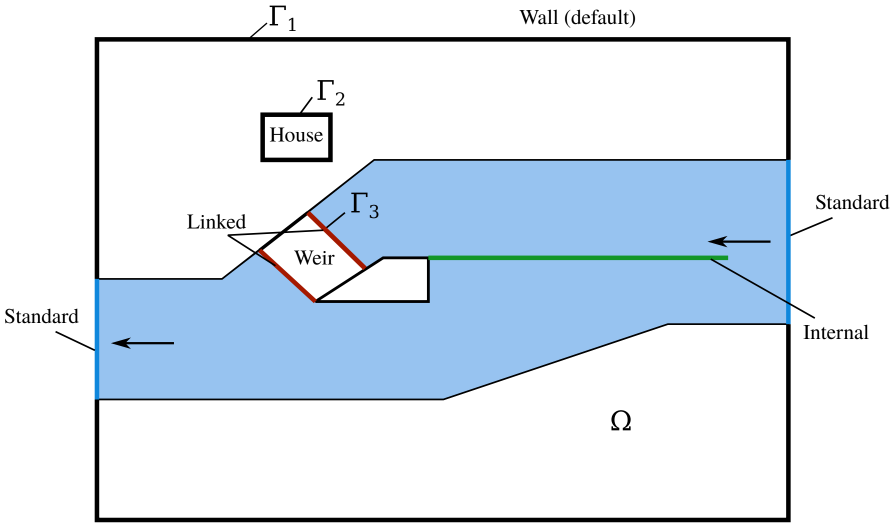

Figure 1.1 *Modeling domain and types of boundary conditions available. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir.* External *boundary conditions must be provided at* Γ_1, Γ_2 *and* Γ_3 *while* internal *boundary conditions can be specified in any place within* Ω

source can be specified as total discharge $[m^3/s]$ or distributed over time $[mm/h]$. Different approaches are used to manage the behaviour of the external sources:

- Exact: The specified water volume is added or extracted (non conservative)
- Available: The specified water volume to extract is limited by the available water volume in the elements (conservative)
- Infinity: All available water will be abstracted (conservative)

Addition of water always follows the “Exact” behaviour as there is no upper limit. The abstraction of water could also follow the “Exact” behaviour but the simulation might end abruptly if the available water volume is smaller than the volume prescribed. Therefore, the “Available” behaviour aims to avoid this situation. The “Infinity” behaviour abstracts all available water volume.

1.1.4 Boundary Conditions

After the specification of the *closure relations* there are now three equations and three unknowns, namely h, q_x and q_y. In principle, given initial and boundary conditions, one should be able to solve system (eq. 1.1) for h, q_x and q_y as functions of space x, y, and time t. Given the modeling domain described in Figure 1.1, boundary conditions are required at the domain boundary Γ and optionally can be specified within the interior domain Ω.

Therefore, two different types of boundary conditions can be defined:

- External boundary conditions: located at the domain boundary Γ_i
- Internal boundary conditions: located inside the domain Ω

External boundaries (at Γ) represent the limits of the computational domain possibly including also buildings, weirs or structures for water intake (see Figure 1.1).

1.1.4.1 External boundary conditions

At the external boundaries two different types of boundary conditions can be specified: wall or flow boundaries. Flow boundary conditions allow the flow to enter or leave the domain while wall boundary conditions express no mass flux over the boundary. By default, the external boundaries are set as wall.

1.1.4.1.1 Wall boundary

The *Wall* or *reflective* boundary consider the boundary at Γ_i and suppose it physically consists of a fixed, reflective impermeable wall. Then the physical situation is modelled imposing that:

$$\rho \vec{u} \cdot \vec{n} = 0 \quad ; \quad \frac{\partial \vec{u}}{\partial \vec{n}} = 0 \tag{1.7}$$

Where $\vec{n}$ is the outward directed unit vector perpendicular to the wall and $\vec{u} = (u, v)^T$ is the velocity vector. The static pressure is assumed to be zero.

1.1.4.1.2 Flow Boundaries

The *Flow* boundary conditions are defined as *inflow* if they let water entering or as *outflow* if they let water leaving the domain. Flow boundaries are further distinguished into *Standard* and *Linked*. The former are applied on the boundary domain Γ, while the latter establish a *link* between two portions of the domain.

Standard

Inflow boundaries:

This boundary requires the specification of a value for the total volume discharge Q, $[m^3/s]$, which is then divided by the length of the boundary Γ and projected orthogonally to the boundary to obtain the values of q_x and q_y. In case of supercritical flow the following possibilities to specify the value of the water depth h are possible:

- Uniform: h is calculated assuming that local uniform flow conditions. The calculation proceeds as follows:

  $$h = \sqrt[3]{\frac{(Q/b)^2}{g c_f^2 s}} \tag{1.8}$$

  where c_f is the Chézy coefficient, b is the entire length of the boundary Γ and s is the value of the local bed slope that must be specified.

- Explicit: In this case the flow depth h is calculated as follows:

  $$h = \sqrt[3]{\frac{(Q/b)^2}{g Fr^2}} \tag{1.9}$$

where b is the entire length of the boundary and Fr is the value of the local Froude number that must be specified

- zhydrograph: The water surface elevation (wse) at the boundary must be specified by the user. The depth is calculated as:

$$h = wse - z_B \tag{1.10}$$

where z_B is the bottom elevation at the boundary. The flow velocity at the boundary is set to zero.

Outflow boundaries:

At the outflow boundaries a value for the water depth h must be specified. These are the possible options:

- Uniform: the water depth h is calculated using equation (eq. 1.8) specifying a value for the total discharge Q and a local bed slope s. Uniform flow is calculated based on given slope and cell state at boundary (eq. 1.8).
- Weir: This boundary establishes a relation between the approaching discharge q constant and the water depth using the Poleni weir formula:

$$q = \frac{2}{3}\mu\sqrt{2g(h_{up} - w)^3} \tag{1.11}$$

where h_{up} is the water depth of the approaching flow and w is the weir elevation. The Poleni factor μ can be either set as constant ($\mu = 0.75$ by default) or dynamically evaluated as:

$$\mu = \frac{0.611}{a}\frac{0.75}{b}\frac{h_{up} - z_w}{w} \tag{1.12}$$

where a and b must be specified by the user (default values are $a = 0.611$ and $b = 0.075$).
- h-Q relation: The water surface elevation is determined as a function of the discharge, thus a h-Q relation has to be specified.
- zhydrograph: The water surface elevation (wse) at the boundary must be specified by the user. The depth is calculated as:

$$h = wse - z_B \tag{1.13}$$

where z_B is the bottom elevation at the boundary. The flow velocity is calculated with the Riemann solver (Hllc).
- Zero gradient (scientific use only): Transmissive, or transparent boundaries allow the passage of waves without any effect on them. This is mathematically obtained imposing over the entire length of the boundary that:

$$\rho\vec{u}\cdot\vec{n} = \text{const} \quad ; \quad \frac{\partial\vec{u}}{\partial\vec{n}} = 0 \tag{1.14}$$

In this case there is no need to specify further parameters.

Note: This is boundary condition should ***not*** *be used for practical problems and is intended for scientific use only.*

Linked

This type of boundaries establish a *link* between within a certain region of the domain where equations are not solved. Once this domain portion is identified the two boundaries, between which the link is established, must be specified. Let us call them Γ_{in} and Γ_{out}. Then, one inflow boundary condition must be specified at Γ_{in} and one outflow boundary condition at Γ_{out} while in the remaining boundaries wall conditions are automatically assigned. Not necessarily, Γ_{in} and Γ_{out} must have the same number of elements.

Linked boundaries can describe a $h - Q$ relation or a weir, i.e.:

- Weir: Similar to the standard weir boundary, the weir height w has to be specified. No kinetic energy is considered.
- $h - Q$ relation: The flux is calculated given a h-Q relation (see description of the h-Q relation for standard boundaries).
- 2 ways $h-Q$ relation: The internal boundary works as dynamic wall that is controlled by water surface elevation thresholds. If the upper water surface elevation threshold is reached, the internal boundary is removed until the water level reaches the lower water surface elevation, where the wall is re-established.

1.1.4.2 Internal boundary conditions

The internal boundary condition allows a direct cell-cell relation due to the exact same number of elements on the left and on right side of the boundary. Internal boundary conditions can be used to specify internal walls, dynamic walls or an h-Q relation.

- Wall: The wall conditions (eq. 1.7) are applied on both sides of the internal boundary.
- Dynamic Wall: The wall conditions are applied on the internal boundary until reaching a threshold value (time or water depth) after which the wall is removed.
- $h - Q$ relation: A $h - Q$ relation is applied on one side of the internal boundary, while on the other side, wall conditions apply (unidirectional flow).

1.1.5 Flood tracking

The flood tracking aims at extracting the flood arrival time, the maximum water depth, flow velocity and specific discharge along the numerical simulation and over a selected domain area. The area is defined by a regiondef and is required to be flooded (wet cells). The flood tracking provides outputs within a tracking time step defined by the user.

1.2 Morphodynamics

1.2.1 Introduction

Morphodynamic models provide scientific frameworks for advancing our understanding of river systems. The research on involved topics is an important and socially relevant undertaking regarding our environment. Nowadays numerical models are used for different purposes, from answering questions about basic morphodynamic research to managing complex river engineering problems. Due to increasing computer power and the development of advanced numerical techniques, morphodynamic models are now more and more used to predict the bed patterns evolution to a broad spectrum of spatial and temporal scales. The development and the success of application of such models are based upon a wide range of disciplines from applied mathematics for the numerical solution of the equations to geomorphology for the physical interpretation of the results.

Applications of morphodynamic models include:

- Damming of river basins
- Morphological changes due to width changes (e.g. River widenings)
- Effects of sediment mining
- River straightening

1.2.2 Governing Equation

The governing equations are obtained under shallow water conditions imposing mass conservation for the fluid and solid phases and the momentum principle to a flow in an open channel with a cohesionless bottom. Introducing a Cartesian reference system $(x; y; z)$ in which the z axis is vertical and the $x - y$ plane is horizontal, the system of governing equations is described by the system of equations (eq. 1.1) for hydrodynamics coupled with one equation for the conservation of the total sediment mass (the Exner equation (Exner, 1925)), i.e.:

$$(1-p)\frac{\partial z_B}{\partial t} + \frac{\partial q_{B_x}}{\partial x} + \frac{\partial q_{B_y}}{\partial y} - Sl_b = 0 \tag{1.15}$$

where p is the porosity, Sl_b is the source term specifying local input or output of sediment material (e.g. slope collapse or excavation) per unit width and q_{B_x} and q_{B_y} are the specific bed load flux in x and y direction, respectively. The Exner equation describes the bed evolution due to erosion or deposition processes, which results in changes of the bed level z_B.

1.2.3 Closure relations

In order to solve system (eq. 1.1) and equation (eq. 1.31) we need to specify the closure relations. For the friction terms S_{fx}, S_{fy} and the value of lateral inflow/outflow discharge per unit width S_h we can use the relations already introduced in the Hydrodynamic part (Section 1.1.3). For the Exner equation we need relations quantifying the bedload discharges.

1.2.3.1 Bedload sediment transport: Fundamentals

The key dimensionless parameter quantifying sediment mobility is the Shields parameter defined as:

$$\theta = \frac{\tau_b}{(\rho_s - \rho) g d} \tag{1.16}$$

where τ_b is the bottom shear stress (drag force acting on the particle), d is the sediment diameter, ρ and ρ_s are the water and sediment density, respectively. The Shields parameter can be interpreted as the ratio scaling the impelling force of flow drag acting on a particle to the Coulomb force resisting motion acting on the same particle. The bed shear stress is usually estimated by a closure condition using an empirical or semi-empirical formula. Here we use the quadratic friction law which relates the depth-averaged velocities to the bed shear stress as follows:

$$\tau_{bx} = \rho \frac{|\vec{u}|u}{c_f^2} \quad ; \quad \tau_{by} = \rho \frac{|\vec{u}|v}{c_f^2} \tag{1.17}$$

where τ_b is the bottom shear stress and ρ_s and ρ are the density of sediments and water,respectively.

1.2.3.1.1 Threshold conditions for sediment movement

When a granular bed is subjected to a turbulent flow, it is found that virtually no motion of the grains is observed below a critical value (θ_{cr}) of the Shileds parameter. According to the Shileds' theory Shields (1936), θ_{cr} can be expressed as a function of the Reynolds number $Re^* = \frac{du_*}{\nu}$. Alternatively, the diagram of incipient motion (see Figure 1.2) can be plot as a function of the dimensionless grain diameter D^* ($\theta_{cr} = f(D^*)$), where

$$D^* = d \left[\frac{g(s-1)}{\nu^2} \right]^{1/3}$$

.

The curve representing the particle incipient motion ($\theta = \theta_{cr}$) can be divided into three parts in the log-log graph:

- for $D^* \leq 3$, can be approximated by a linear segment;
- for $3 \leq D^* \leq 100$ this is represented by a curve with a relative minimum;
- for \$D^* > 100 \$ by a constant trend.

An approximation of the original Shields diagram was proposed by van Rijn (1984):

$$\begin{array}{lll}
\theta_{cr} = 0.24(D^*)^{-1} & \text{for} & 1 \leq D^* \leq 4 \\
\theta_{cr} = 0.14(D^*)^{-0.64} & \text{for} & 4 < D^* \leq 10 \\
\theta_{cr} = 0.04(D^*)^{-0.1} & \text{for} & 10 < D^* \leq 20 \\
\theta_{cr} = 0.013(D^*)^{0.29} & \text{for} & 20 < D^* \leq 150 \\
\theta_{cr} = 0.055 & \text{for} & D^* > 150
\end{array} \tag{1.18}$$

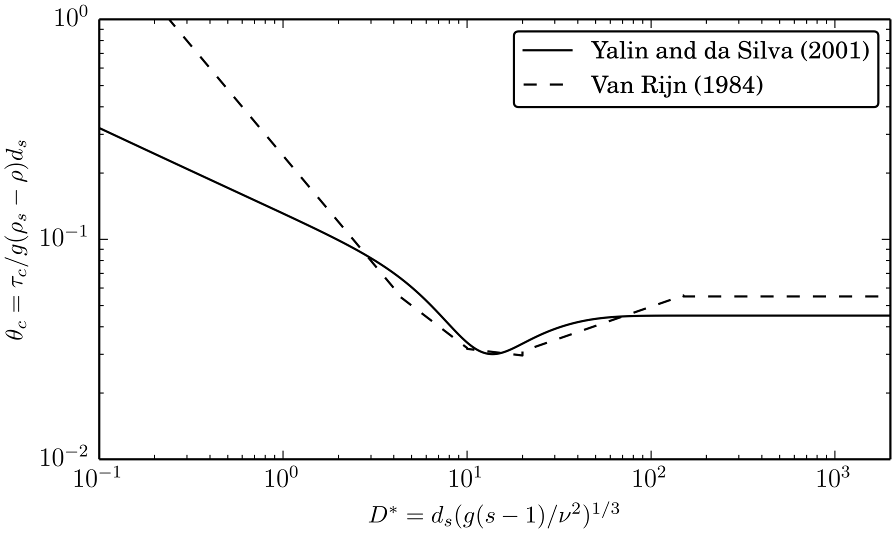

Figure 1.2 *Modified Shields diagram for initiation of sediment motion*

Another explicit formulation of the Shields curve was proposed by Yalin and Silva (2001). It reads

$$\theta_{cr} = 0.13 D^{*-0.392} \exp(-0.015 D^*) + 0.045\,(1 - \exp(-0.068 D^*)) \tag{1.19}$$

1.2.3.1.2 Influence of Local Slope on Incipient Motion

The threshold condition for incipient motion of grains developed by Shields is valid for almost horizontal bed. In case of sloped bed in flow direction or transverse to it, the stability of grains is either increased or reduced due to the gravity. The critical shear stress value can be adapted consequently to account for the influence of local slopes. One approach is to multiply the critical shear stress for almost horizontal bed with correction factors for the local bed slope in the flow direction and transverse to it. The corrected critical bed shear stress becomes:

$$k_\beta k_\delta \theta_{cr} \tag{1.20}$$

The correction factors $k_\beta k_\delta$ are calculated as suggested by van Rijn (1989):

$$k_\beta = \begin{cases} \dfrac{sin(\gamma - \beta)}{sin\gamma} & \text{if slope} < 0 \\ \dfrac{sin(\gamma + \beta)}{sin\gamma} & \text{if slope} > 0 \end{cases} \qquad k_\delta = \left\{ cos\delta \sqrt{1 - \dfrac{tan^2\delta}{tan^2\gamma}} \right. \tag{1.21}$$

where β is the angle between the horizontal and the bed along flow direction, δ is the slope angle transversal to the flow direction and γ is the angle of repose of the sediment material.

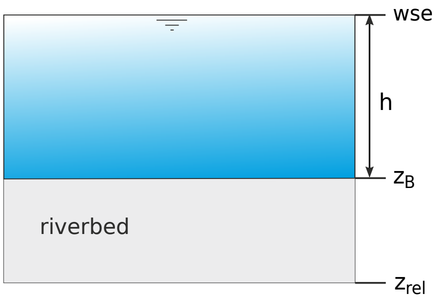

Figure 1.3 *Fixed bed concept and definition*

1.2.3.1.3 Fixed bed concept

Morphodynamic simulations generate deposition and erosion patterns of the riverbed. Erosion processes, if not limited, can proceed indefinitely in the vertical direction. This limit can be imposed by defining a non-erodible fixed bed elevation z_{rel}, below which the river bed is considered as *fixed*. This threshold also determines the amount of sediment available for transport (see Figure 1.3). The fixed bed elevation is defined relative to the initial bottom elevation z_B with $z_{rel} \leq 0$.

The accuracy of the fixed bed correction is guaranteed by defining the maximal overshoot below the fix bed elevation and the maximal number of iterations required for the correction.

1.2.3.2 Closure relations for Bed Load Transport

Let us now introduce the dimensionless bed load transport rate Φ also known as the Einstein bed load number, first introduced by Hans Albert Einstein in 1950, and given by

$$\Phi = \frac{q_B}{\sqrt{(s-1)gd^3}} \tag{1.22}$$

where $s = \rho_s/\rho$.

It is common practice to quantify bedload transport empirically relating Φ with either the Shields stress θ or the excess of the Shields stress θ above some appropriately defined “critical” Shields stress $(\theta - \theta_{cr}$. θ_{cr} is defined so as to fit experimenatl or field data and provide a threshold for which the bedload transport rate is too low to be of interest.

In what follows we describe the bedload transport formulas that are implemented to calculate the transport capacity $q_B = |\vec{q_B}|$ where $\vec{q_B} = (q_{B_x}, q_{B_y})$. The Shields parameter, takes the following form:

$$\theta = \frac{h\sqrt{S_{fx}^2 + S_{fy}^2}}{(s-1)} \tag{1.23}$$

and the specific bed load flux has the same direction as the water flow.

1.2.3.2.1 Meyer-Peter and Müller (MPM)

The bed load transport formula of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) reads as:

$$\Phi_B = \alpha(\theta - \theta_{cr})^m \tag{1.24}$$

Herein, α denotes the bed load coefficient, m the bed load exponent. In the original form of the formula $\alpha = 8$ and $m = 3/2$.

Meyer-Peter and Müller observed in their experiments that the first grains moved already for $\theta_{cr} = 0.03$. But as their experiments took place with steady conditions they used a value for which already 50% of the grains where moving. They proposed the value of $\theta_{cr} = 0.047$. The formula of Meyer-Peter and Müller is applicable in particular for coarse sand and gravel with grain diameters larger than 1 mm (Malcherek, 2001).

The bed load coefficient α, the exponent m and the critical Shields parameter θ_{cr} can be adapted by the user in the MPM-like formula.

1.2.3.2.2 Grass formula

The Grass formula (Grass, 1981) does not require the evaluation of the Shields stress:

$$\Phi_B = \alpha(\theta - \theta_{cr})^m \tag{1.25}$$

where $\alpha \in [0, 1]$ is a dimensional constant that encompasses the effects of grain size and kinematic viscosity and is usually determined from experimental data and m being chosen in the range $[1 - 4]$. The two-dimensional projection of (eq. 1.33) is obtained as follows:

$$q_{Bx} = \alpha \frac{q_x |\vec{q}|^{m-1}}{h^m} \quad , \quad q_{By} = \alpha \frac{q_y |\vec{q}|^{m-1}}{h^m} \ .$$

The coefficient α characterizes the interaction between the sediment and the fluid phase. The smallest α the weaker the interaction.

1.2.3.2.3 Engelund and Hansen

Engelund and Hansen (1972) proposed a transport formula for uniform bed material taking into account at the same time the presence of both bed- and suspended-load

This formula is commonly used as a bulk load formula and reads

$$\Phi_B = 0.05\sqrt{(s-1)g}\, c_f^2 \tag{1.26}$$

This formula formula does not consider the critical shear stress as threshold condition for incipient motion.

1.2.3.3 Correction of Bed Load Direction

The 2D projection of the solid discharge along x and y is obtained through standard procedures, that iare mostly based on empirical basis and which account for the downward effect of gravity on sediment particles due to local bed slope and the presence of spiral flow motion in curved riches.

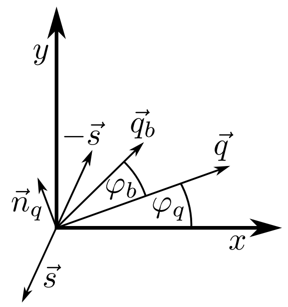

Figure 1.4 *Bed load transport deviation angle φ_b from the flow direction $\vec{q}$ due to the lateral bed slope $\vec{s}$ (Vonwiller, 2017)*

1.2.3.3.1 Lateral Bed Slope

Empirical bed load formulas were originally derived for situations where bed slope equals flow direction. However, in case of lateral bed slope with respect to flow direction, the bed load direction differs from the flow direction due to gravity acting on the bed material. Figure 1.4 illustrates the deviation of the bed load transport direction due to lateral bed slope in a Cartesian coordinate system.

The bed load direction is corrected for lateral bed slope based on the following approach (e.g. see Ikeda (1982) and Talmon et al. (1995)):

$$\tan\varphi_b = \left(\frac{-r}{\theta}\right)\vec{s}\cdot\ \vec{n}_q \quad \text{for} \quad \vec{s}\cdot\vec{n}_q < 0 \tag{1.27}$$

$$r = N_l\theta_{cr}^{1/2} \tag{1.28}$$

where φ_b = bed load direction with respect to the flow vector $\vec{q}$, N_l = lateral transport factor ($0.75 \le N_l \le 2.63$), $\vec{s} = \left(\frac{\partial z_B}{\partial x}, \frac{\partial z_B}{\partial y}\right)$ bed slope (positive uphill, negative downhill), $\vec{n}_q$ = unit vector perpendicular to $\vec{q}$ pointing in downhill direction ($\vec{s}\cdot\vec{n}_q < 0$) , θ = effective dimensionless shear stress and θ_{cr} = critical dimensionless shear stress of sediment.

The direction of the bed load transport under the influence of lateral bed slope is written as:

$$\frac{q_{B_y}}{q_{B_x}} = \tan(\varphi_b + \varphi_q) \tag{1.29}$$

1.2.3.3.2 Curvature Effect

Curvature in rivers may cause deviation of the bed load direction from the depth averaged flow direction. Due to three dimensional spiral flow motion, the bed load direction tends to point towards the inner side of the curve, while the flow direction points towards the outer side (Figure 1.5). This curvature effect is taken into account according to an approach proposed by Engelund (1974) , where the deviation angle φ_c of the bottom shear stress $\vec{\tau}_b$ (positive counterclockwise and vice versa) from the main flow direction is determined as

$$\tan\varphi_c = \frac{|\vec{\tau}_{bn}|}{|\vec{\tau}_{bs}|} = -N_*\frac{h}{R} \tag{1.30}$$

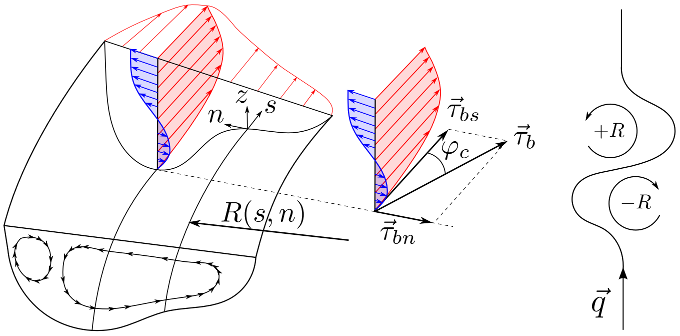

Figure 1.5 *Effect of spiral motion in river bend on bed shear stress* $\vec{\tau}_b$ *with deviation angle from main flow direction* φ_c *(Vonwiller, 2017)*

where $\vec{\tau}_{bn}$ and $\vec{\tau}_{bs}$ are the bed shear stress normal to and in the flow direction respectively, h denotes the water depth, N_* is a curvature factor, and R denotes the radius of the river bend (positive for curvature in counterclockwise direction and vice versa).

Note that the curvature factor N_* mainly depends on bed roughness. Therefore, $N_* \approx 7$ for natural streams (Engelund, 1974), and values up $N_* \approx 11$ for laboratory channels (Rozovskii, 1961).

1.2.4 Uniform Sediment Transport

1.2.4.1 Governing Equation

The conservation of bed material is ensured by the Exner equation (eq. 1.31), named after the Austrian sedimentologist Felix M. Exner (Exner, 1925). The Exner equation allows to describe the bed evolution due to erosion or deposition, which results in the elevation change of the actual bed level z_B:

$$(1-p)\frac{\partial z_B}{\partial t} + \frac{\partial q_{B_x}}{\partial x} + \frac{\partial q_{B_y}}{\partial y} - Sl_b = 0 \tag{1.31}$$

where p is the porosity, Sl_b is the source term per unit width specifying local input or output of sediment material (e.g. slope collapse or excavation) and $\vec{q}_B = \begin{pmatrix} q_{B_x} \\ q_{B_y} \end{pmatrix}$ is the specific bed load flux.

The Exner equation is solved in a decoupled way, meaning that the shallow water equations and the Exner equation are solved in sequence. This approach makes the assumption that the bed load flux is much slower than the water flow velocity (Soares-Frazão and Zech, 2011).

1.2.4.2 Closures for Bed Load Transport

The following section describes the bedload transport formulas that are implemented to calculate the transport capacity $q_b = |\vec{q}_b|$. The specific bed load flux has the same direction as the water flow. For practical purposes, the bed load transport formula can be calibrated by a pre-factor.

1.2.4.2.1 Meyer-Peter and Müller (MPM)

The bed load transport formula of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) is written as follows:

$$q_B = \alpha(\theta - \theta_{cr})^m \sqrt{(s-1)gd^3} \tag{1.32}$$

Herein, α denotes the bed load coefficient (originally $\alpha = 8$), m the bed load exponent (originally $m = 1.5$), q_B is the specific bed load transport rate, θ is the dimensionless bed shear stress (Shields parameter), θ_{cr} is the critical dimensionless bed shear stress, d is the grain diameter, $s = \rho_s/\rho$ and g stands for the gravitational acceleration. Meyer-Peter and Müller observed in their experiments that the first grains moved already for $\theta_{cr} = 0.03$. But as their experiments took place with steady conditions they used a value for which already 50% of the grains where moving. They proposed the value of $\theta_{cr} = 0.047$. The formula of Meyer-Peter and Müller is applicable in particular for coarse sand and gravel with grain diameters larger than 1 mm (Malcherek, 2001).

The bed load coefficient α, the exponent m and the critical Shields parameter θ_{cr} can be adapted by the user in the MPM-like formula.

1.2.4.2.2 Grass formula

The Grass model (Grass, 1981) proposes a simple bedload transport formula, where q_b is a function of the flow velocity and a dimensional constant α.

$$q_B = \alpha(u - u_c)^m \tag{1.33}$$

With u_c the critical velocity. The exponent m is usually set to m = 3. The threshold condition for incipient motion of grains is set to zero, meaning that the bedload transport and the fluid motion start simultaneously. The coefficient α characterizes the interaction between the bed and the fluid. If $\alpha = 0$, no sediment transport occurs. If $\alpha = 1$ the interaction between the bed and fluid is the largest.

1.2.4.2.3 Engelund and Hansen

Engelund and Hansen (1972) proposed a bedload transport formula for uniform bed material:

$$q_B = 0.05\sqrt{(s-1)g}\, c_f^2 \theta^{2.5} d^{1.5} \tag{1.34}$$

where d denotes the median sediment size of the bed material and θ the Shields parameter. The Engelund and Hansen formula for bed load transport does not consider the critical shear stress as threshold condition for incipient motion.

1.2.4.3 External Sources Terms

The source term Sl_b represents additional sediment mass input or output (sink) that occurs locally on the computational domain on a set of elements defined by regions. The source can be specified as total volume flux including porosity $[m^3/s]$. Different approaches are used to manage the behaviour of the external sources in case of a negative flux (sink):

- Exact: The specified sediment volume is added or extracted (non conservative)
- Available: The specified sediment volume to extract is limited by the defined fixed bed elevation of the elements (conservative)
- Infinity: All available sediment will be abstracted (conservative)

Addition of sediment always follows the “Exact” behaviour as there is no upper limit. The abstraction of sediment could also follow the “Exact” behaviour but the simulation might end abruptly if the available sediment volume is smaller than the volume abstracted. Therefore, the “Available” behaviour aims to avoid this situation. The “Infinity” behaviour abstracts all available sediment volume.

1.2.5 Boundary Conditions

After the specification of the *closure relations* for the sediment transport, the system of governing equations (eq. 1.1) and (eq. 1.31) can be solved within the modeling domain described in Figure 1.1, provided boundary conditions (morphologic boundary conditions) are specified at the domain boundary Γ. For the sediment transport only *external boundaries* that allow sediment flowing into or out of the domain can be specified. A morphologic boundary condition can ‘sit’ on a hydraulic boundary condition. In case no hydraulic boundary condition is specified, the boundary will behave as a wall and sediment transport will not occur.

1.2.5.1 Upstream boundary condition

The bed load input type is given by the upstream boundary condition. Three types of upstream boundary condition are available:

- Sediment discharge: based on a sediment hydrograph describing the bed load inflow as function of time (constant or variable). The bed load is defined as a volumetric flow rate $Q_b = \frac{\mu_s}{\rho_s}$ $[m^3/s]$, where μ_s is the sediment mass flow rate $[kg/s]$ and ρ_s the sediment density $[kg/m^3]$. Notice that the porosity is not considered in the bed load input and is specified separately as own parameter value.
- Transport capacity: the sediment inflow is defined by calculating the equilibrium transport capacity according to the hydraulic state at the boundary. The bed load is defined as a compact volumetric flow rate (without porosity) Q_b $[m^3/s]$.
- Equilibrium: this upstream boundary condition called IOup grants a constant bed load inflow. The same amount of sediment leaving the first computational cell in flow direction enters the cell from the upstream boundary. This leads to a constant bed elevation at the boundary condition.

For the sediment discharge and transport capacity boundary condition types, the specific sediment discharge q_b is distinguished by three weighting schemes:

1. Geometrical weighting with respect to the total nodestring length L_n.

$$q_b = \frac{Q_b}{L_n} \qquad \left[\frac{m^3}{s \cdot m}\right] \tag{1.35}$$

2. Wetted area weighting

$$q_b = \frac{Q_b}{A_{w,tot}} \cdot h \qquad \left[\frac{m^3}{s \cdot m^2}\right] \tag{1.36}$$

3. Conveyance weighting

$$q_b = \frac{Q_b}{K_{tot}} h\sqrt{c_f h} \qquad \left[\frac{m^3}{s \cdot m}\right] \tag{1.37}$$

with $K_{tot} = A_{w,tot}\sqrt{c_f h}$ the total conveyance and c_f the friction coefficient.

1.2.5.2 Downstream boundary condition

Two types of downstream boundary condition are available:

- Equilibrium: all sediment entering the last computational cell will leave the cell over the downstream boundary.
- Check-dam: the equilibrium downstream boundary condition is activated only if the bed level reaches a threshold value. Before reaching the threshold value, a wall type boundary is assumed.

2

Numerical Models

2.1 General View

The governing equations of hydro- and morphodynamics are conservation laws expressing conservation of mass and momentum. The aim of the numerical simulation is to solve these equations over the computational domain and for a given time. The computational domain is discretized by a computational mesh (Figure 2.1) consisting of elements (often having triangular shape) and conservation equations are applied on each domain element. In order to numerically solve the conservation equations, the mathematical model is approximated by numerical schemes, i.e. the numerical approximation consists of the spatial and temporal discretization of the conservation equations including an algorithm that solves the discretized equations.

The conservation equations can be formulated either in integral or differential form. Different numerical schemes exist to discretise the equations:

- Finite difference: The discrete values are considered as point values defined at mesh points
- Finite element: The discrete values are determined in terms of the nodal values of the mesh
- Finite volume: The discrete values are averaged over finites volumes of the mesh

In BASEMENT, the spatial discretisation of the domain is based on an unstructured mesh made of triangular elements. For the conservation equations, the spatial discretisation follows the finite volume scheme, while for the temporal discretisation an explicit first order Euler scheme is used. The numerical model processes the hydro- and morphodynamic equations in a decoupled way (Figure 2.2).

The discretization and the solution method for the hydro- and morphodynamic equations will be presented in the following sections.

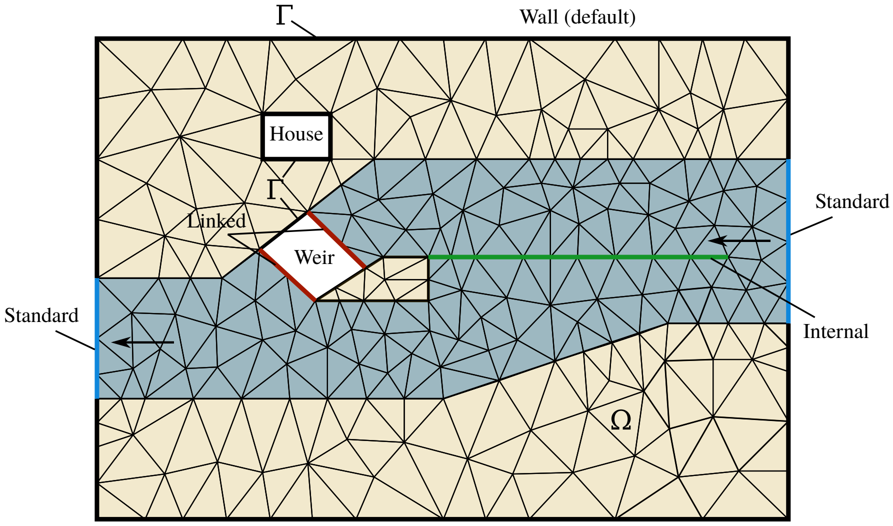

Figure 2.1 *Modeling domain, types of boundary conditions and computational mesh. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir.* External *boundary conditions must be provided at* Γ_1, Γ_2 *and* Γ_3 *while* internal *boundary conditions can be specified in any place within* Ω

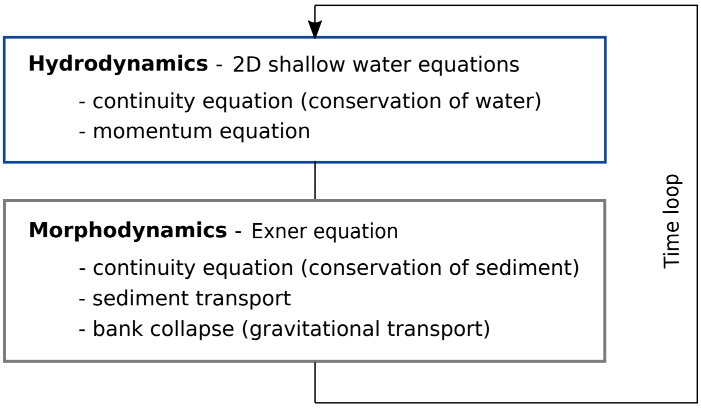

Figure 2.2 *Overview of the numerical model*

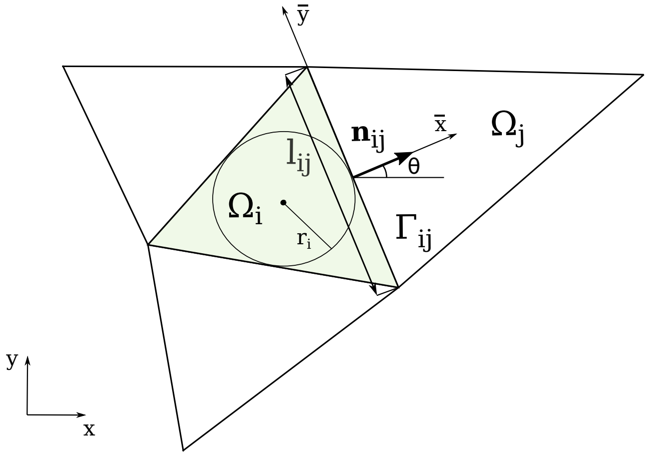

Figure 2.3 *Element (shaded triangle) of unstructured triangular mesh and used notation*

2.2 Discretization

The problem is discretised adopting a finite volume approach over unstructured triangular meshes. A conforming triangulation T_Ω of the computational domain $\Omega \subset \mathbb{R}^2$ by elements Ω_i such that $T_\Omega = \bigcup \Omega_i$, is assumed. Hereafter we will use the following notation: given a finite volume Ω_i, $j = 1, 2, 3$ is the set of indexes such that Ω_j is a neighbour of Ω_i; Γ_{ij} is the common edge of two neighbour cells Ω_i and Ω_j, and l_{ij} its length. $\mathbf{n}_{ij} = (n_{ij,x}, n_{ij,y})$ is the unit vector which is normal to the edge Γ_{ij} and points toward the cell Ω_j (see Figure 2.3). Data are represented by cell averages $\boldsymbol{U}_i^n$ and the numerical solution sought at time $t^{n+1} = t^n + \Delta t$, is denoted by $\boldsymbol{U}_i^{n+1}$.

2.3 Numerical solution of Hydrodynamics

2.3.1 Vectorial form of the governing equations

For numerical convenience, the system of governing equations (eq. 1.1) is rewritten in vectorial form in terms of the water surface elevation $H = h + z_B$. It now reads:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} = \boldsymbol{S} \tag{2.1}$$

where the vector of unknowns is

$$\boldsymbol{U} = \begin{pmatrix} H \\ q_x \\ q_y \end{pmatrix} \tag{2.2}$$

the vector fluxes are

$$\boldsymbol{F}_x = \begin{pmatrix} q_x \\ uq_x + \frac{1}{2}g(H^2 - 2Hz_b) \\ uq_y \end{pmatrix} \quad ; \quad \boldsymbol{F}_y = \begin{pmatrix} q_y \\ vq_x \\ vq_y + \frac{1}{2}g(H^2 - 2Hz_b) \end{pmatrix} \tag{2.3}$$

and the vector of source terms is

$$\boldsymbol{S} = \begin{pmatrix} S_h \\ gHS_x \\ gHS_y \end{pmatrix} \ . \tag{2.4}$$

The motivation of using H instead of h lies in the fact that it is easier to develop numerical schemes which preserve depth positivity and satisfy the well-balanced property.

2.3.2 Spatial discretisation

In order to discretise the system of governing equations, the domain is meshed by a set of triangular elements. The spatial discretization of the conservation equations is carried out by the finite volume method, where the differential equations are integrated over the single elements, i.e. control volumes. The water surface elevation is defined at the element center and is equally distributed over the element.

By integrating the governing system of equations eq. 2.1 in the control volume $V = [\Omega_i] \times [t^n, t^{n+1}]$, we obtain

$$\boldsymbol{U}_i^{n+1} = \boldsymbol{U}_i^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^{3} l_{ij} \left[\boldsymbol{F}_{ij}\right] + \Delta t \boldsymbol{S}_i \ . \tag{2.5}$$

2.3.3 Flux estimation

2.3.3.1 Rotational invariance of the shallow water equations

The flux $\boldsymbol{F}_{ij}$ are evaluated taking advantage of the rotational invariance property of the shallow water equations. According to this property the two-dimensional homogeneous shallow water equations satisfy the following equality (Toro, 2009):

$$\boldsymbol{n}_{ij} \cdot [\boldsymbol{F}_x(\boldsymbol{U}), \boldsymbol{F}_y(\boldsymbol{U})] = \boldsymbol{T}^{-1}(\theta)\boldsymbol{F}_x[\boldsymbol{T}(\theta)\boldsymbol{U}] \tag{2.6}$$

where θ is the angle between the vector $\boldsymbol{n}_{ij}$ and x-axis, measured counter clockwise from the x-axis (see Figure 2.3) and

$$\boldsymbol{T}(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \tag{2.7}$$

being

$\boldsymbol{T}^{-1}(\theta) =$ inverse of $\boldsymbol{T}(\theta)$.

2.3.3.2 Computation of the flux

The flux $\boldsymbol{F}_{ij}$ is obtained at every edge of the finite volume mesh, as the solution of the one-dimensional projected Riemann problem along the normal direction of the two conservation laws eq. 2.1. The computational steps can be summarized as follows:

- First, the vector of conserved variables $\boldsymbol{U}$ is transformed into the local coordinate system ($\bar{x}$, $\bar{y}$) (see Figure 2.3) at the edge with the operation $\boldsymbol{T}(\theta)\boldsymbol{U}$.
- A one-dimensional, local Riemann problem is formulated and solved in the normal direction of the edge. From this calculation the new flux vector over the edge $\boldsymbol{F}[\boldsymbol{T}(\theta)\boldsymbol{U}]$ is defined.
- The flux vector, formulated in the local coordinate system is transformed back to the global coordinates (Cartesian) with $\boldsymbol{T}^{-1}\boldsymbol{F}[\boldsymbol{T}(\theta)\boldsymbol{U}]$. The sum of the fluxes of all edges of an element gives the total fluxes in the x- and y directions.

The fluxes are calculated in the normal direction of the element edges. The normal direction of the edge is defined positive from element i (L) to element j regarding the edge direction.

2.3.3.3 The HLLC approximated Rieman solver

The HLLC approximate Riemann solver (Toro, 1994) is a modified HLL (Harten, Lax and van Leer) approximate Riemann solver that includes the shear wave.

The numerical flux at the cell interface is computed as follows:

$$\boldsymbol{F}_{ij}^{HLLC} = \begin{cases} \boldsymbol{F}_i & if \quad 0 \leq S_i, \\ \boldsymbol{F}_{*i} = \boldsymbol{F}_i + S_i(\boldsymbol{U}_{*L} - \boldsymbol{U}_i) & if \quad S_i \leq 0 \leq S_*, \\ \boldsymbol{F}_{*j} = \boldsymbol{F}_j + S_j(\boldsymbol{U}_{*R} - \boldsymbol{U}_j) & if \quad S_* \leq 0 \leq S_j, \\ \boldsymbol{F}_j & if \quad 0 \geq S_j. \end{cases} \tag{2.8}$$

The wave speed velocities are estimated as:

$$S_i = u_i - \sqrt{gh_i}\xi_i \ ; \ S_j = u_j + \sqrt{gh_j}\xi_j \tag{2.9}$$

where $\xi_{K=(i,j)}$ is defined as:

$$\xi_K = \begin{cases} \sqrt{\frac{1}{2}\left[\frac{(h_*+h_K)h_*}{h_K^2}\right]} & if \quad h_* > h_K, \\ 1 & if \quad h_* \leq h_K. \end{cases} \tag{2.10}$$

with h_*, an estimate for the exact solution of the water depth in the star region obtained using the depth positivity condition. It reads as

$$h_* = \frac{1}{2}(h_L + h_R) - \frac{1}{4}(u_R - u_L)(h_L - h_R)/(\sqrt{gh_L} + \sqrt{gh_R}) \tag{2.11}$$

In case of dry-bed conditions, the wave speeds are estimated as the exact dry front speed, i.e.:

$$S_i = \begin{cases} u_i - 2\sqrt{gh_i} & if \quad h_i = 0, \\ \text{usual estimate} & if \quad h_i > 0, \end{cases}$$
$$S_j = \begin{cases} u_j + 2\sqrt{gh_j} & if \quad h_j = 0, \\ \text{usual estimate} & if \quad h_j > 0. \end{cases} \tag{2.12}$$

And the middle estimated wave speed S_* corresponds to the front wave speed in case of dry-bed problem.

The expression of the states $\boldsymbol{U}_{*i}, \boldsymbol{U}_{*j}$ and the middle wave speed S_* can be found in the book of Toro (2009).

2.3.4 Numerical stability

Numerical stability is assured by choosing the time step Δt for time integration such that it obeys the Courant-Friedrichs-Lewy (CFL) condition. In 2-D the Courant number (CFL) can be defined as follows:

$$CFL = \frac{(\sqrt{u^2+v^2}+c)\Delta t}{r_i} \tag{2.13}$$

where r_i is the radius of the inscribed circle that defines the element center (Figure 2.3), u, v are the corresponding velocities of the element and $c = \sqrt{gh}$. The HLLC scheme is stable for

$$0 < CFL \leq 1 \tag{2.14}$$

2.3.5 Discretisation of Source terms

2.3.5.1 Bed slope source term

The bed slope source term (eq. 1.2) is discretized using the robust modified-state approach proposed by Duran et al. (2013). The discretization presents a motionless steady states-preserving scheme:

$$\boldsymbol{S}_{b,i} = \sum_{j=1}^{m} l_{ij}\boldsymbol{S}_{b,ij} = \sum_{j=1}^{m} l_{ij} \begin{pmatrix} 0 \\ gH^*_{ij}(z_i - \bar{z}_{ij})\vec{\boldsymbol{n}}_{ij} \end{pmatrix} \tag{2.15}$$

where $\bar{z}_{ij} = \check{z}_{ij} - \Delta_{ij}$ with $\check{z}_{ij} = \max(z_{bi}, z_{bj})$ the maximum bed elevation between cells i and j and $\Delta_{ij} = \max(0, \check{z}_{ij} - H_i)$. H^*_{ij} is the approximated value of the water surface elevation H at the cell interface Γ_{ij}.

2.3.5.2 Friction source term

We handle the inhomogeneous character of system eq. 1.1 due to the presence of frictional source terms by adopting a robust splitting technique Toro (2001). We initially consider the initial value problem (IVP)

$$\left.\begin{array}{llll} PDE: & \mathcal{A}(\boldsymbol{U}) & = & \mathcal{S}(\boldsymbol{U}) \\ IC: & \boldsymbol{U}(x,y,0) & = & \boldsymbol{U}_i^n \end{array}\right\} \text{IVP} \; .$$

where $\mathcal{A}$ represents the advective operator

$$\mathcal{A}(\boldsymbol{U}) = \frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} = \mathbf{0} \; ,$$

and $\mathcal{S}$ represents the frictional source term operator.

The numerical solution is then obtained by subsequently integrating *two* initial value problems (IVPs):

$$\left.\begin{array}{llll} ODEs: & \frac{\mathrm{d}\boldsymbol{U}}{\mathrm{d}t} & = & \mathcal{S}(\mathbf{U}) \\ ICs: & \boldsymbol{U}(x,y,0) & = & \boldsymbol{U}_i^n \end{array}\right\} \overset{\Delta t}{\Longrightarrow} \overline{\boldsymbol{U}}_i \quad \text{IVP1} \; ,$$

$$\left.\begin{array}{llll} PDEs: & \mathcal{A}(\mathbf{U}) & = & 0 \\ ICs: & \boldsymbol{U}(x,y,0) & = & \overline{\boldsymbol{U}}_i \end{array}\right\} \overset{\Delta t}{\Longrightarrow} \boldsymbol{U}_i^{n+1} \quad \text{IVP2} \; ,$$

The initial condition (IC) for IVP1 is $\mathbf{U}_i^n$, corresponding to the initial condition of the full problem IVP. The solution of IVP1 is obtained solving a system of ordinary differential equations (ODEs) after integration by a time step Δt and is denoted by $\overline{\boldsymbol{U}}_i$. IVP2 is then integrated by a time step Δt, with initial condition given by the solution of IVP1 $\overline{\boldsymbol{U}}_i$. The solution of IVP2 $\boldsymbol{U}_i^{n+1}$ is obtained solving an hyperbolic homogeneous system of partial differential equations (PDEs) and represents the approximate solution of the full problem IVP.\ Since we adopt an implicit second-order Runge-Kutta method for solving the ODEs systems IVP1 and an explicit finite volume method for solving IVP2, the integration time step Δt is determined accordingly with the CFL stability condition for IVP2.

2.3.5.3 External Source Term

An external source is defined as specific mass flux δ (m/s), uniformly distributed over a number of elements of the domain with a specific surface area. The external source can either be specified as discharge (m^3/s) or precipitation intensity (mm/h) for a specific region of the domain. The external source value is divided among the cells composing the region and converted to cell specific mass flux δ_i. The volume allocated is characterized by different behaviors:

$$\begin{array}{llll} \text{Exact:} & S_{h,i} = \delta_i & & \\ \text{Available:} & S_{h,i} = \delta_i & \text{if} & \delta_i \cdot \Delta t > 0 \\ & S_{h,i} = \max(\delta_i, -h_i) & \text{if} & \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & S_{h,i} = \delta_i & \text{if} & \delta_i \cdot \Delta t > 0 \\ & S_{h,i} = -h_i & \text{if} & \delta_i \cdot \Delta t < 0 \end{array} \tag{2.16}$$

Where h_i is the water depth of the element i. The external source volume is added to the initial water volume.

$$h_i^{t+1} = h_i^t + S_{h,i} \cdot \Delta t \tag{2.17}$$

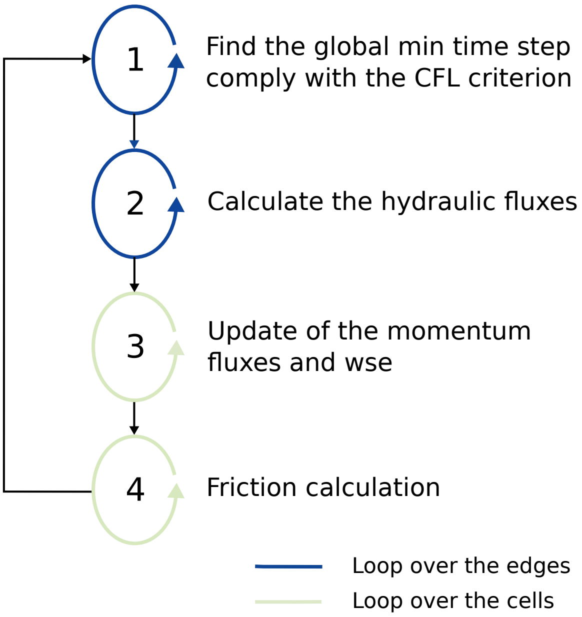

Figure 2.4 *Numerical solution procedure of hydrodynamic simulation for each time step* Δt

2.3.6 Solution procedure

The numerical solution procedure of BASEMENT explains how the discretised shallow water equation (eq. 1.1) is solved inside a defined time step Δt through a sequence of loops over the edges or cells (Figure 2.4).

First, a global minimum time step Δt should be defined. Then, the hydraulic fluxes (liquid mass, x-momentun and y-momentum) are calculated with a HLLC Riemann solver at the element edges according to the initial states of the left and right cells (Section 2.3.3). Subsequently, the hydraulic state variables i.e. cell centered quantities are updated and finally, the friction (source term) is calculated using an implicit scheme, thus looping twice over the cell.

2.4 Numerical solution of Morphodynamics

2.4.1 Numerical solution of the Exner equation

2.4.1.1 Fundamentals

The Exner equation assures that sediment mass is conserved in the bed and is used to model the riverbed time evolution. The rate of sediment transport is determined using a closure equation. The cell centered finite volume approach is used to discretise the Exner equation and in particular the HLL approximate Riemann solver with a wave speed estimator defined in Soares-Frazão and Zech (2011) is adopted. The shallow water and the Exner equations create a system of equations that is solved in a decoupled way (Figure 2.2).

2.4.1.2 Spatial discretization

In order to discretise the the Exner equation, we use the same unstructured mesh adopted for the hydrodynamic part and the same finite volume approach. As a consequence, the bed level z_B is defined at the element center and is equally distributed over the element.

By integrating the Exner equation in the control volume $V = [\Omega_i] \times [t^n, t^{n+1}]$, we obtain

$$z_{Bi}^{n+1} = z_{Bi}^{n} - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^{3} \left[q_{Bij \cdot l_{ij}} \right] + \Delta t \boldsymbol{S}_i \ . \tag{2.18}$$

The calculation of the sediment flux at the cell interface proceeds as follows:

1. loop over the cells and calculate:

    1. correction terms for the bed-load vector directions (if selected by the user), therefore:

    - calculation of the local bed slope, for the lateral-transport correction (see section Section 1.2.3.3.1)
    - calculation of the local curvature of the flow field, for the spiral flow correction (see section Section 1.2.3.3.2)

2. loop over the cell interfaces and:

    1. calculate the flux projection along the normal vector ($n_{ij,x}$,$n_{ij,y}$ of edge Γ_{ij}, i.e.: $q_{Bi,n} = q_{Bi,x} \cdot n_{ij,x} + q_{Bi,y} \cdot n_{ij,x}$ and $q_{Bj,n} = q_{Bj,x} \cdot n_{ij,x} + q_{Bj,y} \cdot n_{ij,x}$ with j=1,2,3
    2. compute the flux at the interface using the approximate HLL Riemann solver at the interface

    - Evaluate the wave speeds at the interface. this is obtained following the approach proposed by Soares-Frazão and Zech (2011), for which the wave speeds can be calculated as an approximation of the smallest eigenvalue of the system of governing equations, i.e. Shallow water and Exner. They read:

$$\lambda_1 = 1/2(u_n - c - \sqrt{(u_n - c)^2 + 4a_2c^2}) \tag{2.19}$$

$$\lambda_2 = 1/2(u_n - c + \sqrt{(u_n - c)^2 + 4a_2c^2}) \tag{2.20}$$

where $u_n = u \cdot n_{ij,x} + v \cdot n_{ij,y}$, $c = \sqrt{gh}$ and $a_2 = \dfrac{\partial q_{b,n}}{\partial q_n}$ which is the derivative of the bed load discharge in the normal flow direction with respect to the hydraulic flux direction. Then the speeds estimate are

$$S^- = \min(\lambda_{1,L}, \lambda_{1,R}) \tag{2.21}$$

and

$$S^+ = \max(\lambda_{2,L}, \lambda_{2,R}) \tag{2.22}$$

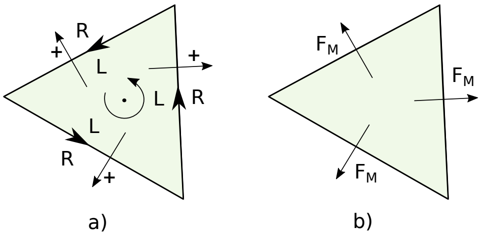

Figure 2.5 *a) Sign convention for the edge direction: counterclockwise b) Positive morphological flux direction at edges: from left (L) to right (R)*

- Flux calculation:

$$q_{Bij}^{HLL} = \begin{cases} q_{Bi,n} & if \quad S^- \geq 0, \\ \dfrac{q_{Bi,n} S^+ - q_{Bj,n} S^- + S^- S^+ \left(z_{Bj} - z_{Bi} \right)}{S^+ - S^-} & if \quad S^- < 0 < S^+, \\ q_{Bj,n} & if \quad S^+ \leq 0. \end{cases}$$

The convention for the positive bed load flux direction is the same as for the hydrodynamic flux and is presented on Figure 2.5

2.4.1.3 Discretization of External Source Term

The source term Sl_b describes a local input or removal of sediment mass into a river.

An external source is defined as specific mass flux δ (m/s), uniformly distributed over a number of elements of the domain (region) with a specific surface area. The external source can be specified as the total volume flux (m^3/s) for a specific region of the domain. The external source value is divided among the cells composing the region and converted to cell specific mass flux δ_i. The volume allocated is characterized by different behaviors:

$$\begin{array}{lll} \text{Exact:} & S_{b,i} = \delta_i & \\ \text{Available:} & S_{b,i} = \delta_i & \text{if} \quad \delta_i \cdot \Delta t > 0 \\ & S_{b,i} = \max(\delta_i, -(z_{Fix} - z_i) & \text{if} \quad \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & S_{b,i} = \delta_i & \text{if} \quad \delta_i \cdot \Delta t > 0 \\ & S_{b,i} = -(z_{Fix} - z_i) & \text{if} \quad \delta_i \cdot \Delta t < 0 \end{array} \tag{2.23}$$

Where z_i is the bottom elevation and z_{Fix} the fixed bed elevation of the element i. The external source volume is added to the initial bottom elevation of element i.

$$z_i^{t+1} = z_i^t + S_{b,i} \cdot \Delta t \tag{2.24}$$

2.4.2 Solution procedure

The numerical solution procedure of BASEMENT explains how the discretised Exner equation (eq. 1.31) is solved through a sequence of loops over the edges or cells (Figure 2.6).

In the numerical simulation, the hydrodynamic and morphodynamic simulations are performed in a decoupled way. The morphodynamic simulation is executed after the

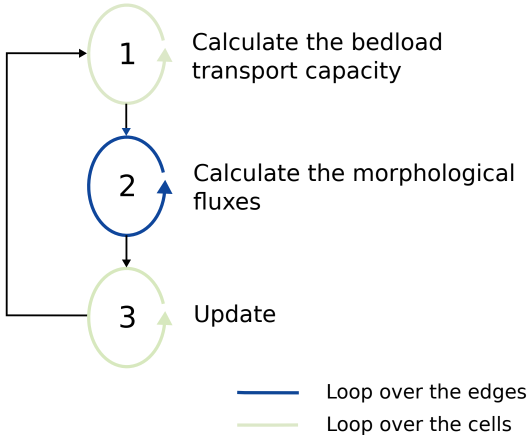

Figure 2.6 *Numerical solution procedure of morphodynamic simulation for each time step* Δt

hydrodynamic simulation, using the hydraulic fluxes to calculate the morphological fluxes. This approach assumes that the sediment transport is much slower than the water velocity, which is an accurate assumption for the numerical modelling of slow flood with morphological changes occurring over a long period (Soares-Frazão and Zech, 2011). The numerical solution procedure of Figure 2.6 is performed after the step 4 of Figure 2.4 inside the same time step Δt.

The numerical solution of the Exner equation starts with a loop over the cells in order to find the bedload transport capacity q_b with a potential correction due to a curvature effect or lateral bed slope. Then, the morphological fluxes F_M are calculated at the element edges and finally, the bed elevation z_b is updated over the cells.

3

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BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZRAD SIMULATION

TUTORIALS & TEST CASES

VERSION 3.0
September 2019

BASEMENT

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1

Tutorials

1.1 Hydrodynamics and sediment transport at the river Flaz

1.1.1 Introduction

The river Flaz is located in the canton Graubünden in Switzerland. A reach of 1.5 km long is taken as example for this tutorial. The reach contains a widening section created to protect the village of Samadan from flood event. The aim of this tutorial is to show the setup of the three configuration files for the numerical simulation with BASEMENT. First, a hydraulic simulation is performed to obtain a calibrated model at steady state. Then a morphological simulation is performed adding the morphological part to the result of the hydraulic simulation.

1.1.2 Computational mesh

The computational mesh of the Flaz is imported from the tutorial of BASEMENT version 2.8. The 2dm file has been modified as explain in the pre-processing tutorial for small meshes in the User manual. There are two stringdefs for the inflow and outflow boundaries. The mesh has 14’457 cells, 7’446 vertices and the interpolation method “weighted” is used to convert the mesh from version 2.8 to a 3.0 compatible computational mesh. Figure 1.1 shows the bottom elevation of the river Flaz used in this tutorial.

1.1.3 Hydraulics

The configurations files (model.json, simulation.json and results.json) can be created and modified with the graphical user interface (GUI) or any text editor. The configuration files are saved in one folder and the simulation will automatically generate a new folder called “run” which contains the output.

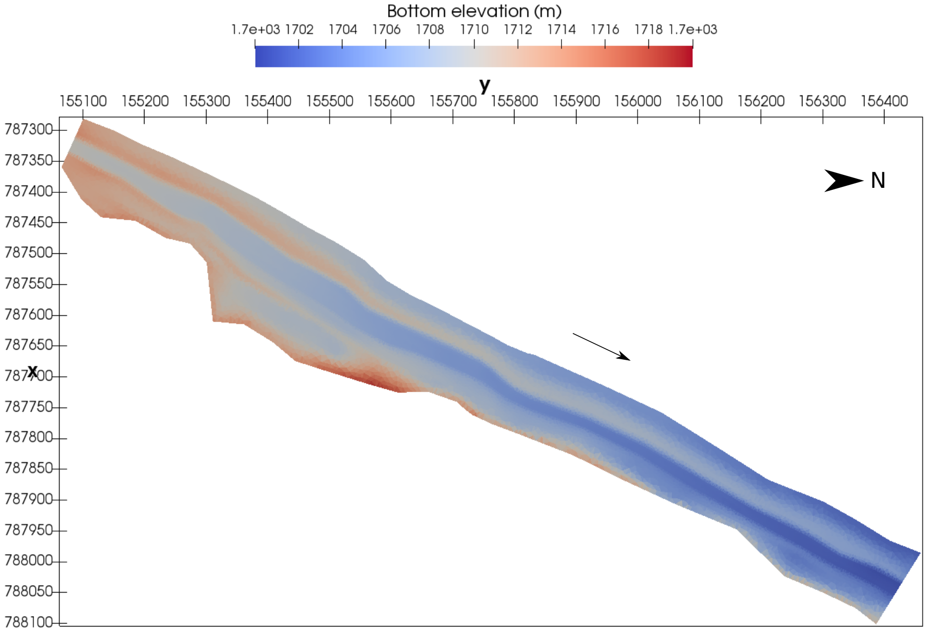


Figure 1.1 *Planar view of the initial bottom elevation of the river Flaz*

1.1.3.1 Set up the configuration file model.json

The configuration file model.json for a hydrodynamic simulation has the following structure:

```
{
   "SETUP":{
        "simulation_name":"Flaz_steady_state",
        "DOMAIN": {
            "PHYSICAL_PROPERTIES": {...},
            "BASEPLANE_2D": {
                "GEOMETRY": {...},
                "HYDRAULICS": {
                    "PARAMETER": {...},
                    "FRICTION": {...},
                    "BOUNDARY": {...},
                    "INITIAL": {...}
                }
            }
        }
    }
}
```

The blocks PHYSICAL_PROPERTIES and BASEPLANE_2D are mandatory. The physical property is the gravity and the components of the BASEPLANE_2D contain information about the domain (GEOMETRY) and the simulation type (HYDRAULICS).

```
"PHYSICAL_PROPERTIES": {
                "gravity": 9.81
            }
```

The GEOMETRY part contains the link to the mesh file and different subsections as the interpolation method, a list of STRINGDEF for boundary conditions and a list of REGIONDEF to assign the friction, external sources and different interpolation methods.

```
 "GEOMETRY": {
                    "mesh_file": "Flaz_mesh.2dm",
                    "INTERPOLATION": {
                        "method": "weighted"
                    },
                    "STRINGDEF": [...],
                    "REGIONDEF": [...]
               }

"STRINGDEF": [
                    { "name": "Inflow",
                    "upstream_direction": "left"},
                    { "name": "Outflow",
                    "upstream_direction": "left"}
                    ],
"REGIONDEF": [
                        {
                            "name": "one",
                            "index": [1] },
                        {
                            "name": "two",
                            "index": [2] },
                        {
                            "name": "three",
                            "index": [3] },
                        ...
             ]
```

The HYDRAULICS block contains the subsections PARAMETER for the hydraulic simulation only, FRICTION for each region, BOUNDARY for the flow conditions and INITIAL for the condition at time t=0.0.

```
"PARAMETER": {
                        "CFL": 0.95,
                        "minimum_water_depth":0.002,
                        "fluid_density": 1000.0,
                        "max_time_step": 100
                    }

"FRICTION": {
                    "type": "strickler",
                    "default_friction": 30,
                    "regions": [
                            {"region_name": "one",
                             "friction": 28.0},
```

```
                            {"region_name": "two",
                             "friction": 30.0},
                            {"region_name": "three",
                             "friction": 35.0},
                            ...
                        ]
                    }

"BOUNDARY":{
                        "STANDARD": [
                            {"name": "Inflow",
                            "string_name": "Inflow",
                            "type": "uniform_in",
                            "discharge_file": "Inflow_stationary.txt",
                            "slope": 0.02},
                            {"name": "Outflow",
                            "string_name": "Outflow",
                            "type": "uniform_out",
                            "slope": 0.02}
                        ]
                    }

"INITIAL":{
                        "type": "dry"
                    }
```

The hydrograph is defined constant in a file “Inflow_stationary.txt”, where the time in seconds (left) and discharge in m^3/s (right) is indicated.

```
0.0, 50.0
3600.0, 50.0
```

1.1.3.2 Set up the configuration file simulation.json

The configuration file simulation.json defines the simulation time parameters (seconds) in the block TIME and the different output types inside the OUTPUT block.

```
{
    "SIMULATION":{
        "TIME": {
            "start": 0.0,
            "end": 3600,
            "out": 600
        },
        "OUTPUT": [
            "water_surface",
            "flow_velocity_abs",
            "ns_hyd_discharge",
```

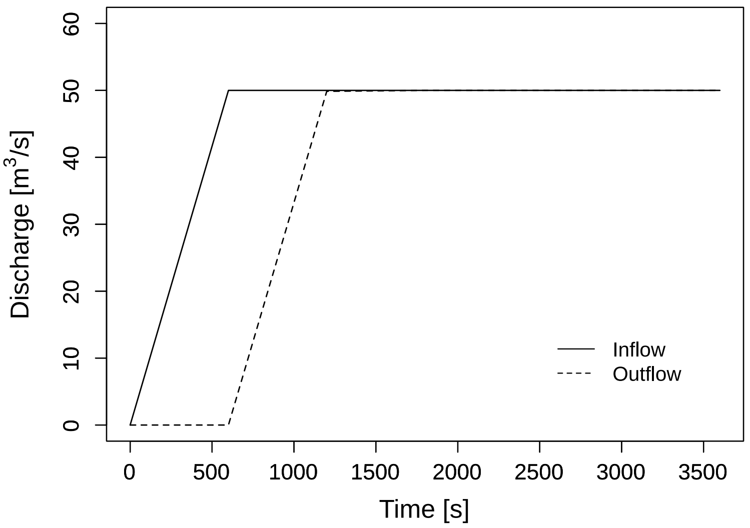


Figure 1.2 *Inflow and outflow hydrograph at boundaries*

```
            "bottom_elevation",
            "spec_discharge",
            "water_depth"
        ]
    }
}
```

1.1.3.3 Set up the configuration file results.json

The configuration file results.json defines the output format in the block EXPORT. Currently, xmdf is the only output format available.

```
{
    "RESULTS": {
        "EXPORT": [
            {"format": "xdmf"}
        ]
    }
}
```

1.1.3.4 Steady flow simulation

The simulation results are stored inside the results.h5 binary. By calling the python script, the discharge values at boundaries are extracted and stored in the Discharge.csv file, where the rows are the time steps and the columns represents the stringdef in their definition order (inside the .2dm file). The steady state is reached after 1200 seconds (Figure 1.2).

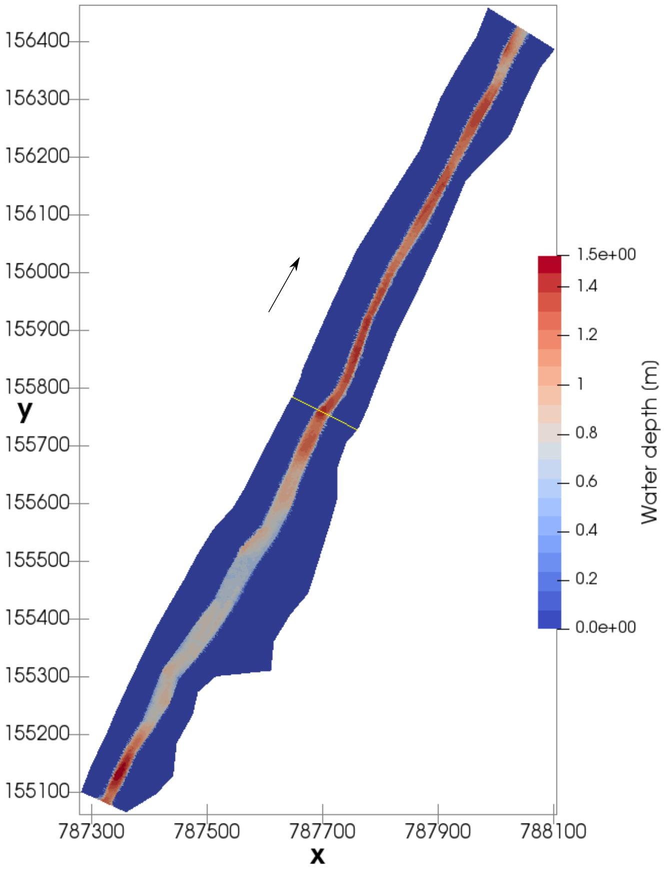


Figure 1.3 *Water depth at the end of the steady flow simulation (t=3600 s) with the cross section location (yellow line)*

1.1.3.5 Model calibration

The calibration of the friction value is done by comparing the water surface elevation between BASEMENT version 3.0 and version 2.8 at a cross section located in the middle of the channel (Figure 1.3). The water surface elevation and the water depth values along the cross section were obtained using the software ParaView.

The resulting water depth and water surface elevation are compared in Figure 1.4. The steady flow simulation of BASEMENT version 3.0 provides similar results to those obtained with BASEMENT version 2.8. There is no need to modify the friction value defined in Section 1.1.3.1.

1.1.3.6 Unsteady flow simulation

The hydrograph based on the flood event of July 2004 provides unsteady flow conditions for the numerical simulation. The results of the steady flow simulation are stored in the binary Flaz_steady_state_results.h5 inside the run/ folder and taken as initial state. The other parameters defined in Section 1.1.3.1 don't change, except for the boundary block where the new discharge file (Inflow_transient.txt) replaces the stationary hydrogrpah. The initial block:

```
"INITIAL":{
```

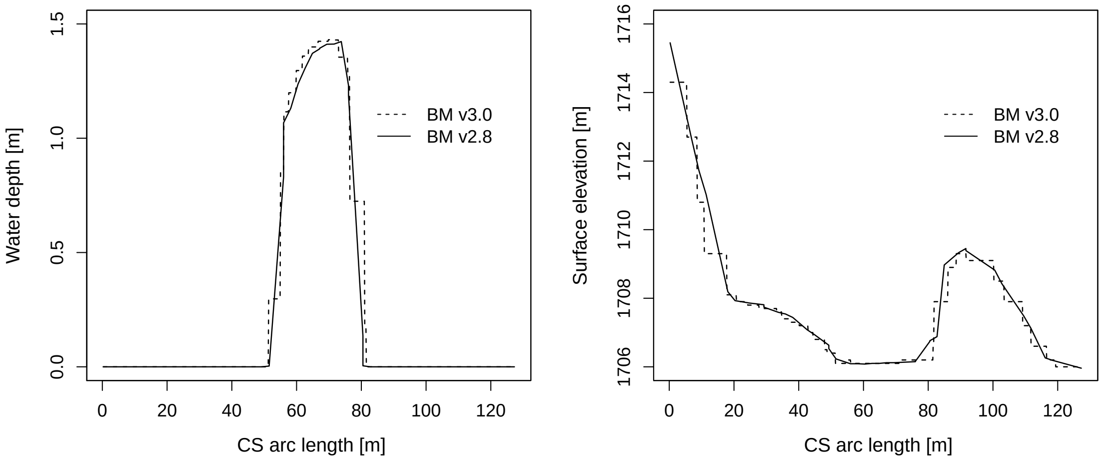


Figure 1.4 *Cross sectional view of the water depth and surface elevation facing the opposite flow direction at the end of the steady flow simulation (t=3600 s)*

```
                "type": "continue",
                "file": "../run/Flaz_steady_state_results",
                "time": 3000.0
            }
```

The running time in the configuration file simulation.json is increased to the last value of the discharge file (Inflow_transient.txt). A higher "end" value will take the last discharge value written on the hydrograph to run the simulation. The starting time corresponds to the smallest time value of the discharge file Inflow_transient.txt.

```
"TIME": {
            "start": 0.0,
            "end": 82000,
            "out": 2000
        }
```

After changing the discharge file, modifying the initial block in the setup and the time of the simulation, the model is ready to proceed the numerical simulation.

1.1.4 Morphology

1.1.4.1 Set up the configuration file model.json

The unsteady flow simulation is now converted into a morphodynamic simulation with a morphology block and starting from the results of the steady flow simulation. The inflow hydrograph and the initial blocks are the same as described in Section 1.1.3.6. Additionally, the block morphology is defined inside the model.json file with the following structure

```
{
```

```
   "SETUP":{
        "simulation_name":"Flaz_unsteady_morph",
        "DOMAIN": {
            "PHYSICAL_PROPERTIES": {...},
            "BASEPLANE_2D": {
                "GEOMETRY": {...},
                "HYDRAULICS": {...},
                ""MORPHOLOGY": {
                    "INITIAL":{...},
                    "PARAMETER": {...},
                    "BEDMATERIAL": {...},
                    "BEDLOAD": {...}
                }
            }
        }
    }
}
```

Inside the morphology block, the initial conditions look like:

```
"INITIAL":{
                        "type": "mesh"
                    }
```

The morphology parameters defines the density of sediments, the porosity and the time at which the morphodynamic simulation starts.

```
"PARAMETER": {
                        "morphodynamic_start": 0.0,
                        "sediment_porosity": 0.4,
                        "sediment_density" : 2650.0
                    }
```

The bed material is composed of uniform grains with one diameter (m). Fixed bed elevations are assigned to different regions to prevent a high erosion. The erosion is unlimited if the fix bed is not defined.

```
"BEDMATERIAL": {
                        "GRAIN_CLASS": {
                            "diameters": [0.050]
                        },
                        "FIXED_BED": {
                            "type": "region_defined",
                            "correction_accuracy": 0.0,
                            "max_iteration": 300,
                            "regions": [
                                {"region_name": "one",
                                 "z_rel": -0.8},
```

```
                    {"region_name": "two",
                    "z_rel": 0.0},
                    {"region_name": "three",
                    "z_rel": 0.0},
                    {"region_name": "four",
                    "z_rel": -2.0},
                    {"region_name": "five",
                    "z_rel": 0.0},
                    {"region_name": "six",
                    "z_rel": -2.0},
                    {"region_name": "seven",
                    "z_rel": -2.0},
                    {"region_name": "eight",
                    "z_rel": 0.0},
                    {"region_name": "nine",
                    "z_rel": 0.0},
                    {"region_name": "ten",
                    "z_rel": 0.0},
                    {"region_name": "eleven",
                    "z_rel": -0.2},
                    {"region_name": "twelve",
                    "z_rel": -0.4}
                ]
            }
        }
```

In the bedload block, the bedload transport formula is chosen, the lateral bed slope according to the formula of Ikeda is defined as well as the morphological boundary conditions. The boundary condition is defined as transport_capacity at the inflow boundary. The value of the sediment flux is averaged over the stringdef length and equally distributed (same value) among the edges. The outflow boundary has been reduced to the bed width composed of 6 nodes only. Therefore, the nodes located on the channel levee of the outflowing stringdefs have been removed from the .2dm file (computational mesh) manually using a text editor. The stringdef definition remains unchanged and the outflow boundary is defined as equilibrium_out with the reference bottom elevation set to 1700.68 m.

```
"BEDLOAD": {
                    "FORMULA": {
                        "type": "MPM_like",
                        "factor":1.0,
                        "coefficient":3.2,
                        "exponent":1.6,
                        "critical_value":0.047
                    },
                    "DIRECTION": {
                        "IKEDA": {
                            "factor": 1.5
                        }
                    },
```

```
                        "BOUNDARY":{
                            "STANDARD": [
                                {
                                    "name": "inflow_MOR",
                                    "string_name": "Inflow",
                                    "type": "transport_capacity",
                                    "boundary_factor": 0.8
                                },
                                {
                                    "name": "outflow_MOR",
                                    "string_name": "Outflow",
                                    "type": "equilibrium_out",
                                    "reference_bed_elevation": 1700.68
                                }
                            ]
                        }
                    }
```

1.1.4.2 Set up the configuration file simulation.json

The simulation time defined in the simluation.json file is the same as for the unsteady flow in the hydraulics simulation and two additional outputs are defined.

```
{
        "OUTPUT": [
            "...",
            "water_depth",
            "delta_z",
            "ns_mor_discharge"
        ]
    }
}
```

1.1.4.3 Results

The morphological changes of the river bed are observed on Figure 1.5. The software ParaView was used for the post-processing of the output file (.xdmf).

1.2 Post-processing

BASEMENT version 3.x simulation results are generated inside the scenario directory and stored in binary format ".h5". These results are converted into specific output type that can be visualized and modified by external softwares. Two types of output are available, ".xdmf" for the values calculated over the cells and ".csv" for the values calculated at stringdefs. The ".xdmf" output type is defined in the configuration file results.json (Section 1.1.3.3). The delimited text file (.csv) is generated by calling the python script "BMv3NodestringResults.py".

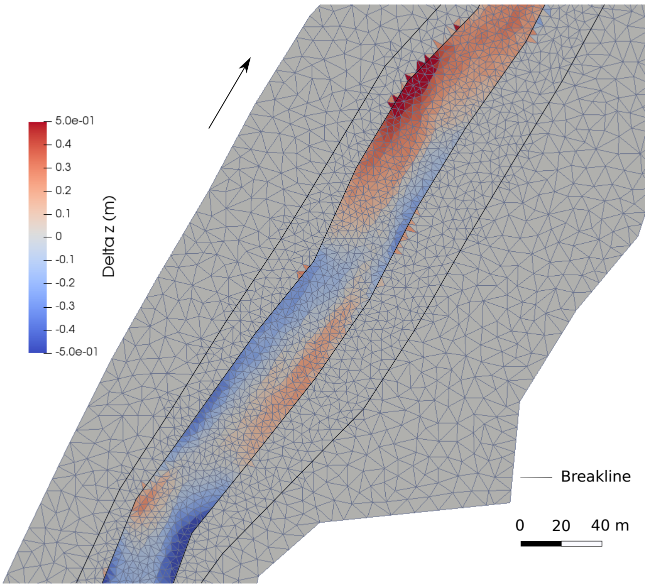


Figure 1.5 *Planar view of the widening part of the river Flaz with the change in bed elevation (Delta z) due to the flood event at the end of the morphodynamic simulation (t= 84'000 s)*

1.2.1 ParaView

The free and open source application ParaView is used to generate 2D views of BASEMENT version 3.x simulation results. The .xdmf file can be imported into ParaView to visualize the output data calculated over the cells like for example the water_depth, bottom_elevation and flow_velocity_abs.

Figure 1.5 gives an example of post-processing using ParaView for the morphological changes (delta z). A tutorial of the software ParaView is given in section 2.3 of BASEMENT 2.8 Tutorial for 3D visualization of the results. Be careful, only 2D visualization is available in ParaView for the output of BASEMENT version 3.x. Therefore, only a planar view of the results is available (see Figure 1.5).

1.2.2 Extract data from result file

This tutorial shows how to extract values from the stringdefs, i.e. boundaries to obtain the results of Figure 1.2. The python script BMv3NodestringResults.py can be downloaded from www.basement.ethz.ch and should be saved inside the scenario directory generated. The python script will read the stringdef data stored inside the _results.h5 file and convert them into a delimited text format (.csv). The data calculated at the stringdef are the discharge, the mean water surface elevation (wse), the wetted area, the mean bottom elevation, reference elevation, wetted geometric length, total water volume stored in cells of the stringdef, total conveyance of cells, the morphological flux and the bedload transport.

To generate the .csv text file:

1. Save the BMv3NodestringResults.py file inside the scenario directory
2. Open a command window

3. Change folder and go inside the scenario directory
4. Call the python script with

```
$ python BMv3NodestringResults.py
```

As output, a result.csv, discharge.csv and time step.csv are generated. The discharge.csv provides the discharge value for each stringdef (columns) listed in the same order of appearance as in the .2dm file. The rows stand for the simulation time step at which the output are generated (first row is the initial time t= 0.0 s). The number of time step is given as a list in the time step.csv file. Every available result of the stringdefs is defined in the header of the results.csv file, where the rows correspond to the list of stringdefs in the same order of appearance as in the .2dm file and for every time step.

2

Test cases

2.1 Introduction and Backends

2.1.1 Introduction

The test cases present well-defined hydro- and morphodynamic numerical simulations that are used to asses the performance and accuracy of the simulations with BASEMENT version 3.0. The test cases have an analytical solution to which the numerical solution is compared in order to evaluate the accuracy of the results. The numerical simulations are executed on different backends that influence the performance of the simulation.

2.1.2 Backends

Different backends are used to execute the simulations of the test cases. A central processing unit (CPU) with a sequential application on 1 core, CPU with parallel applications (OpenMP) on 2, 4, 8, 16 and 32 cores, double graphic processing units (GPU) with a compute unified device architecture (CUDA) running on 1 core for low application programming interface (API) and finally single GPUs for high API. The features of the GPU backends are shown in Table 2.1.

Table 2.1 *Features of the GPU hardware used for the numerical simulations*

Card	K20	P100	GTX 1080 Ti	GTX 1070 Ti	GTX 1050 Ti	Quadro P620
Memory [GB]	5	12	11	8	4	2
Architecture	Kepler	Pascal	Pascal	Pascal	Pascal	Pascal
Bandwidth [GB/s]	208	549	484	256	112	80
CUDA cores	2496	3584	3584	2432	768	512

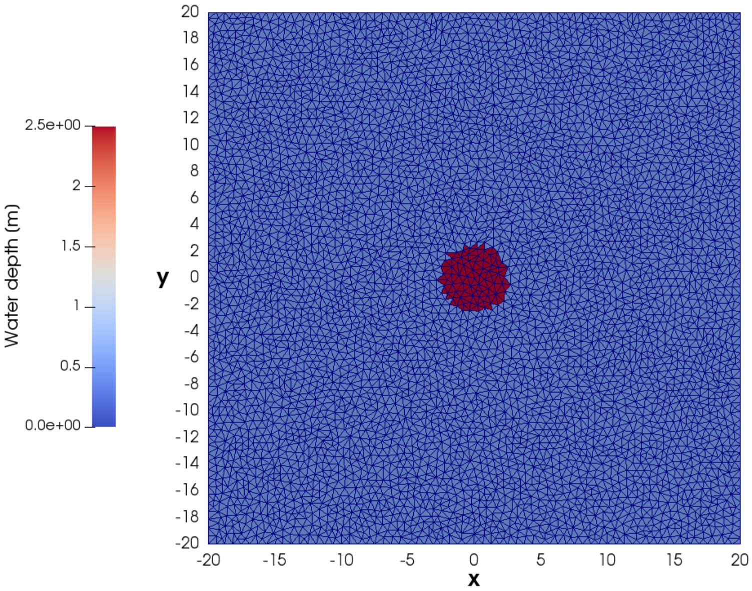


Figure 2.1 *Computational domain of the circular dam break (10k cells) with initial water depth.*

2.2 Circular dam break

2.2.1 Description

The circular dam break problem represents a 2D Riemann problem based on the sudden collapse of an idealized circular dam over a horizontal bottom. The aim is to evaluate the ability of the model to solve the wave propagation, i.e. the complex interaction of shock and rarefaction waves induced by a dam break event. The results are quantitatively compared with a reference solution obtained as described in Toro (2001).

2.2.2 Geometry and initial conditions

The computational domain is a squared area of size 40 x 40 m and composed of unstructured triangular cells. The circular dam has a diameter of 5 m and is located at the center of the computational domain ($x = 0$, $y = 0$). Initially, the water is at rest and the depth inside the circular dam is 2.5 m and 0.5 m over the surrounding domain. No friction and no slope (horizontal bottom) is considered and the CFL number is set to 0.9. As the simulation starts (time 0.0 s), the dam is removed and the subsequent wave pattern is observed during 4.7 s, after which the simulation stops. Different mesh resolutions are used in the test case, the smallest mesh resolution contains exactly 9'927 cells (10k), the second 49'450 cells (50k), the third 99'416 cells (100k), the fourth 497'092 cells (500k) and the finest mesh resolution contains 994'092 cells (1000k). Figure 2.1 shows the initial conditions of the circular dam break with the computational domain of 10k cells.

2.2.3 Results

The evolution of the water depth is described along a reference cross-section located between ($x = -20$, $y = 0$) and ($x = 20$, $y = 0$), see Figure 2.2. The reference solution is obtained from Toro (2001) using the exact Riemann solver on a mesh of about 1000 cells. After the collapse of the circular dam at t = 0.0 s, the primary shock wave propagates outwards. At the same time, a rarefaction wave that propagates towards the center of the dam is observed. The rarefaction wave will implode at the grid center before t=0.4 s and then travel in outward direction inducing a rapid drop of the water elevation which will reach a level below the initial outer water surface elevation (t=1.4 s) in the center area. The primary shock wave travels outwards with decreasing strength while a secondary shock wave develops in opposite direction towards the center and finally generates a jump in the water depth at the grid center (t=4.7 s).

The results on Figure 2.2 show how the solution obtained with BASEMENT version 3.0 (first order HLLC method) correctly converges to the reference solution as the grid is refined. The cylindrical symmetry of the wave propagation in BASEMENT is maintained, even if water surface modulations are observed along the primary shock wave.

The relative error is computed for the water depth (e_H) and speed (e_u) using eq. 2.1 and for various reference elevations. The result is displayed in Figure 2.3.

$$e_X = \frac{|X_{BM} - X_{ref}|}{X_{ref}} \tag{2.1}$$

Where X stands either for the water surface elevation H or the velocity u with X_{BM} the result of the simulation with BASEMENT and X_{ref} the reference value of Toro (2001).

The relative L^2 norm error (eq. 2.2, e.g Vanzo et al. (2016)) is calcutated for each mesh size using the water surface elevation of the simulation result of BASEMENT (H_{BM}) and the references solution (H_{ref}) of Toro (2001). The result is shown on Table 2.2. The relative norm error decreases for finer meshes.

$$L^2 = \sqrt{\frac{\sum_{i=1}^{N}(H_{ref}(i) - H_{BM}(i))^2}{\sum_{i=1}^{N} H_{ref}(i)^2}} \tag{2.2}$$

Table 2.2 *Relative L^2 norm error of the water surface elevation H compared to the reference solution of Toro (2001) at t=4.7 s.*

	10k	50k	100k	500k	1000k
L^2	0.1134	0.0523	0.0453	0.0184	0.0145

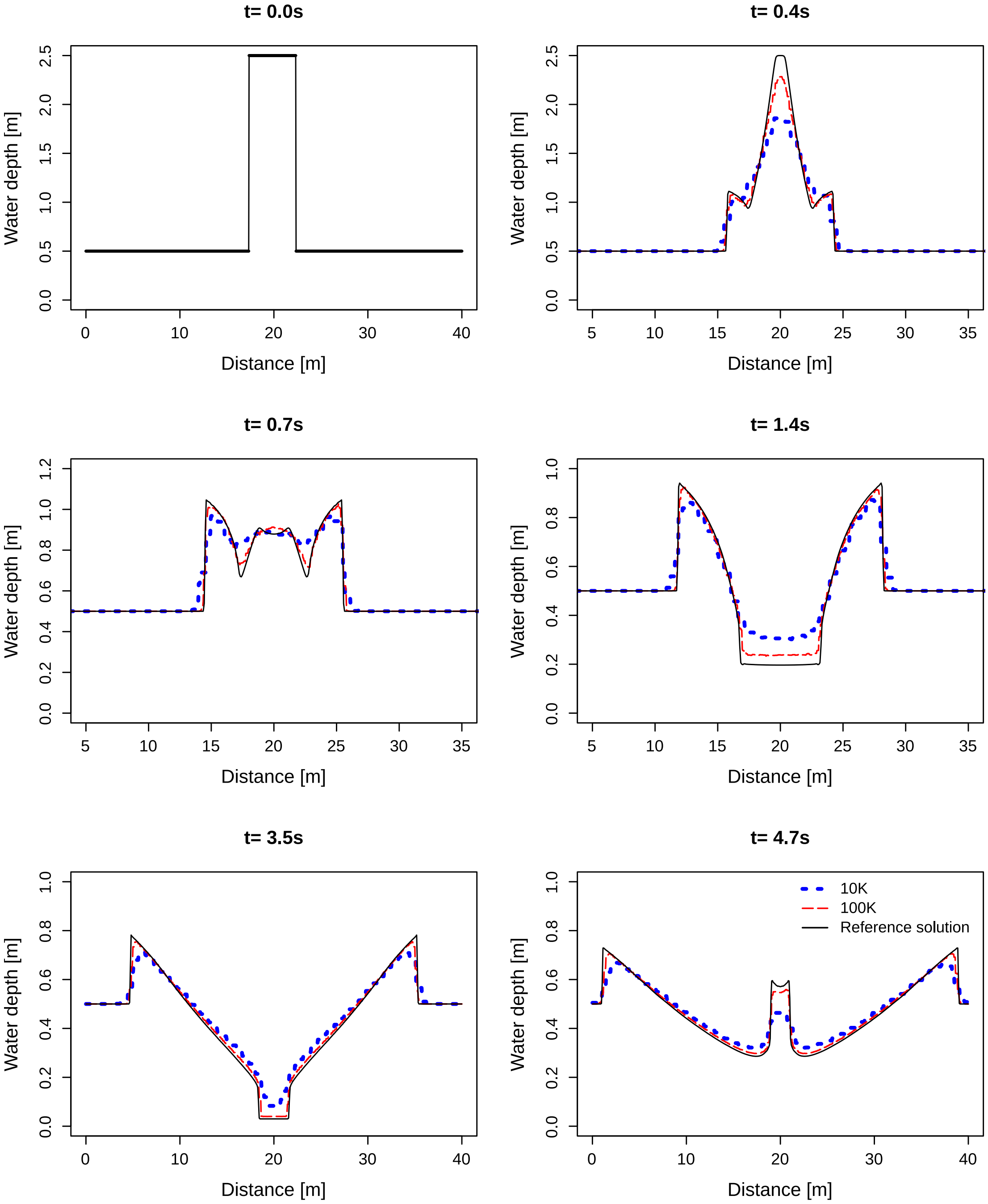


Figure 2.2 *Snapshots of the water depth evolution along the reference cross-section. Comparison between BASEMENT simulations with a computational grid of 10k cells, 100k cells and the reference solution of Toro (2001).*

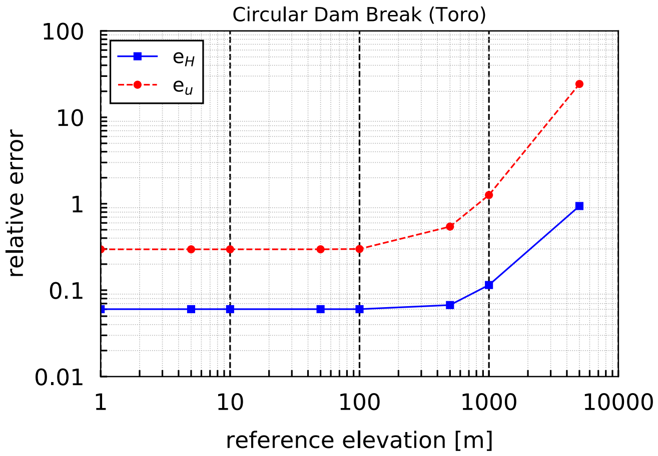


Figure 2.3 *Relative error compared to the reference solution of Toro (2001)*

2.2.4 Performance

The performance is measured as speedup S, which is defined as the ratio between the reference execution time T_1 (Xeon 1) and execution time of parallel or GPU backends T_N. The speedup states how much faster the parallel and GPU applications run compared to the reference execution time. The actual speedup is determined by several factors whose influences largely depend on size and type of the simulation.

2.2.4.1 Ubuntu

Tables 2.3, 2.4 and 2.5 contain the execution time and speedup of all the simulations performed on different backends under Linux. The backends belong to two cathegories, either in Central Processor Units (CPU) or Graphics Processor Units (GPU). The CPU run simulations exclusively with a double precision, while GPU can perform simulations with a single or double precision. More details are explained in Section 2.1.2.

Table 2.3 *Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Ubuntu 16.04 (Intel Xeon Gold 6154, 3.00GHz)*

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
10k	0.36	0.19 (1.89x)	0.11 (3.27x)	0.06 (6.00x)	0.04 (9.00x)	0.04 (9.00x)
50k	3.98	2.08 (1.91x)	1.13 (3.52x)	0.61 (6.52x)	0.34 (11.71x)	0.22 (18.09x)
100k	11.48	5.98 (1.92x)	3.19 (3.60x)	1.68 (6.83x)	0.89 (12.90x)	0.52 (22.08x)
500k	137.57	70.18 (1.96x)	36.76 (3.74x)	18.82 (7.31x)	9.57 (14.38x)	4.93 (27.90x)
1000k	409.59	200.36 (1.96x)	108.98 (3.76x)	55.55 (7.37x)	28.15 (14.55x)	14.38 (28.48x)

Table 2.4 *Computational time (s) and speedup (in parentheses) of the circular dam break simulations for GPU simulations*

Mesh size	Xeon 1 Double	Quadro P620 Single	Quadro P620 Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
10k	0.36	0.05 (7.20x)	0.06 (6.00x)	0.04 (9.00x)	0.04 (9.00x)	0.04 (9.00x)	0.04 (9.00x)
50k	3.98	0.28 (14.21x)	0.48 (8.29x)	0.16 (24.88x)	0.21 (18.95x)	0.18 (22.11x)	0.19 (20.95x)

Mesh size	Xeon 1 Double	Quadro P620 Single	Quadro P620 Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
100k	11.48	0.66 (17.39x)	1.24 (9.26x)	0.34 (33.76x)	0.46 (24.96x)	0.36 (31.89x)	0.39 (29.44x)
500k	137.57	5.83 (23.60x)	12.94 (10.63x)	2.29 (60.07x)	3.89 (35.37x)	2.17 (63.40x)	2.58 (53.32x)
1000k	409.59	16.39 (24.99x)	37.32 (10.98x)	5.84 (70.14x)	10.56 (38.79x)	5.11 (80.15x)	6.35 (64.50x)

Table 2.5 *Computational time (s) and speedup (in parentheses) of the circular dam break simulations for GPU simulations*

Mesh size	Xeon 1 Double	GTX 1050 Single	GTX 1050 Double	GTX 1070 Single	GTX 1070 Double	GTX 1080 Single	GTX 1080 Double
10k	0.36	0.03 (12.00x)	0.05 (7.20x)	0.03 (12.00x)	0.03 (12.00x)	0.03 (12.00x)	0.04 (9.00x)
50k	3.98	0.21 (18.95x)	0.35 (11.37x)	0.13 (30.62x)	0.18 (22.11x)	0.13 (30.62x)	0.16 (24.88x)
100k	11.48	0.48 (23.92x)	0.78 (14.72x)	0.30 (38.27x)	0.41 (28.00x)	0.25 (45.92x)	0.34 (33.76x)
500k	137.57	3.60 (38.21x)	7.25 (18.98x)	1.96 (70.19x)	3.17 (43.40x)	1.62 (84.92x)	2.46 (55.92x)
1000k	409.59	9.80 (41.79x)	20.57 (19.91x)	4.94 (82.91x)	8.40 (48.76x)	3.96 (103.43x)	6.40 (64.00x)

Figure 2.4 shows the speedup achieved by the different backends, where the biggest time improvement is observed for the GPU single precision. The speedup increases particularly for meshes with a fine resolution (500K and 1000K) using GPU.

Figure 2.5 compares the speedup with the number of threads (CPU) between the different mesh resolutions. The simulations were performed using the CPU backend type Intel Xeon Gold 6154 (3.00GHz). The speedup is more effective for meshes with a fine resolution than for those of coarse resolution, where the increase in number of cores leads to a plateau.

2.2.4.2 Windows

Tables 2.6 contains the execution time and speedup of all the simulations performed on different backends under Windows. The simulations were run on Intel Xeon E5-2667 v3, 3.20GHz processors with a double precision.

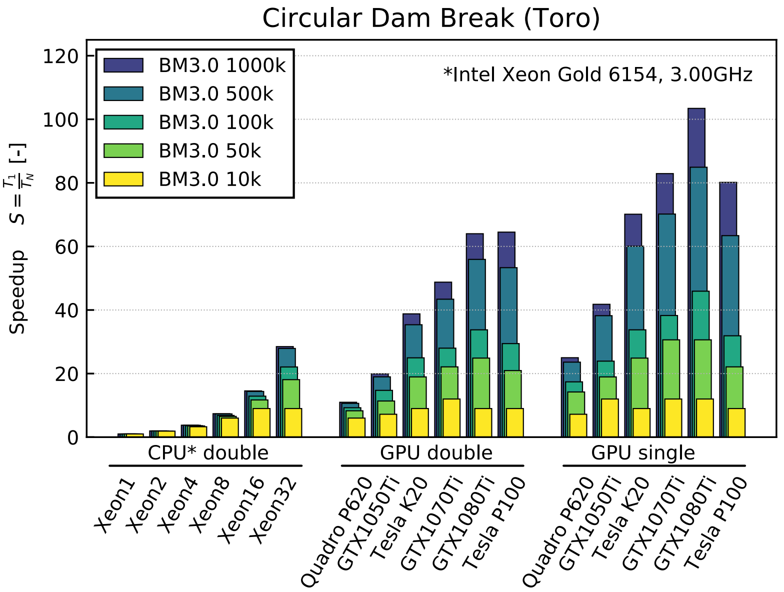


Figure 2.4 *Speedup of the computational time [T_N] for CPU (double) and GPU (single and double) compared to the time of the sequential backend Xeon1 [T_1] for the circular dam break*

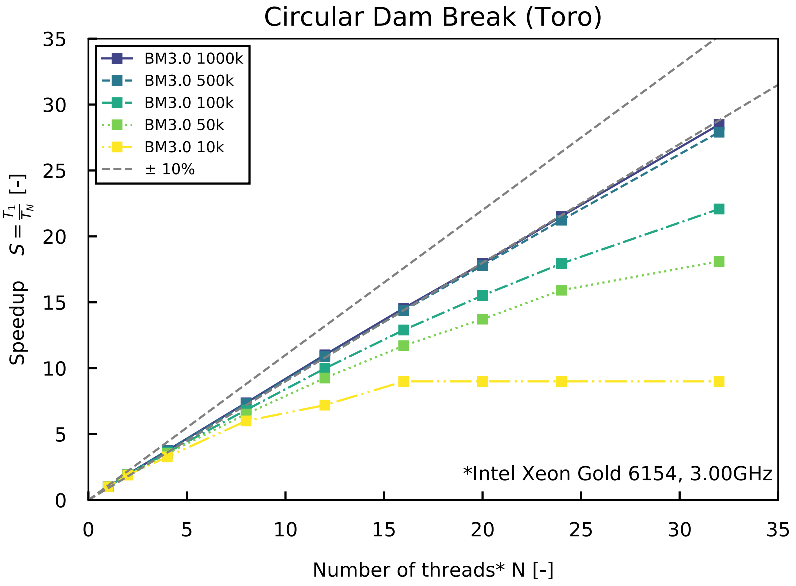


Figure 2.5 *Speedup of the computational time [T_N] using different number of threads (CPU) compared to the time of the sequential backend Xeon1 [T_1] for the circular dam break*

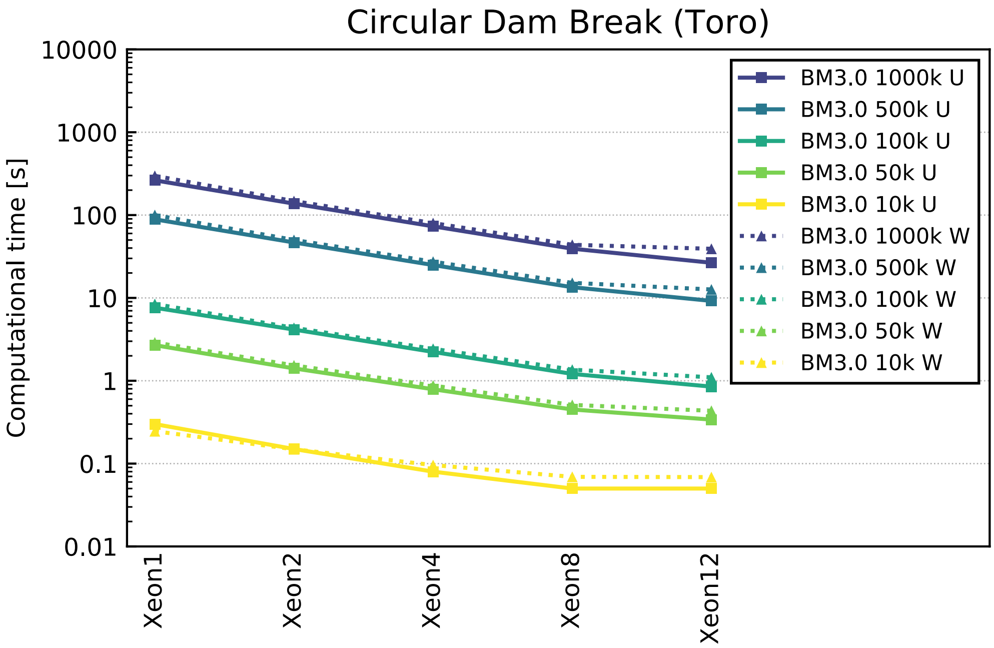


Figure 2.6 *Comparison of computational time using different number of threads (CPU) under Windows and Ubuntu on Intel Xeon E5-2667 v3, 3.20GHz processors.*

Table 2.6 *Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Windows 10 (Intel Xeon E5-2667 v3, 3.20GHz)*

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 12 Double
10k	0.25	0.17 (1.53x)	0.10 (2.50x)	0.07 (3.57x)	0.07 (3.57x)
50k	2.90	1.53 (1.90x)	0.88 (3.30x)	0.51 (5.68x)	0.43 (6.74x)
100k	8.44	4.35 (1.94x)	2.44 (3.45x)	1.36 (6.2x)	1.10 (7.67x)
500k	100.12	50.09 (1.99x)	27.40 (3.69x)	15.20 (6.58x)	12.65 (7.91x)
1000k	297.61	147.53 (2.00x)	80.06 (3.71x)	43.81 (6.9x)	39.18 (7.58x)

The comparison of the executation time between Windows and Ubuntu in Figure 2.6 shows a very similar performance. The scalability under Ubuntu seems slightly better than under Windows 10.

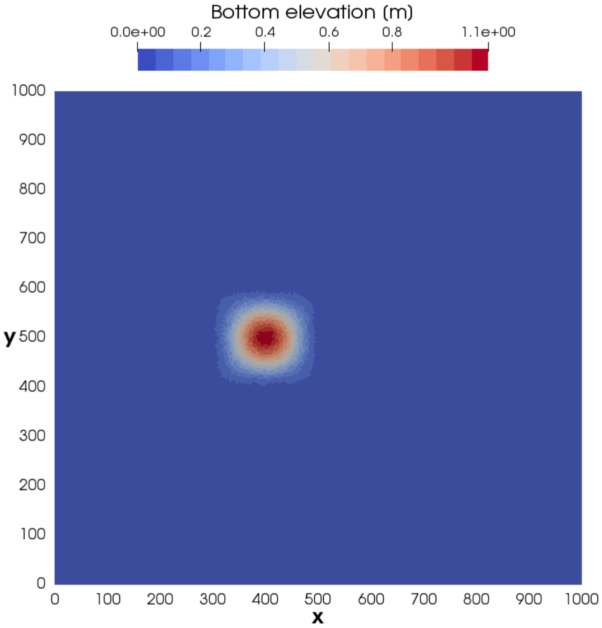


Figure 2.7 *Initial bottom elevation of the conical dune, maximum elevation of 1.1 m at [x=400, y=500].*

2.3 Conical dune

2.3.1 Description

The conical dune test proposed by Hudson and Sweby (2005) is used to assess the performance of two dimensional morphodynamic models under sub-critical flow and without friction. The simulation describes the evolution of an initial conical dune of sediments that evolves in a star shaped pattern characterized by a spread angle α_s. Numerical results are compared with the approximate analytical solution for the spread angle of the disturbance front proposed by de Vriend (1987).

2.3.2 Geometry and initial conditions

The computational mesh is a squared area of size 1000 x 1000 m with an initial bottom elevation $z_{B,initial}$ (see Figure 2.7):

$$z_{B,initial} = \begin{cases} 0.1 + sin^2\left(\frac{\pi(x-300)}{200}\right) sin^2\left(\frac{\pi(y-400)}{200}\right) & \text{for } x \in [300, 500] \\ & \text{and } y \in [400, 600] \\ 0.1 & \text{otherwise} \end{cases} \tag{2.3}$$

An inflow boundary condition of Froude type is defined along the y-axis at x=0 setting a constant unit discharge of 10 m/s. At x=1000 m, a h-Q relation is defined as outflow boundary condition. The initial water depth is 10 m and the water surface elevation is kept constant at the boundaries. The Strickler coefficient is set to $K_s = 10^7 [m^{1/3}/s]$ in order to obtain an almost frictionless simulation. The CFL number is set to 0.8, the

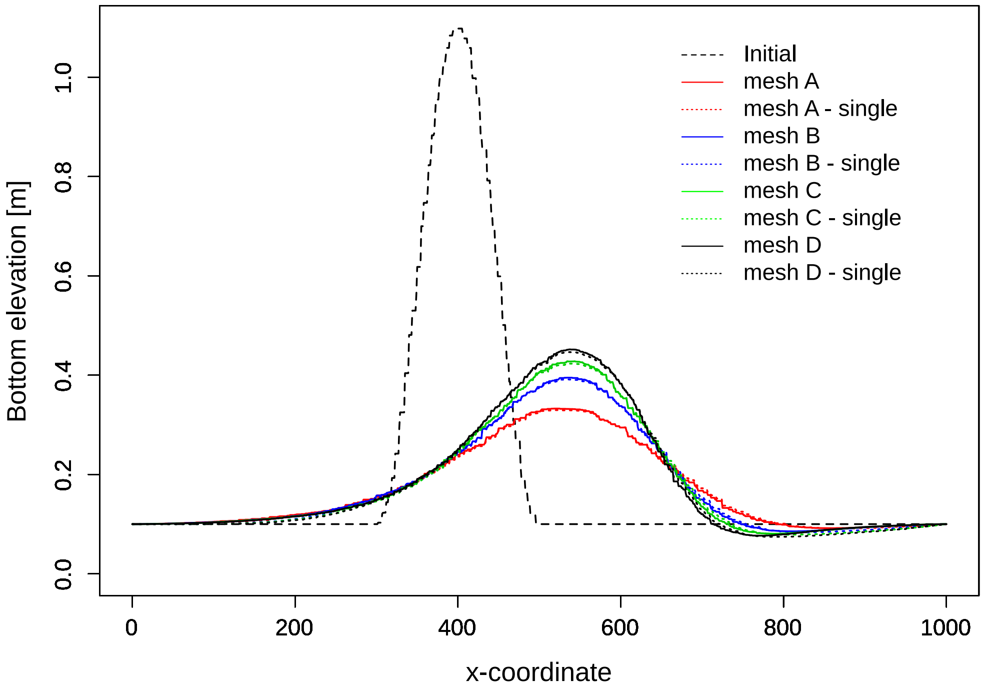


Figure 2.8 *Longitudinal bottom elevation profile at y= 500 m for initial conditions and after 100h of simulation for the meshes A, B, C and D with double and single precision*

porosity to 0.4 and the morphodynamic boundary conditions are at equilibrium. Bed load transport is computed using the Grass formula with the parameters $A_G = 0.001002$ and $m_G = 3$ assuming a slow interaction between the sediment layer and the water flow. The analytical solution for the spread angle (eq. 2.4) proposed by de Vriend (1987) gives a value of $\alpha_{s,ref} = 21.787°$.

$$\alpha_s = arctan\left(\frac{3\sqrt{3}(m_G - 1)}{9m_G - 1}\right) \tag{2.4}$$

The tests were performed with different computational mesh resolution, mesh A has 30160 cells (30k), mesh B 61201 cells (60k), mesh C 91083 cells (90k) and mesh D 126020 cells (120k). The simulation results were analyzed after 100 hours and each test was performed using different backends.

2.3.3 Results

Figure 2.8 shows the bed elevation profile at $y = 500$ m along the x-coordinates at the beginning and after 100 h of the simulation for the four different meshes (A, B ,C and D) performed with double and single precision. The results are exactly the same for all processor types, except for the simulation performed with CUDA-single, where the values are slightly different due to the reduced precision.

Table 2.7 summarizes the results obtained from the numerical simulations at t=100h for

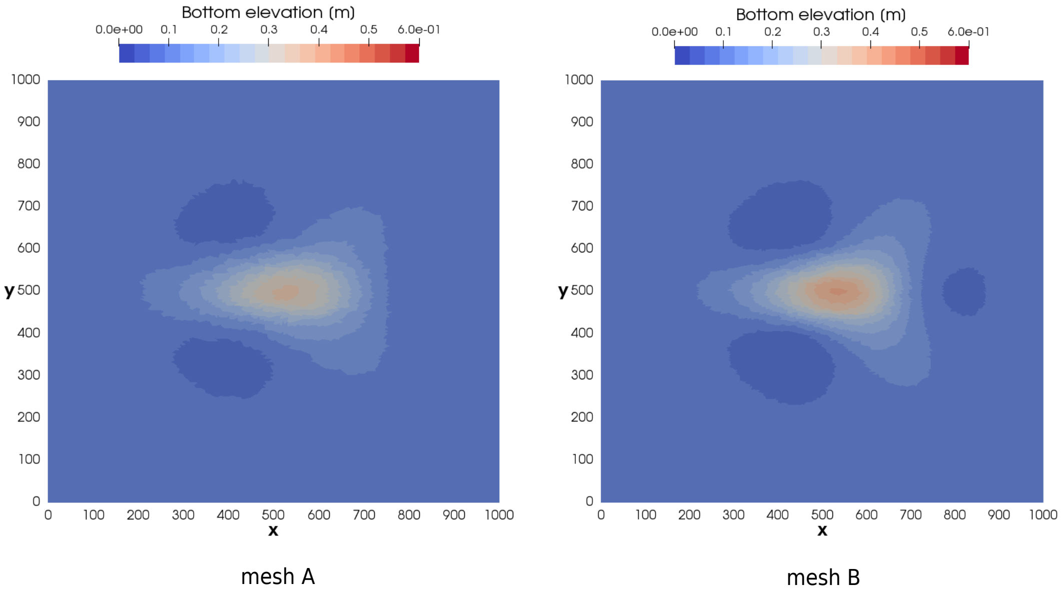


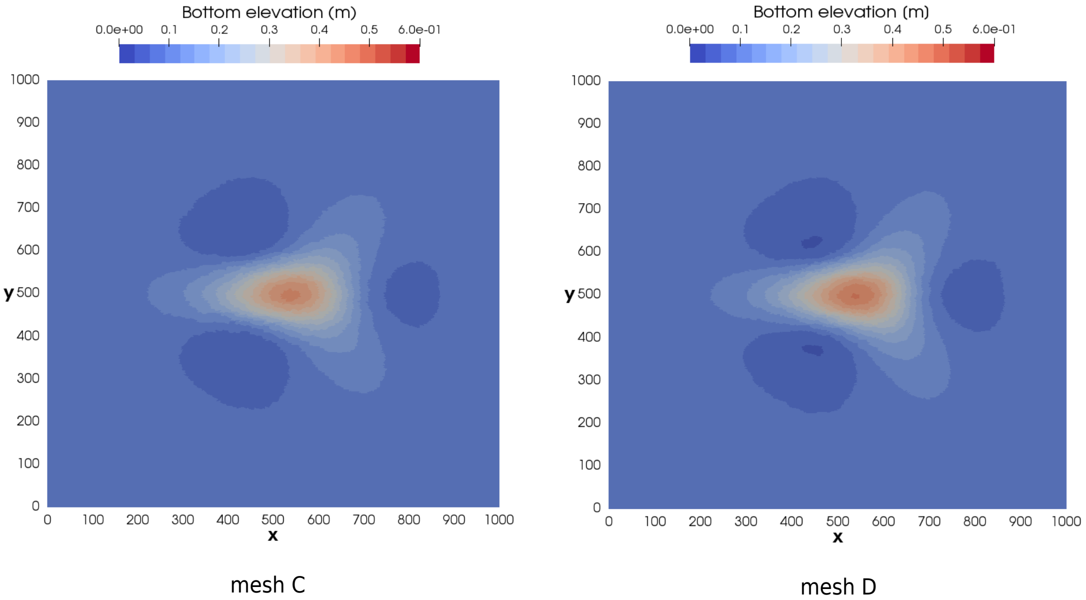
Figure 2.9 *Planar view of the bottom elevation after 100 hours of simulation for the meshes A and B.*

the different meshes using the backend types CPU and GPU-double. The spread angle α_s is measured between $y = 500$ m and the line passing through the initial conical dune center point and the farthest point in the x-direction where the conical dune spread for a similar bottom elevation (Figure 2.9 and Figure 2.10). The spread angle was measured at time t=25h, 50h, 75h and 100h for each mesh size and the mean value is reported in Table 2.7. The accuracy of the simulations is assessed by the relative deviation between the measure spread angle α_s and the spread angle defined by de Vriend (1987) $\alpha_{s,ref}$.

Table 2.7 *Summary of the simulation results performed with CPU and GPU double at t=100h for different computational meshes*

Mesh	Number of cells [-]	Max. cone elevation [m]	α_s [°]	Relative deviation [%]
A	30160	0.3327	25.57	16.0
B	61201	0.3950	25.12	14.2
C	91083	0.4279	23.94	9.4
D	126020	0.4518	23.35	6.9

The maximum bottom elevation after 100h increases with the mesh resolution while the spread angle decreases (Table 2.7). The results are more accurate for finer meshes (mesh C and mesh D, Figure 2.8), where less diffusive sediment transport is observed and thus the maximum bottom elevation after 100h is higher than for coarser meshes. This increase in accuracy for finer meshes is also observed in Figure 2.9 and Figure 2.10 by a well defined star shaped sediment transport and a spread angle that becomes closer to the value proposed by de Vriend (1987).



mesh C

mesh D

Figure 2.10 *Planar view of the bottom elevation after 100 hours of simulation for the meshes C and D.*

2.3.4 Performance

In total, 18 simulations were performed on different backends. The execution time depends on the mesh size, the computing processor and the number of cores used. The execution time is at maximum using the sequential platform and decreases using CPU accordingly to the number of cores used. The best performance reaches a speedup of two orders of magnitude using the GPU backend (Tables 2.8, 2.9 and 2.10).

The performance of the different running platforms is compared with respect to the sequential running time (1 core). CUDA GPU-based processor proves its efficiency by showing a speedup increase for finer meshes, while the speedups of the CPU-based OpenMP platform increase with the increasing number of core, independently from the mesh type.

Table 2.8 *Computational time (h) and speedup S (inside brackets) of the conical dune simulations for CPU simulations (Intel Xeon E5-2667 v3, 3.20GHz)*

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 12 Double	Xeon 14 Double
30k	7.26	3.88 (1.87x)	2.01 (3.61x)	1.04 (6.95x)	0.75 (9.71x)	0.65 (11.09x)
60k	23.08	11.95 (1.93x)	6.10 (3.78x)	3.15 (7.33x)	2.19 (10.52x)	1.94 (11.93x)
90k	38.47	20.45 (1.88x)	10.47 (3.67x)	5.40 (7.13x)	3.58 (10.74x)	3.27 (11.75x)
120k	61.30	32.48 (1.89x)	16.52 (3.71x)	8.43 (7.27x)	5.87 (10.44x)	5.19 (11.81x)

Table 2.9 *Computational time (s) and speedup S (inside brackets) of the conical dune simulations for GPU simulations*

Mesh size	Xeon 1 Double	Quadro P620 Single	Quadro P620 Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
30k	7.26	0.59 (12.34x)	1.12 (6.49x)	0.53 (13.69x)	0.38 (18.98x)	0.28 (25.85x)	0.32 (22.44x)
60k	23.08	1.40 (16.46x)	2.98 (7.73x)	1.15 (20.08x)	0.78 (29.61x)	0.51 (45.66x)	0.63 (36.45x)
90k	38.47	2.06 (18.64x)	4.71 (8.17x)	1.68 (22.87x)	1.10 (35.07x)	0.67 (57.51x)	0.84 (45.70x)
120k	61.30	3.13 (19.64x)	7.40 (8.29x)	2.41 (25.47x)	1.45 (42.15x)	0.87 (70.25x)	1.22 (50.19x)

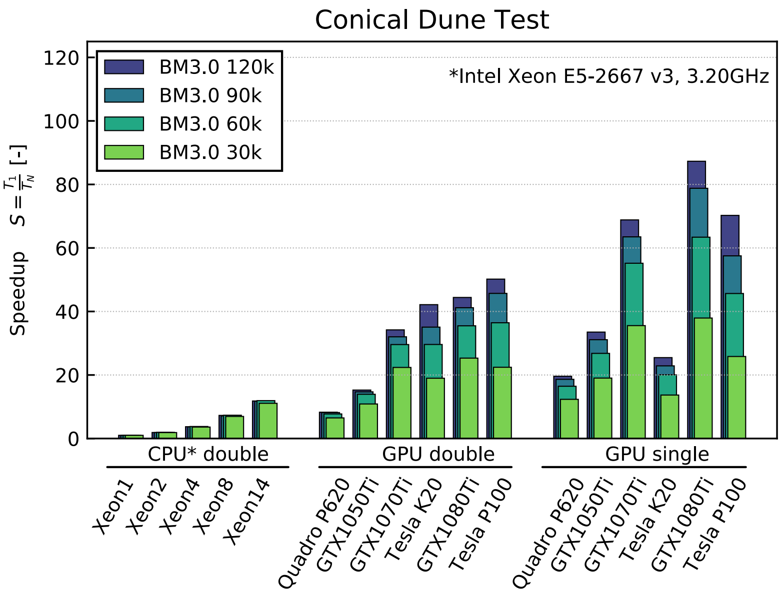


Figure 2.11 *Speedup of the computational time [T_N] for CPU (double) and GPU (single and double) compared to the time of the sequential backend Xeon1 [T_1] for the conical dune test case*

Table 2.10 *Computational time (s) and speedup S (inside brackets) of the conical dune simulations for GPU simulations*

Mesh size	Xeon 1 Double	GTX 1050 Single	GTX 1050 Double	GTX 1070 Single	GTX 1070 Double	GTX 1080 Single	GTX 1080 Double
30k	7.26	0.38 (19.03x)	0.67 (10.87x)	0.20 (35.55x)	0.32 (22.38x)	0.19 (37.94x)	0.29 (25.31x)
60k	23.08	0.86 (26.81x)	1.66 (13.93x)	0.42 (55.19x)	0.78 (29.58x)	0.36 (63.39x)	0.65 (35.49x)
90k	38.47	1.24 (31.11x)	2.62 (14.69x)	0.61 (63.50x)	1.20 (32.02x)	0.49 (78.79x)	0.93 (41.18x)
120k	61.30	1.83 (33.51x)	4.02 (15.26x)	0.89 (68.83x)	1.79 (34.21x)	0.70 (87.30x)	1.38 (44.41x)

Figure 2.11 shows the speedup achieved by the different backends, where the biggest time improvement is observed for the GPU single precision.

Figure 2.12 compares the speedup with the number of threads (CPU) between the different mesh resolutions. The simulations were performed using the CPU backend on an Intel Xeon E5-2667 v3 (3.20GHz) processor.

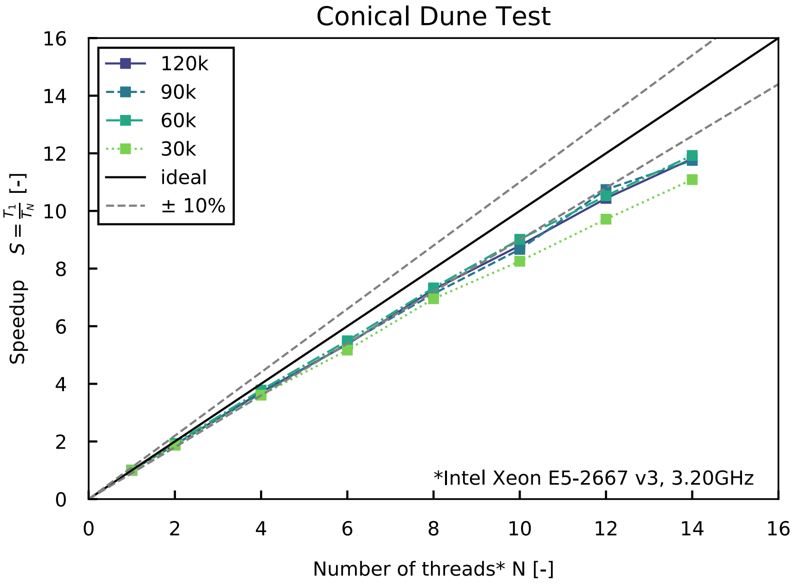


Figure 2.12 *Speedup of the computational time [T_N] using different number of threads (CPU) compared to the time of the sequential backend Xeon1 [T_1] for the conical dune test case*

3

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APPENDIX

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1

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PCRE2

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included in the distribution is a just-in-time compiler that can be used to
optimize pattern matching. This is an optional feature that can be omitted when
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THE BASIC LIBRARY FUNCTIONS
---------------------------

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2006-Jan-27

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