

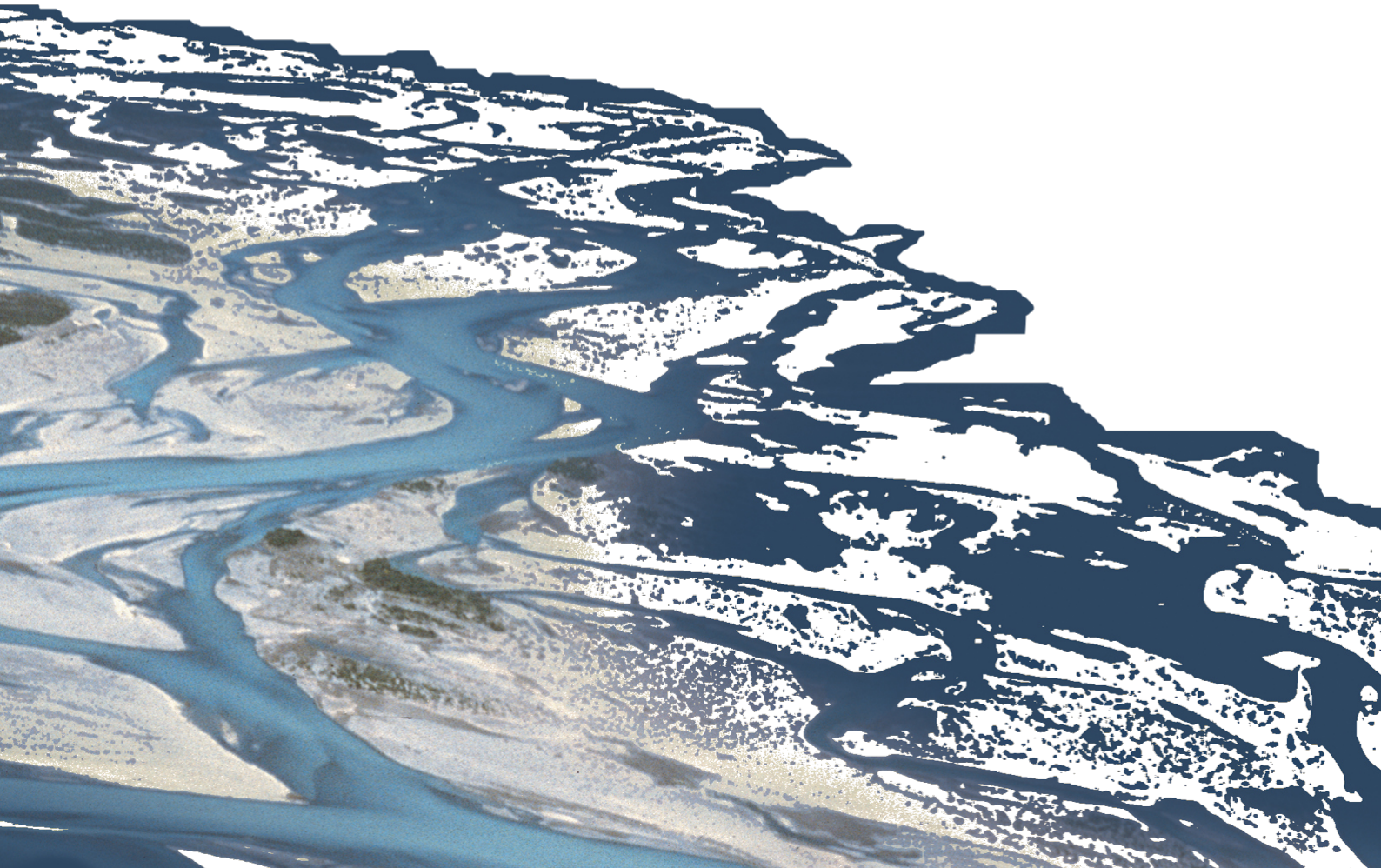


BASEMENT

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

SYSTEM MANUALS

**VERSION 3.2
May 2022**



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 customer 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.



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 customer 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. Fähr 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 3.2.0

May 2022

Credits

Current Team Members

Software Development, Documentation and Test (alphabetical)

M. Bürgler, MSc. ETH Environmental Eng.

F. Caponi, MSc. Environmental Eng.

Dr. D. Conde, MSc. Civil Eng.

S. Kammerer, MSc. ETH Environmental Eng.

Dr.techn. M. Weberndorfer, MSc.

Scientific Board

Prof. Dr. R. Boes, Director VAW, Member of Project Board

Dr. A. Siviglia, MSc, Scientific Advisor

Dr. D. Vanzo, MSc. Environmental Eng., Scientific Advisor

Dr. D. Vetsch, Dipl. Ing. ETH, Project Director

Former Project Members

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

Commissioned and co-financed by

Swiss Federal Office for the Environment (FOEN)

Contact

Website: <https://www.basement.ethz.ch>

User forum: <https://people.ee.ethz.ch/~basement/forum>

© 2022 ETH Zurich / Laboratory of Hydraulics, Glaciology and Hydrology (VAW)

For list of contributors see <https://www.basement.ethz.ch>



Laboratory of Hydraulics,
Hydrology and Glaciology



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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. 2022. System Manuals of BASEMENT, Version 3.2.0. 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, 2022. <https://www.basement.ethz.ch>

For Software:

BASEMENT – Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation. Version 3.2.0 © ETH Zurich, VAW, 2022.

License

End-User License Agreement (EULA)

THIS EULA IS INTENDED FOR COMMERCIAL AND NON-COMMERCIAL PURPOSES. FOR QUESTIONS RELATED TO THIS AGREEMENT PLEASE CONTACT: Dr. David Vetsch, basement@ethz.ch

This End-User License Agreement (“EULA”) is a legal agreement between you (“You”) (an individual or acting on behalf of a company) and ETH Zurich, Raemistrasse 101, 8092 Zurich (Switzerland) (“ETH Zurich”) for the binary software code of **BASEMENT** and associated media, and may include “online” or electronic documentation (“SOFTWARE”).

The SOFTWARE simulates water flow, sediment and scalar transport in rivers and according interaction in consideration of movable boundaries and morphological changes. Further information and description of the SOFTWARE is available here: <https://basement.ethz.ch/>

The SOFTWARE is protected by copyright laws. The SOFTWARE is hereby licensed, not sold.

In order to install and use the SOFTWARE, You must indicate agreement with the following terms and conditions by clicking “ACCEPT” at the end of this EULA during the installation process.

1 LICENSE GRANT

- (i) ETH Zurich hereby grants to You, and in case You are acting on behalf of a company also to the employees of such company, a free-of-charge, single, non-exclusive, world-wide, non-transferable, non-sublicensable right to install, execute and display the SOFTWARE on device(s) running a validly licensed copy of the operating system for which the SOFTWARE was designed. Such rights are granted for commercial and non-commercial purposes.
- (ii) With respect to electronic documents included with the SOFTWARE, You may make an unlimited number of copies (either in hardcopy or electronic form), provided that such copies shall be used only for internal purposes and are not republished or distributed to any third party.

2 USE OF RESULTS GENERATED BY THE SOFTWARE

You are allowed to use the content generated by the SOFTWARE (“SOFTWARE RESULTS”) for commercial and non-commercial purposes.

Note that any attribution (e.g. ETH Zurich logo) on the SOFTWARE RESULTS must be retained. You are not allowed to alter, cancel or fade, after a few seconds, such attribution.

3 THIRD PARTY CODE

The SOFTWARE may contain other program code from third parties. A list of other third party code and libraries used by this SOFTWARE is available here: <https://basement.ethz.ch/about/thirdpartysoftware>

Their license applies to such third party code and libraries contained herein. Refer to the above internet site for the licenses and copyrights.

4 DURATION OF LICENSE AND TERMINATION

This EULA enters into effect on the date of acceptance of this EULA by You. This EULA,

- (i) may be terminated by ETH Zurich at any time for any reason;
- (ii) will terminate automatically without notice from ETH Zurich if (a) You fail to comply with any term(s) of this EULA or (b) You refuse, after the notification in accordance with clause 10 (i), to accept the new EULA term and conditions provided by ETH Zurich;
- (iii) is terminated as soon as You cease to use the SOFTWARE and destroy all copies, full or partial, of the SOFTWARE;

Upon termination pursuant to (i) and (ii), you must cease all use of the SOFTWARE and destroy all copies, full or partial, of the SOFTWARE.

5 OBLIGATIONS OF YOU

- (i) You may not remove or alter any copyright notices on any and all copies of the SOFTWARE.
- (ii) You may not distribute or assign the SOFTWARE or any copy thereof to third parties. You may not rent, lease, sell, lend, transfer, redistribute, or sublicense the SOFTWARE to any third party.
- (iii) You may not reverse engineer, decompile or disassemble the SOFTWARE, except and only to the extent that such activity is expressly permitted by applicable law despite this limitation.
- (iv) You may not reproduce, modify or adapt the SOFTWARE, except and only to the extent that such activity is expressly permitted by applicable law despite this limitation.
- (v) You must comply with all applicable laws.

6 OWNERSHIP

Except as expressly licensed to You in this EULA, ETH Zurich and its licensors retains all right, title, and interest in and to the SOFTWARE. All title and copyrights in and to the SOFTWARE (including but not limited to any images, photographs, animations, video, audio, music, text, and “applets” incorporated into the SOFTWARE), the accompanying materials, and any copies of the SOFTWARE are owned by ETH Zurich and its licensors. The SOFTWARE is protected by copyright laws. Therefore, You must treat the SOFTWARE like any other copyrighted material. All rights not expressly granted are reserved by ETH Zurich.

7 MAINTENANCE, SUPPORT, UPGRADES OR NEW RELEASES

ETH Zurich has no obligation to provide maintenance, support, upgrades, new releases, enhancements or modifications and disclaims all costs associated with service, repair or correction of the SOFTWARE. If any supplemental software code is provided to You by ETH Zurich, this supplemental software code shall be considered part of the SOFTWARE and is subject to the terms and conditions of this EULA if not otherwise explicitly written. It is expressly acknowledged by You that no rights to receive maintenance, support, upgrades, new releases, enhancements or modifications may be derived from this EULA.

8 NO WARRANTY

YOU EXPRESSLY ACKNOWLEDGE AND AGREE THAT USE OF THE SOFTWARE IS AT YOUR SOLE RISK AND THAT THE ENTIRE RISK AS TO SATISFACTORY QUALITY, PERFORMANCE, ACCURACY, AND EFFORT IS WITH YOU. TO THE MAXIMUM EXTENT PERMITTED BY APPLICABLE LAW, THE SOFTWARE AND ANY SERVICES PERFORMED OR PROVIDED BY THE SOFTWARE ARE PROVIDED “AS IS” AND “AS AVAILABLE”, WITH ALL FAULTS AND WITHOUT WARRANTY OF ANY KIND, AND ETH ZURICH HEREBY DISCLAIMS ALL WARRANTIES AND CONDITIONS WITH RESPECT TO THE SOFTWARE AND ANY SERVICES, EITHER EXPRESS, IMPLIED, OR STATUTORY, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES AND/OR CONDITIONS OF MERCHANTABILITY, OF SATISFACTORY QUALITY, OF FITNESS FOR A PARTICULAR PURPOSE, OF ACCURACY, OF QUIET ENJOYMENT, AND OF NON-INFRINGEMENT OF THIRD-PARTY RIGHTS. ETH ZURICH DOES NOT WARRANT AGAINST INTERFERENCE WITH YOUR ENJOYMENT OF THE SOFTWARE, THAT THE FUNCTIONS CONTAINED IN OR SERVICES PERFORMED OR PROVIDED BY THE SOFTWARE WILL MEET YOUR REQUIREMENTS, THAT THE OPERATION OF THE SOFTWARE OR SERVICES WILL BE UNINTERRUPTED OR ERROR-FREE, OR THAT DEFECTS IN THE SOFTWARE OR SERVICES WILL BE CORRECTED. NO ORAL OR WRITTEN INFORMATION OR ADVICE GIVEN BY ETH ZURICH OR ITS AUTHORIZED REPRESENTATIVE SHALL CREATE A WARRANTY. SHOULD THE SOFTWARE OR SERVICES PROVE DEFECTIVE, YOU ASSUME THE ENTIRE COST OF ALL NECESSARY SERVICING, REPAIR, OR CORRECTION. SOME JURISDICTIONS DO NOT ALLOW THE EXCLUSION OF IMPLIED WARRANTIES OR LIMITATIONS ON APPLICABLE STATUTORY RIGHTS OF A CONSUMER, SO THE ABOVE EXCLUSION AND LIMITATIONS MAY NOT APPLY TO YOU.

9 LIABILITY

In no event shall ETH Zurich be liable for any damages (including, without limitation, lost profits, business interruption, or lost information) arising from the use of or inability

to use the SOFTWARE through You or the employees of the company You are legally representing. In no event will ETH Zurich be liable for loss of data or for indirect, special, incidental, consequential (including loss of profit), or other damages based in contract, tort or otherwise.

The above limitation of liability shall not be construed to amend or limit any party's statutory liability.

10 GENERAL PROVISIONS

- (i) ETH Zurich reserves the right to change the terms and conditions of this EULA at any point in time. In such event, ETH Zurich will notify You in due time of the changes to the terms of the EULA.
- (ii) Rights and duties derived from this EULA shall not be transferred to third parties without the written acceptance of the ETH Zurich.
- (iii) You shall not infer from this EULA any other rights, including licenses, than those that are explicitly stated herein.
- (iv) This EULA shall exclusively be governed by and interpreted in accordance with the laws of Switzerland, without reference to its conflict of laws principles. The exclusive place of jurisdiction is Zurich (Switzerland).

11 ACKNOWLEDGMENT

You acknowledge that you have read this EULA, understand it, and had an opportunity to seek independent legal advice prior to agreeing to it. In consideration of ETH Zurich agreeing to provide the SOFTWARE, You agree to be bound by the terms and conditions of this EULA. You further agree that it is the complete and exclusive statement of the agreement between you and ETH Zurich, which supersedes any proposal or prior agreement, oral or written, and any other communication between you and ETH Zurich relating to the subject of this EULA.

Notice:

Third party software copyright notices and third party software licenses can be found in the appendix.

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

INTRODUCTION & INSTALLATION

**VERSION 3.2
May 2022**



BASEMENT

Contents

1	Summary of Contents	3
1.1	Introduction	3
1.2	Content of System Manuals	3
1.2.1	Introduction & Installation	3
1.2.2	User Manual	3
1.2.3	Reference Manual	4
1.2.4	Tutorials and Test Cases	4
2	Setup and First Start	5
2.1	Setup and First Start	5
2.1.1	System operator requirements	5
2.1.1.1	Microsoft Windows	5
2.1.1.2	Linux	5
2.1.1.3	Hardware Configuration	6
2.1.2	Installing under Windows	6
2.1.2.1	Getting the binaries	6
2.1.2.2	Installation procedure under Windows 10	7
2.1.3	Installing under Linux	8
2.1.3.1	Getting the binaries	8
2.1.3.2	Installation procedure	8
2.2	Running BASEMENT	10
2.2.1	Windows 10	10
2.2.2	Linux	10
3	Migration Guide Version 2.8 to 3.2	11
3.1	General	11
3.2	Major Changes from version 2.x to 3.x	11
3.2.1	Workflow	11
3.2.2	Input data	12
3.2.2.1	Mesh features	12
3.2.2.2	Model setup	13
3.2.3	Simulation	18
3.2.4	Results	21
3.3	Case example	21
3.3.1	Description	21
3.3.2	Computational mesh	22
3.3.2.1	Quality mesh	22
3.3.2.2	Computational mesh	22

3.3.2.3	Import of a 2.x to a compatible 3.x computational mesh . . .	24
3.3.3	Setup and simulation	27
3.3.4	Results and discussion	28
3.3.4.1	Hydraulic results	28
3.3.4.2	Boundary conditions	29
3.3.4.3	Discussion	31
3.4	Performance	32
3.4.1	Introduction	32
3.4.2	Scalability	32
3.4.3	Computational Time	32
4	Release Notes	35
4.1	Version 3.0	35
4.1.1	General	35
4.1.2	Hydraulics	35
4.1.3	Morphology	36
4.1.4	System manuals	36
4.2	Version 3.0.1	36
4.2.1	Bug Fixes	36
4.3	Version 3.0.2	37
4.3.1	General	37
4.3.2	Bug Fixes	37
4.3.3	Known Issues	37
4.4	Version 3.1	37
4.4.1	General	38
4.4.2	Bug Fixes	39
4.4.3	Known Issues	40
4.5	Version 3.1.1	40
4.5.1	General	40
4.5.2	Bug Fixes	40
4.5.3	Known Issues	40
4.6	Version 3.2	41
4.6.1	General	41
4.6.2	Bug Fixes	41
4.6.3	Known Issues	41
5	Summary of Features Version 3.2	43
5.1	Hydrodynamic features	43
5.2	Morphodynamic features	45
5.2.1	Bedload transport	45
5.2.2	Suspended load transport	47
5.3	Tracers	48
5.4	Vegetation	49
6	References	51

Summary of Contents

1.1 Introduction

BASEMENT version 3 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 and guides the user through the process of using BASEMENT version 3.

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 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 familiar with BASEMENT. The release notes summarize the changes introduced by BASEMENT version 3 and the summary of features provides an overview of the available functionalities of BASEMENT version 3.

1.2.2 User Manual

The user manual provides information about the simulation environment of BASEMENT version 3. 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.

1.2.4 Tutorials and Test Cases

This part is composed of three tutorials and two test cases. The tutorials guide the user through the pre-processing, the numerical simulation and post-processing stages of BASEMENT version 3 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 accuracy of the simulations performed with BASEMENT version 3 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 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 version 3.2.0 is available for the following Linux (x86-64) systems:

- Ubuntu 18.04 (LTS), alias “Bionic Beaver”:
 - Kernel version 5.4
 - 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)
- Ubuntu 20.04 (LTS), alias “Focal Fossa”:
 - Kernel version 5.13
 - GNU C Library (glibc) version 2.31
 - VTK-version: 9
 - 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 is **only** possible for CUDA-enabled (Compute Unified Device Architecture) GPUs produced by NVIDIA. BASEMENT version 3 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	RTX 2080Ti
Memory [GB]	5	12	11	8	4	11
Architecture	Kepler	Pascal	Pascal	Pascal	Pascal	Turing
Bandwidth[GB/s]	208	549	484	256	112	616
CUDA cores	2496	3584	3584	2432	768	4352

2.1.2 Installing under Windows

BASEMENT version 3 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.

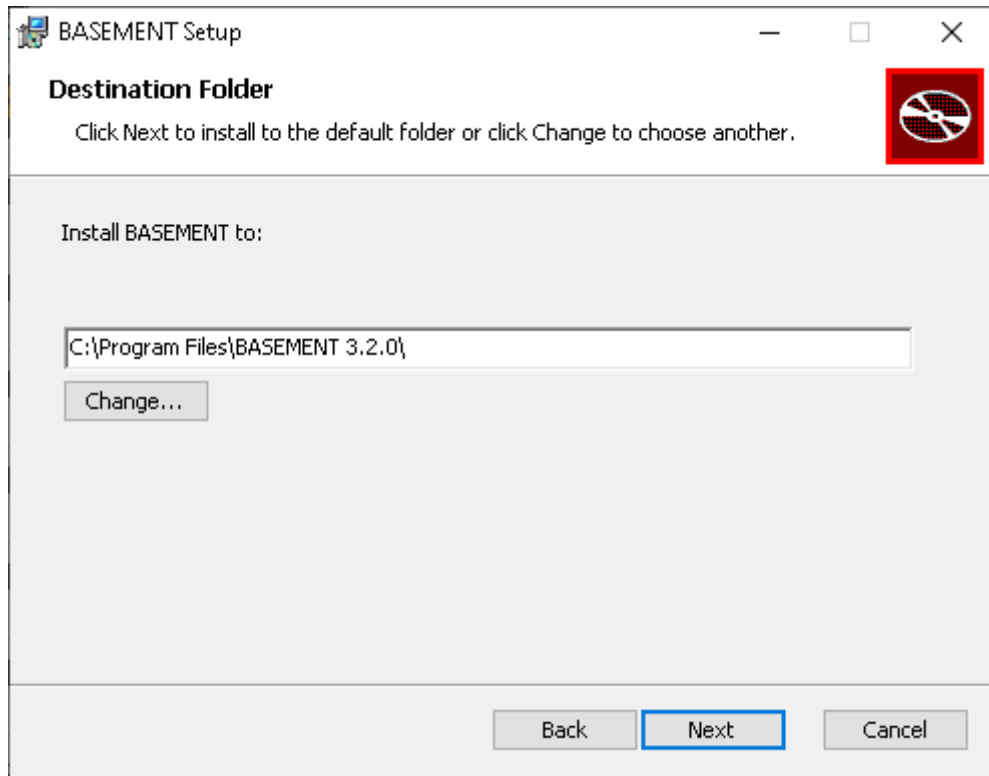


Figure 2.1 Select the installation folder.

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 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 3.2.0” (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

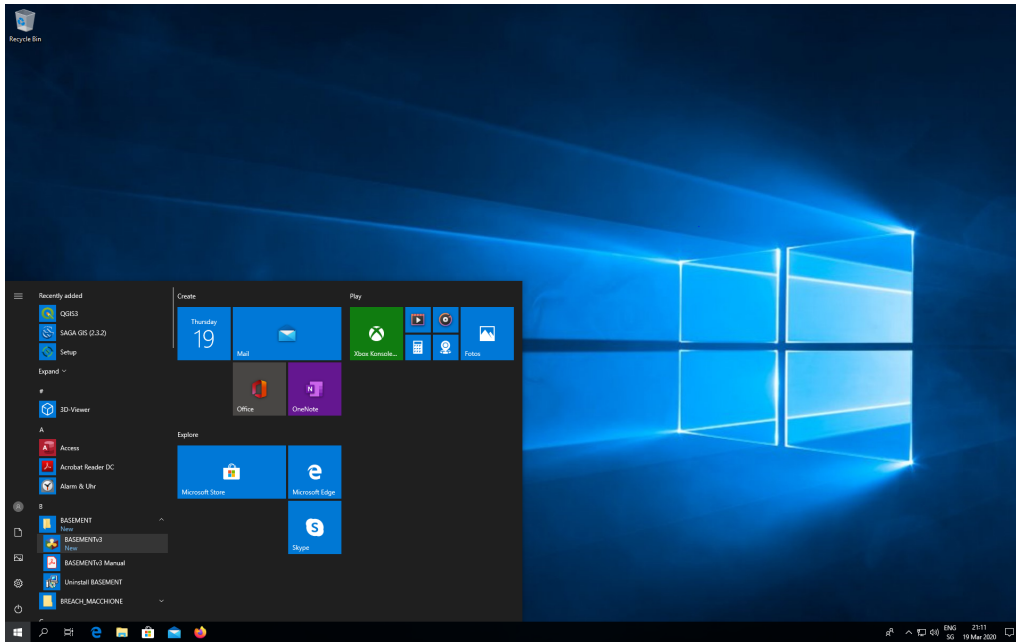


Figure 2.2 Start BASEMENT over the icon in the Start Menu folder.

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.

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
```

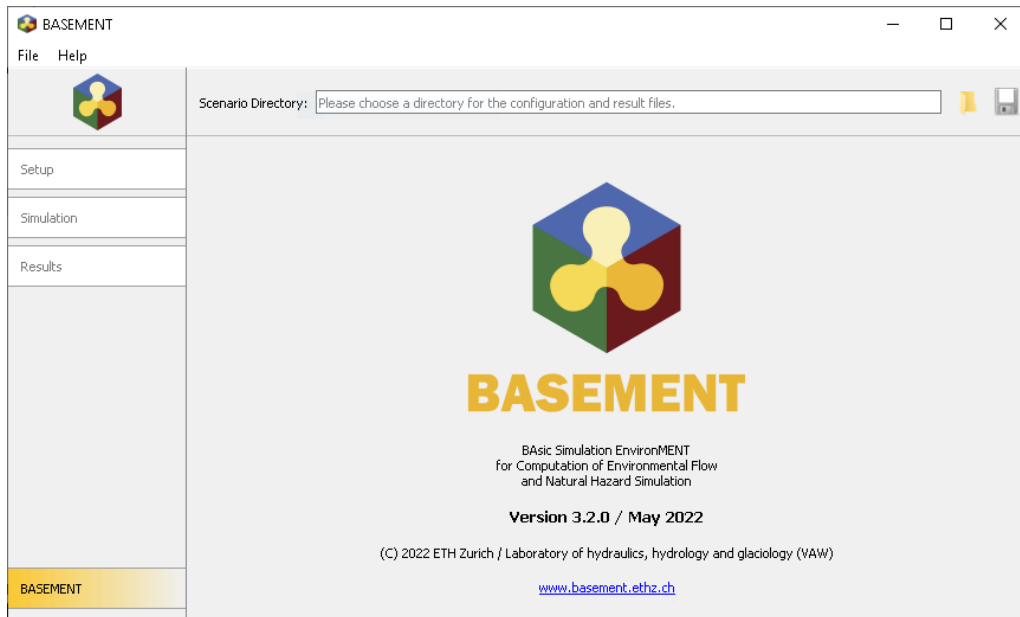


Figure 2.3 The graphical user interface.

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 3.2

3.1 General

Table 3.1 List of BASEMENT main features

	Version 2.8	Version 3.2
1-D model	✓	
2-D model	✓	✓
Hydrodynamics	✓	✓
Morphodynamics:		
- Bed load	✓	✓
- Suspended load	✓	✓
Tracer advection		✓
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 3.2
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 3.2
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 <code>element_ids</code>	Domain differentiation with <code>regiondef</code>

Table 3.4 Main changes regarding the grid generation with BASEmesh

Version 2.8	Version 3.2
Single procedure to generate a .2dm file with BASEmesh	Single procedure to generate a .2dm file with BASEmesh
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 3.2
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 3.2
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 3.2
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	- hydrograph	Standard uniform_in uniform_out
	- zhydrograph	Standard zhydrograph Linked zhydrograph_linked, zhydrograph_linked_kinE
	zero_gradient weir	zero_gradient_out weir_out_constant, weir_out_dynamic Linked weir_linked_constant, weir_linked_dynamic
	gate	-

	Version 2.8	Version 3.2
	- HQ_relation	Standard hqrelation_out Linked 2way_hqrelation_linked, hqrelation_linked
	coupling - wall	- Internal: wall_internal wall_internal hqrelation_internal
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	yes
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 3.2
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 scaling	no	with morphological factor
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	.2dm mesh or over region (index)
Bedload		
Bedload transport	Simple upwind scheme	HLL-type Approximate Riemann Solver (Soares-Frazão and Zech, 2011)

	Version 2.8	Version 3.2
Closure formula	mpm - engelundhansen mpmh power_law mpm_multi wilcockcrowe ashidamichiue parker rickenmann smartjaeggi smartjaeggi_multi wu vanrijn	MPM MPM-like (adaptable) Engelund and Hansen - Grass-like (adaptable) - - - - - - smartjaeggi - - -
Boundary		Standard
- Inflow	- sediment_discharge - - IOUp transport_capacity - -	sedimentograph sedimentograph_warea sedimentograph_conveyance equilibrium_in 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 curvature_effect_static curvature_effect_dynamic	LATERAL_SLOPE - CURVATURE
Inner boundary	weir, open -	Internal: equilibrium_linked
Incipient motion	angle_of_repose local_slope_vanrijn local_slope_chen	repose_angle van_rijn chen_et_al

	Version 2.8	Version 3.2
Gravitational transport	yes	yes
Source		
Type	sediment_discharge dredge	sediment_discharge -

*Table 3.8 Introduction of the **tracers** block in the domain BASEPLANE_2D*

	Version 2.8	Version 3.2
Parameters:		
Number of species	no	num_tracers (max. 5)
Starting time	no	tracers_start
Boundary		
Type	no	Standard discharge_in discharge_in_warea concentration_in zero_gradient_out
External source		
Type	no	total and concentration
Sink behavior	no	exact, available, infinity
Initial		
Type	no	zero uniform continue region_defined

3.2.3 Simulation

Table 3.9 Main changes regarding simulation parameters

	Version 2.8	Version 3.2
Command file type	run.bmc	simulation.json

	Version 2.8	Version 3.2
Simulation time	start_time total_run_time output_time_step restart_time_step console_time_step reference_time	start end out - - -
Timestep	initial_time_step minimum_time_step	init minimum

	Version 2.8	Version 3.2
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	suspended_conc
	susp_deltaz	delta_z
	susp_total_pickup	-
	susp_total_deposition	-
	susp_grain_pickup	-
	susp_grain_deposition	-
	-	suspended_theta
	theta_critical	theta_critical
	grain_size	-
	grain_bedload	-
	bedload_vec	-
	saturation	-
	sediment_sum	-
	-	bed_gradient
	-	theta
	-	trsp_capacity
	-	trsp_capacity_abs
	-	flow_radius
	-	flow_curvature
	-	flood_tracking
	pore_pressure	-
	-	ns_hyd_discharge
	-	ns_mor_discharge
	external_source_discharge	-
	radius_curvature	-
	radius_curvature_abs	-
	-	turb_k
	-	turb_reynolds

	Version 2.8	Version 3.2
	momentum	-
	water_table	-
	biomass	-
	carrying_cap	-
	source_friction	-
	source_wall_friction	-
	source_internal_friction	-
	source_bed	-
	balance_discharge_fluxes	-
	balance_momentum_fluxes -	- tracer1
	-	tracer2
	-	tracer3
	-	tracer4
	-	tracer5

3.2.4 Results

Table 3.10 Main changes regarding the results parameters

	Version 2.8	Version 3.2
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 3.2 (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 3.11.

Table 3.11 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 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 3.12 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 3.12. 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

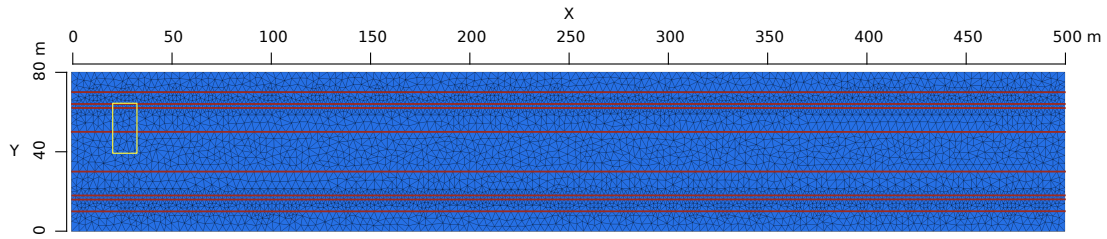


Figure 3.1 Quality mesh used for the case example with breaklines (red)

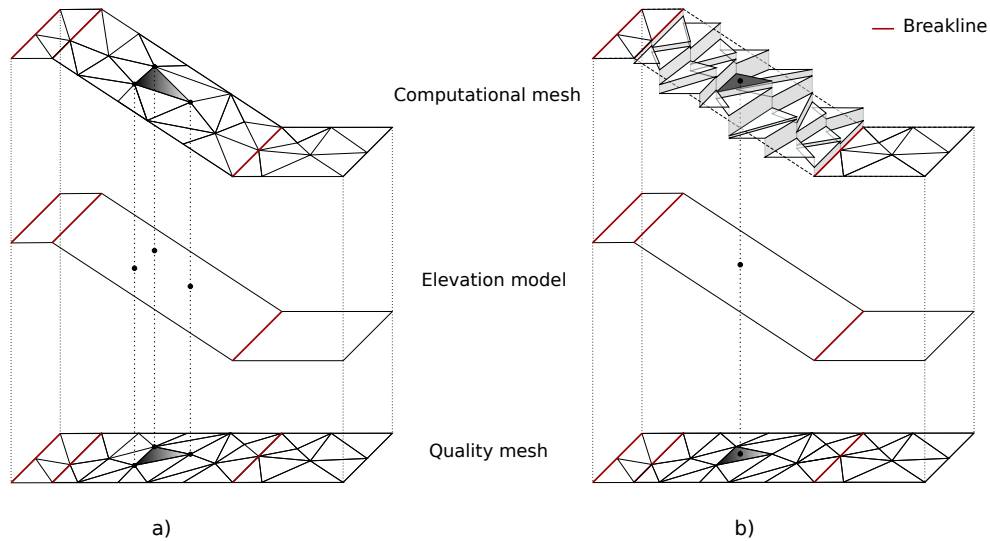


Figure 3.2 Schematic sketch of the elevation interpolation methods with breaklines (red):
 a) BASEMENT version 2.x b) BASEMENT version 3.x

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 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 guaranteed by two breaklines).

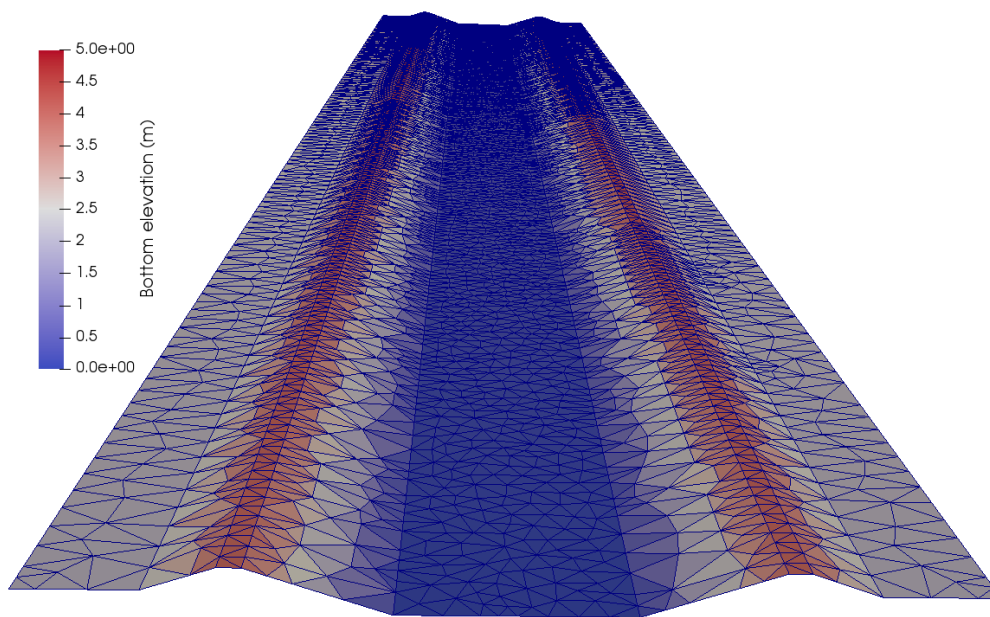


Figure 3.3 Computational grid BASEMENT version 2.x with breaklines (view from downstream)

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:

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:

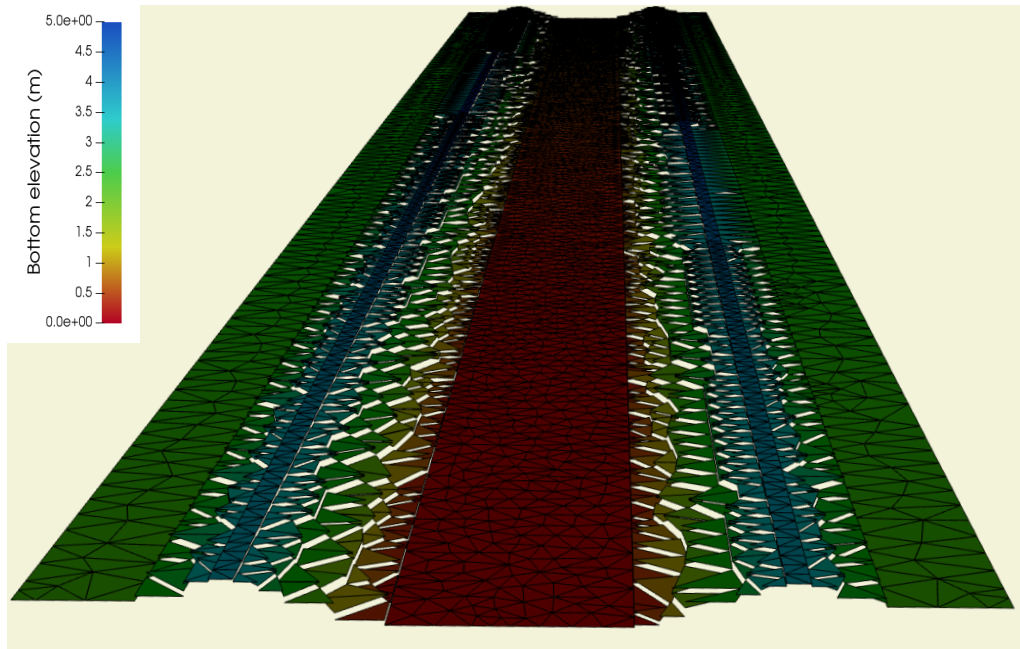


Figure 3.4 Computational grid BASEMENT version 3.x with breaklines (view from downstream)

```

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)

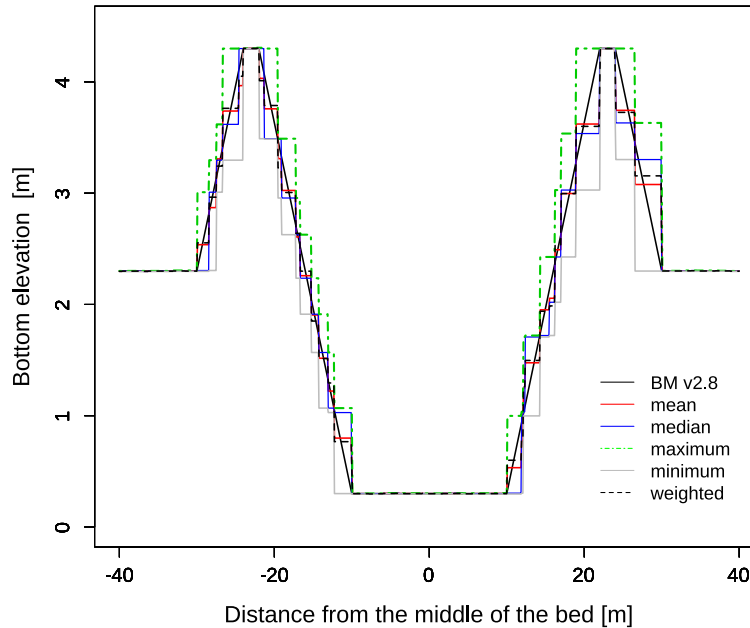


Figure 3.6 Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at $x=150$ m of the trapezoidal channel with breaklines

- 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

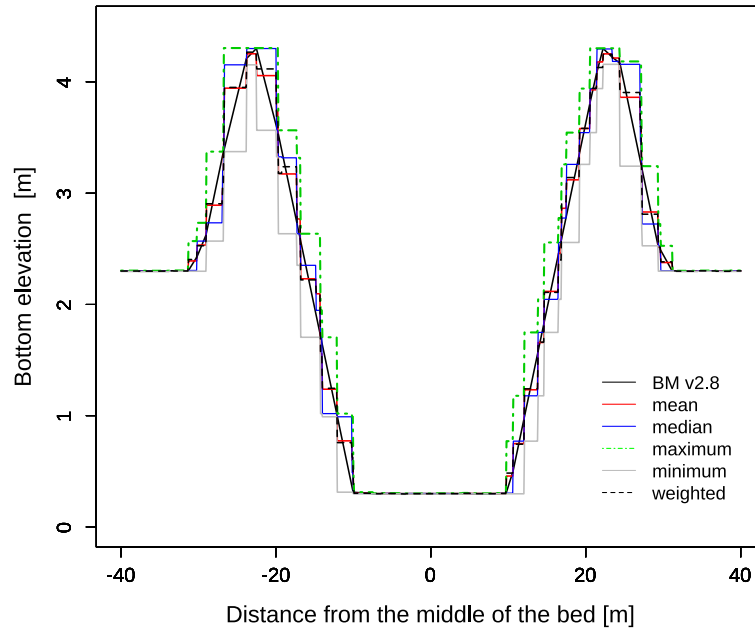


Figure 3.7 Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at $x=150$ m of the trapezoidal channel with only one breakline defined at the bank crest

the bank elevation, independently from the chosen interpolation methods. Otherwise, the 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. 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:

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

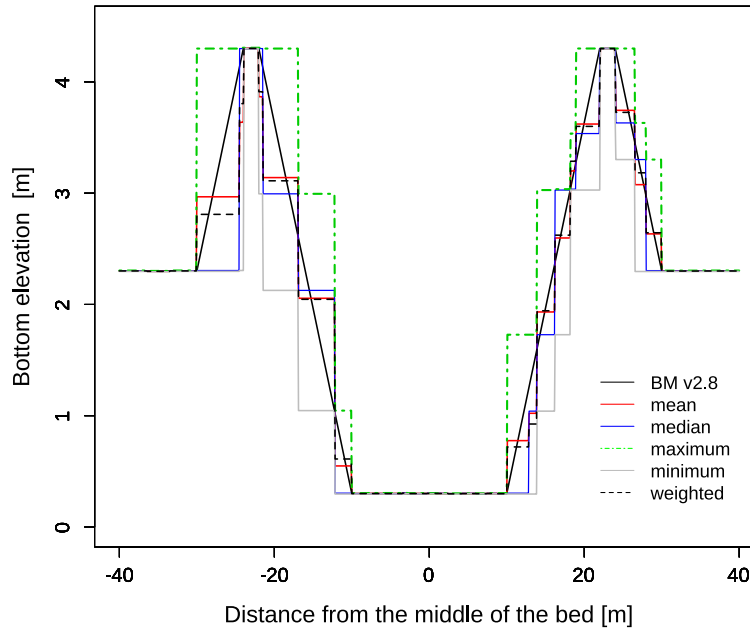


Figure 3.8 Comparison of interpolation methods with the mesh of BASEMENT version 2.8 (BM v2.8) on a cross section at $x=150$ m of the trapezoidal channel with breaklines and for a coarser mesh resolution

- Boundary condition data (.txt)

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 described in Section 3.3.2.3, the specification of stringdefs, 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 3.10 and Table 3.9).

3.3.4.1 Hydraulic results

The result of the simulations with BASEMENT version 3 for different interpolation methods are compared in a stage discharge rating curve (Figure 3.9). The mesh features are summarized in Tables 3.11 and 3.12.

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”.

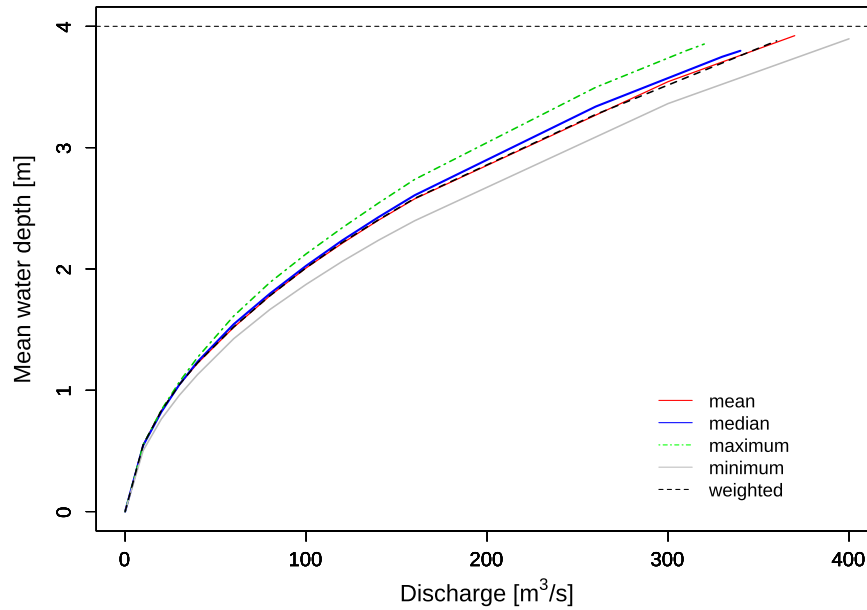


Figure 3.9 Comparison of H - Q relations between the simulations of BASEMENT v3 for different interpolation types on the trapezoidal channel at $x = 150$ m.

3.3.4.2 Boundary conditions

In BASEMENT version 3, the inflow data is averaged over the boundary length and the mean value is uniformly distributed over the cell edges. This assumption simplifies the 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 and BASEMENT version 2.8 respectively.

An inflow boundary defined between the top elevation of the two levees in BASEMENT version 3 (red line in Figure 3.10, a) generates an undesired converging flow from the bank towards the channel center ($Q = 60 \text{ m}^3/\text{s}$) and small flux towards the floodplains as represented on Figure 3.12 for a discharge value $Q = 200 \text{ m}^3/\text{s}$. An inflow boundary

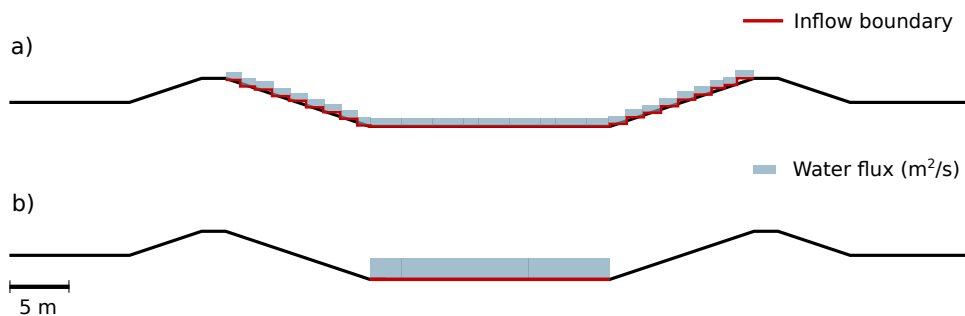


Figure 3.10 Channel cross section and inflow boundary limit in BASEMENT version 3
 a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit

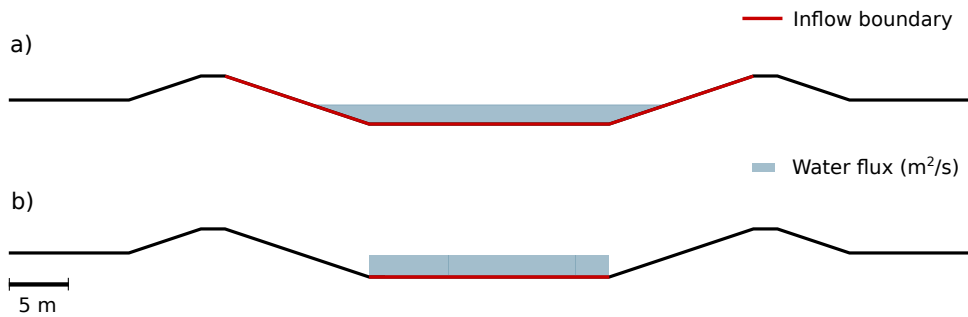


Figure 3.11 Channel cross section and inflow boundary limit in BASEMENT version 2.8
 a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit

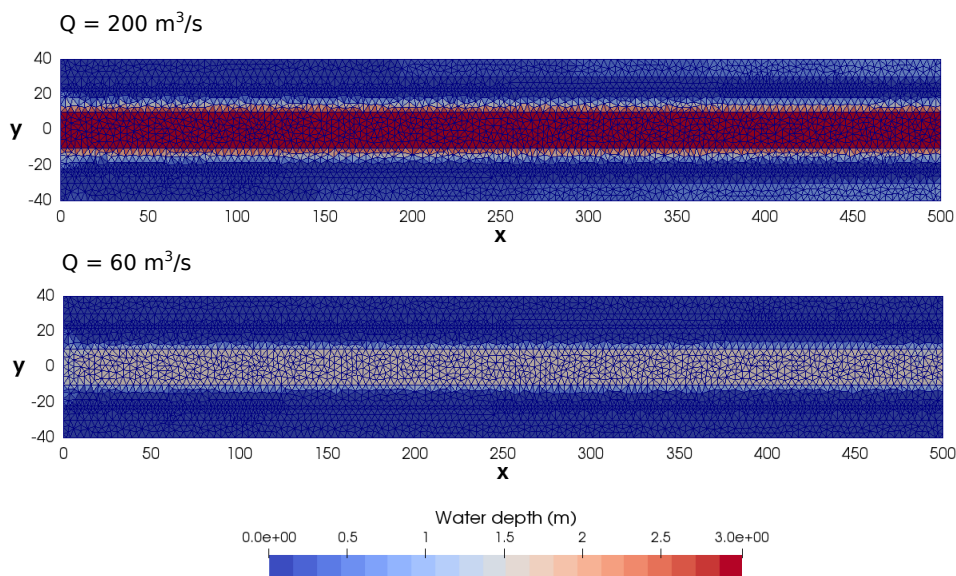


Figure 3.12 Planar view of the simulation results using BASEMENT v3 of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary ($x = 0.0$ m) defined between the top elevation of the levees (Figure 3.10, a), inducing a converging flow from the levee towards the channel center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

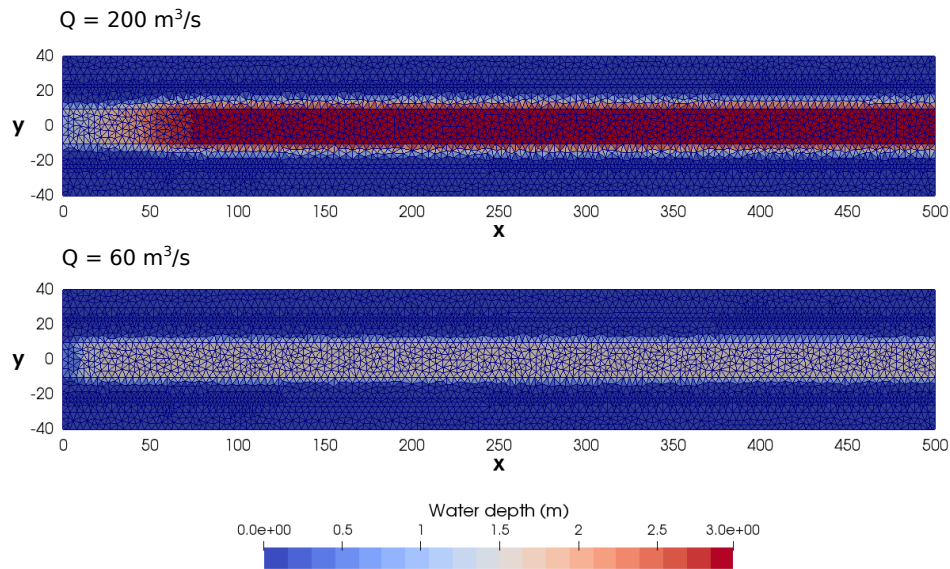


Figure 3.13 Planar view of the simulation results using BASEMENT v3 of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary ($x=0.0\text{m}$) restricted to the channel bed (Figure 3.10, b), inducing an increase of the flow velocity.

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 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 40 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.

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 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 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 in more detail 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 using the CPU backends with up to 32 cores and different GPU cards on Ubuntu 18.04. The backend types are listed and described in more detail in the section “Test case”. Besides, 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 Scalability

The speedup of the simulations performed on CPU hardware is shown in Figure 3.14. The speedup S of the respective version is calculated as the division of the sequential runtime T_1 by the runtime with a certain number of cores T_N . The black line represents the ideal speedup according to the increasing number of threads. The speedup is a measure for the parallelizability of the respective version and indicates how the computing time scales with the number of used processor cores. A linear or ideal increase in speed S results for $S = N$.

For the smallest computational grid (10k), the speedup of both BASEMENT versions only scale linearly up to approximately 4 threads before reaching a plateau. For version 2.8, the scalability does not change significantly for the larger mesh sizes and hence, the performance does not increase significantly anymore when using more than 4 threads. In contrast, the speedup of BASEMENT version 3 scales almost linearly up to 16 threads for the four larger meshes and up to 32 cores for the two largest meshes. Overall, BASEMENT version 3 exhibits significantly improved scalability compared to version 2.8.

3.4.3 Computational Time

The execution time of all the simulations is shown in Figure 3.15. The execution time increases with the computational mesh size for all backends. The execution times obtained on the CPU hardware indicate the significantly improved performance of BASEMENT version 3 compared BASEMENT version 2.8. This increase in performance by a factor of up to 13 is the results of completely restructuring the software. The performance of BASEMENT version 3 can be improved even further by the use of GPU hardware. For example, the runtime for the largest grid (1000 k) on the Intel processor with 32 cores is 8.7 s, while with the RTX2080Ti graphics card (single precision) only 3.6 s are required, which corresponds to a reduction of the runtime by a factor of 2.4. It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem. When using GPUs, however, the significantly better price/performance ratio should be emphasized. For example, the GeForce GTX1080Ti card with double precision

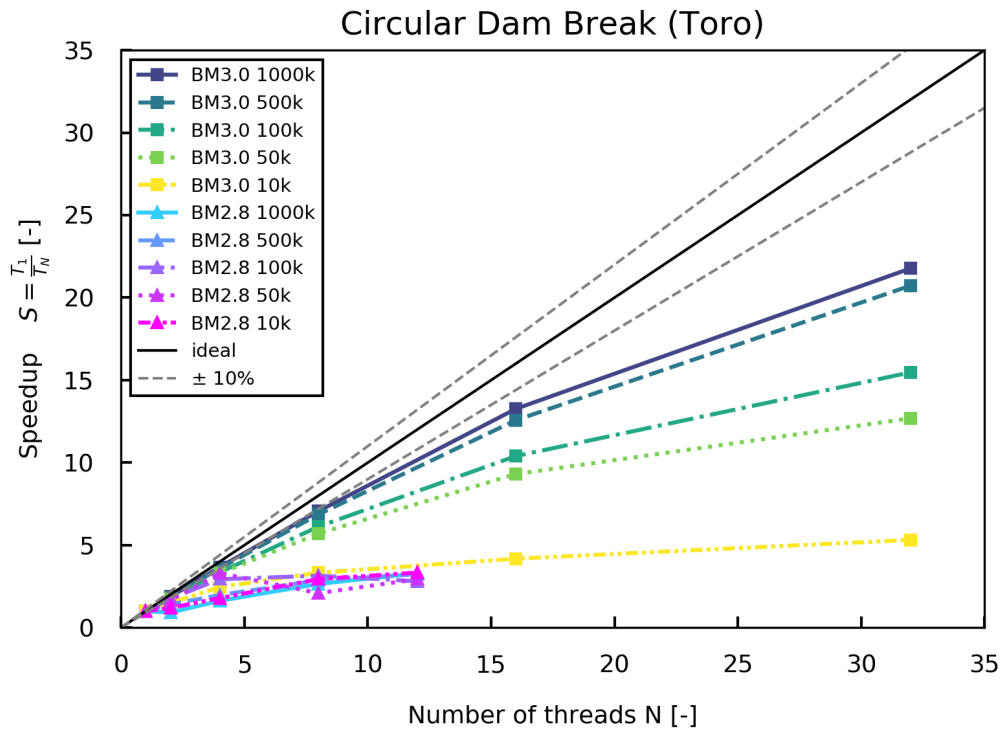


Figure 3.14 Speedup of the circular dam break test case performed on CPU for an increasing number of threads and different mesh sizes

has about the same performance as the Intel Xeon Gold 6154 processors when using 32 cores, but with a 6 times lower purchasing price.

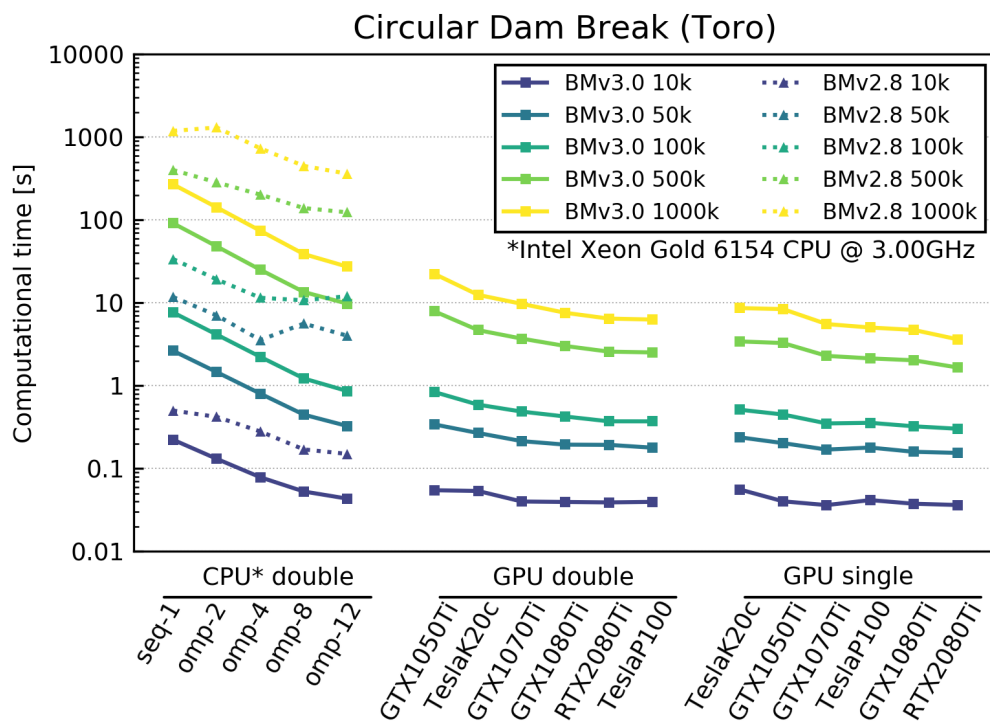


Figure 3.15 Execution time of the circular dam break test case for different backends and mesh sizes

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.

4.4 Version 3.1

In BASEMENT Version 3.1 the bed load transport has been extensively revised and supplemented (e.g. slope collapse). The new features include the transport of passive tracers and additional output variables (e.g. transport capacity or bed shear stress). In general, extensive bug fixes were made and the documentation was revised.

4.4.1 General

- The console output now displays the most recent output of the programs by default.
- Pressing Ctrl+C now aborts the simulation after the current time step.
- Implementation of a tracer transport module.
- Implementation of the bedload transport capacity as output variables (`trsp_capacity` and `trsp_capacity_abs`).
- Implementation of Smart & Jaeggi (1983) bedload transport formula.
- Implementation of the LINKED morphology boundary condition *equilibrium_linked*.
- Implementation of the LINKED hydraulic boundary condition *zhydrograph_linked_kinE*.
- Implementation of the of passive scalar transport by advection
- Implementation of max. bed shear stress as tracking variable (via FLOOD in `model.json`).
- Implementation of gravitational transport (e.g. bank collapse) due to the local bed slope exceeding a critical angle.
- An improved method for the local bed gradient calculation has been implemented. The newly implemented method `secondary_mesh` calculates the bed gradient based on (i) the bed elevation of the neighbouring cells in case of 3 neighbouring cells, (ii) the bed elevation of the two neighbouring cells and the cell itself in case of 2 neighbouring elements or (iii) the bed elevation of the neighbouring cell and the cell itself in case of one neighbouring element. The improved method is used by default, while the previous method (`area_weighted`) is still available but not recommended. The method for the bed gradient calculation can be selected under MORPHOLOGY/PARAMETERS/`bed_gradient_type`. The bed gradient has an influence on the bedload transport direction if the block LATERAL_SLOPE is activated and on the threshold of incipient motion for bedload transport if the block INCIPIENT_MOTION is activated.
- The local bed gradient is available as output variable under the names `bed_gradient` in the `simulation.json` (only if the INCIPIENT_MOTION or LATERAL_SLOPE blocks are activated).
- During the bedload flux computation, the bedload transport flux is split in an advective part (same direction as flow direction) and a diffusive part (due to bedload direction correction from lateral transport and curvature). The advective part is solved with the existing HLLC solver, while an upwind scheme is applied for the diffusive flux. This makes the solver more stable when using bedload transport direction correction due to local slope effects or curvature.
- An improved method for the local velocity gradient calculation has been implemented. The newly implemented method calculates the velocity gradient based on (i) the velocity of the neighbouring cells in case of 3 neighbouring cells, (ii) the velocity of the two neighbouring cells and the cell itself in case of 2 neighbouring elements or (iii) the velocity of the neighbouring cell and the cell itself in case of one neighbouring element. The new method replaces the previous calculation method and results in improved predictions of the curvature effect on the bedload transport direction.
- `2dm-mesh` files are now supported as input for the fixed bed elevation. The topology of the fixed bed mesh must be identical with that of the computational mesh and

must only differ in the elevation information.

- The documentation has be revised and updated.

4.4.2 Bug Fixes

- Xdmf output files that are created using the UI now reference the auxiliary results file using a relative file path.
- A bug in the bedload transport flux calculation has been fixed. The bug resulted in an asymmetrical behavior depending on the orientation of the flux vector with respect to the edge normal.
- The parameter `max_time_step` is now taken into account in the computation of the integration time step.
- The missing file browser for the `'hqrelation_file'` tag of the STANDARD hydraulic boundary condition `'hqrelation_out'` has been added.
- During the calculation of the uniform flow depth in the `uniform_out` boundary condition, incorrect cell dimensions might have been used. This problem has been fixed.
- For elements which (1) did not belong to any of the regions from REGIONDEF or (2) for elements whose region was not listed under FRICTION/regions, the `default_friction` value should have be used. However, this has not been the case. Instead, for case (1) an “out of range” error occurred, while for case (2) a friction value of 0.0 has been used. With the fix, the `default_friction` value is used in both cases (1) and (2).
- In the case of “region_defined” initial conditions, the initial water surface elevation and the specific fluxes in x- and y-direction were set to 0.0 for elements which did not belong to any of the regions in REGIONDEF. With the bugfix, the initial conditions for cells which do not belong to any regions or whose region is not listed under INITIAL/regions “dry” initial conditions are set and the user is informed with a warning.
- A bug in the calculation of the lateral transport direction (Block IKEDA) has been fixed. The bug led to an underestimation of the lateral transport. Further, a more general approach has been implemented for the influence of lateral bed slopes on the bedload transport direction. The block IKEDA has been renamed to LATERAL_SLOPE.
- An inconsistency in the setup resulted in the approach of Van Rijn (1989) being chosen automatically when the INCIPIENT_MOTION block was activated.
- Mathematical operations of incorrect precision (single/double precision) were used by the kernels.
- The non-dimensional bed shear stress and the critical non-dimensional bed shear stress are now available as output variables under the names `theta` and `theta_critical` in the `simulation.json` (only if the MORPHOLOGY block is activated).

4.4.3 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.

Note: Existing installations of BASEMENT version 3.0.1 (or earlier) 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.

4.5 Version 3.1.1

4.5.1 General

- The appearance of the JSON editors in the GUI has been improved. In particular, validation messages (warnings, errors) are now displayed in a corresponding color (yellow, red) and new icons were added.
- The menu bars of the GUI have been restructured. In particular, there is now a “Recently Opened Directories” item that can be used to reopen a recently opened scenario.
- The “Save” button in GUI is now disabled when the scenario directory is invalid or when there are no unsaved changes. In situations where there are unsaved changes, the application now asks the user for confirmation when closing the application.
- The external OP2 library was updated.

4.5.2 Bug Fixes

- A parallelisation issue in the fixed bed correction algorithm was fixed.
- HDF5 files larger than 2 GB were not handled correctly on Windows. This issue has been fixed.
- Due to a bug, the starting time of the tracer kernels was delayed by a small number ($t_0 + 1e-12$ instead of t_0). This has been fixed.

4.5.3 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.

Note: Existing installations of BASEMENT version 3.0.1 (or earlier) 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.

4.6 Version 3.2

BASEMENT Version 3.2 contains novel features for modelling of turbulence, suspended sediment transport and vegetation dynamics and interactions between vegetation and sediment transport. The version for Ubuntu Xenial (16.04) has been replaced by a new version for Ubuntu Focal (20.04). Further, some bug fixes were made and the documentation was revised.

4.6.1 General

- External libraries used by BASEMENT were updated.
- The new version for Ubuntu Focal replaces the version for Ubuntu Xenial.
- Implementation of the riparian vegetation model. The model is intended to reproduce the main feedback between vegetation and sediment transport in mobile bed simulations. Vegetation modifies the flow resistance and the bed shear stresses based on plant characteristics. In turn, vegetation can be uprooted and/or buried in case of bed level changes.
- A block VEGETATION, with the sub-blocks INITIAL and PARAMETER, was added to the model.json file. It allows including the feedback between vegetation, flow, and bedload sediment transport for mobile bed simulations. It, therefore, requires the blocks MORPHOLOGY and BEDLOAD to be activated.
- Three additional output variables were added for the vegetation model: the aboveground biomass density, the belowground biomass density, and the rooting depth.
- A manual and a tutorial for the vegetation model were added to the BASEMENT documentation.
- Implementation of turbulence models of differing complexity (experimental feature). Turbulent and viscous stresses are considered under the eddy viscosity model, following the Boussinesq hypothesis. Different closure models are available for computing the eddy viscosity, namely the mixing length model, the k-epsilon model, or a constant eddy viscosity model. Turbulence computation is expected to noticeably increase simulation times, especially for more complex closure models (k-epsilon).
- Implementation of suspended load sediment transport for uniform sediment (experimental feature). Different closure models are available for the settling velocity of suspended sediment particles and for erosion and deposition rates. Further, shear stress partitioning can be accounted for by providing a value for skin friction, an additional parameter to support model calibration.

4.6.2 Bug Fixes

- Input validation issues (that also affected the GUI) have been fixed.

4.6.3 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.

Summary of Features Version 3.2

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) zhydrograph with kinetic energy (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.

Turbulence

- Parameters:
 - Turbulence start time
 - On/off switch for diffusion of turbulent species (tke, epsilon)
 - Relaxation parameter for turbulent diffusion
 - On/off switch for friction generated turbulence
- Closure model for Reynolds stress:
 - Constant viscosity (default)
 - k-epsilon model
 - Mixing length model
- Initial conditions:
 - Zero, i.e. no turbulence (default)
 - Uniform values for tke and epsilon
 - Region defined values for tke and epsilon
 - Continue
- Boundary conditions (k-epsilon model)
 - STANDARD: k_eps_in, zero_gradient_out

- Source:
 - Type: `k_eps` (force k-epsilon values directly)
 - Sink behaviours: exact (as prescribed), available (as prescribed or less), infinity (as much as possible)

Flood

- Flood tracking of water front arrival time, maximum water depth, maximum flow velocity, maximum specific discharge, maximum bed shear stress (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

5.2.1 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 (coefficient = 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
- Smart and Jaeggi (1983)

Direction

- Lateral bed slope effect (e.g. Ikeda, 1982, p. Talmon1995)
- Curvature effect

Bedload boundary conditions

- WALL: inviscid, default
- STANDARD:
 - INFLOW: equilibrium (reference_bed_elevation), sedimentograph (sediment_discharge), transport capacity (boundary_factor)
 - OUTFLOW: equilibrium (reference_bed_elevation)
 - Weighting scheme for transport capacity and sedimentograph: geometrical (default), wetted area, conveyance
- LINKED: equilibrium (reference_bed_elevation at upstream boundary)

Bed material

- Grain class
- Fixed bed

Gravitational Transport

- Critical angle for wet/dry material
- update time step
- maximum settling velocity
- minimum bed elevation change

Source (sediment volume)

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

5.2.2 Suspended load transport

Parameters

- Relaxation parameter
- Diffusivity coefficient (isotropic, longitudinal/transversal)
- Turbulent diffusivity coefficient (isotropic, longitudinal/transversal)
- Scaling (beta) factor for the suspended source terms

Settling Velocity

- Closure model for the grain settling velocity:
 - Van Rijn
 - Wu and Wang
 - Zhang
- Shape factor parameter (

Shear partition

- Skin friction parameter for suspended load computations
- Default value or region defined

Erosion rate

- Closure model for the erosion rate:
 - Van Rijn
 - Zyserman and Fredsoe
- Critical shields parameter (both)

Deposition rate

- Closure model for the deposition rate:
 - Lin
 - Xu
- Critical shields parameter (Xu)

Initial conditions

- Zero, i.e. no suspended load concentration (default)
- Uniform initial concentration

- Region defined values for concentration
- Continue

Boundary conditions

- STANDARD:
 - INFLOW: concentration_in, discharge_in, discharge_in_warea
 - OUTFLOW: zero_gradient_out

Source (suspended sediment volume)

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

5.3 Tracers

Parameters

- Tracer start time
- Number of tracers (max. 5)
- Molecular diffusivity coefficient (isotropic, longitudinal/transversal)
- Turbulent diffusivity coefficient (isotropic, longitudinal/transversal)

Initial conditions

- Zero, i.e. no tracer concentration (default)
- Uniform initial concentration
- Region defined values for concentration
- Continue

Boundary conditions

- STANDARD:
 - INFLOW: concentration_in, discharge_in, discharge_in_warea
 - OUTFLOW: zero_gradient_out

Source (tracer volume)

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

5.4 Vegetation

Parameters:

- Flow resistance modification (Strickler approach)
- Shear stress partitioning
- Critical Shields parameter modification (with MPM formula)
- Vegetation uprooting
- Plant burial

Initial conditions:

- Continue
- Region defined (regiondef)

Output variables:

- Aboveground biomass [-]
- Belowground biomass [-]
- Rooting depth [m]

6

References

- Chen, X., Ma, J. and Dey, S. (2010). Sediment transport on arbitrary slopes: Simplified model. *Journal of Hydraulic Engineering-ASCE*, 136(5): 311–317.
- Duran, A., Liang, Q. and Marche, F. (2013). On the well-balanced numerical discretization of shallow water equations on unstructured meshes. *Journal of Computational Physics*, 235: 565–586.
- Ikedda, S. (1982). Lateral Bed-Load Transport on Side Slopes. *Journal of the Hydraulics Division-Asce*, 108(11): 1369–1373.
- Smart, G.M. and Jaeggi, M.N.R. (1983). Sediment Transport on Steep Slopes. *VAW-Mitteilung 64*, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW). Zürich, ETH Zürich.
- Soares-Frazão, S. and Zech, Y. (2011). HLLC scheme with novel wave-speed estimators appropriate for two-dimensional shallow-water flow on erodible bed. *International Journal for Numerical Methods in Fluids*, 66.
- Toro, E.F. (2001). Shock-Capturing Methods for Free-Surface Shallow Flows. *John Wiley*, Chichester, New York.
- van Rijn, L.C. (1989). Handbook Sediment Transport by Current and Waves. *Delft Hydraulics Laboratory*, Delft, The Netherlands.

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

USER MANUAL

**VERSION 3.2
May 2022**



BASEMENT

Contents

1	Basic Simulation Environment	3
1.1	Introduction	3
1.2	General Use	3
1.2.1	Problem Description	3
1.2.2	Product Delineation and Employment Domains	4
1.2.2.1	Product Delineation	4
1.2.2.2	Employment Domains	4
1.2.3	Capabilities	4
2	Modelling procedure	7
2.1	General	7
2.2	Preprocessing	8
2.2.1	General	8
2.2.2	Computational Mesh	8
2.2.2.1	Concept	8
2.2.2.2	Breaklines	8
2.2.2.3	Boundary Conditions	9
2.2.2.4	Mesh Quality	9
2.2.3	Hydrological, sediment and tracer data	10
2.2.3.1	Hydrology	10
2.2.3.2	Sediment Transport	10
2.2.3.3	Tracer Transport	10
2.3	Simulation Workflow	11
2.4	Postprocessing	11
2.4.1	Output Files	11
2.4.2	Result Visualization	12
3	Grid Generation with BASEmesh	13
3.1	General	13
3.2	Installation	13
3.3	Mesh generation	14
3.3.1	Quality mesh generation	14
3.3.2	Elevation mesh generation	15
3.3.3	Mesh interpolation	16
4	Simulation workflow	17
4.1	General	17

4.2	Pre-Simulation	18
4.2.1	Command Files	18
4.2.2	Model Setup	19
4.3	Simulation	19
4.3.1	Command File	19
4.3.2	Model Backend	19
4.4	Post-Simulation	19
4.5	Re-Run Simulation	20
4.6	Restart Simulation	21
5	Graphical User Interface (GUI)	23
5.1	Graphical user interface	23
5.1.1	General	23
5.1.2	First Steps	23
5.1.2.1	Scenario Directory	23
5.1.2.2	Load and Save	24
5.1.3	Setup	24
5.1.3.1	Adding and Deleting Items	24
5.1.3.2	Help and Parameter Values	26
5.1.3.3	Run BASEMENT Setup	26
5.1.4	Simulation	26
5.1.4.1	Selecting the Simulation Backend	27
5.1.4.2	Run Simulation	27
5.1.5	Results	27
6	Run the program	29
6.1	Running BASEMENT	29
6.1.1	Graphical user interface (GUI)	29
6.1.2	Batch mode under Linux	29
6.1.2.1	Setup	29
6.1.2.2	Simulation	30
6.1.2.3	Results	31
6.1.3	Batch mode under Windows	32
7	References	35

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 led 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;

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.

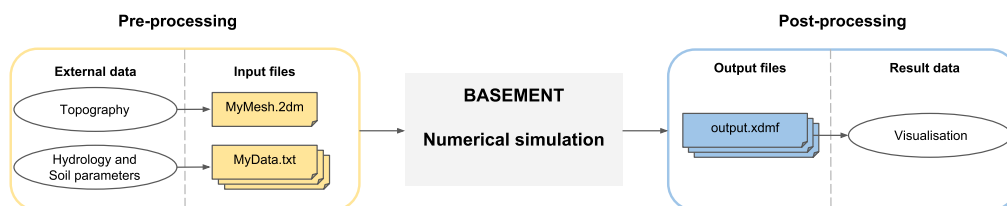


Figure 2.1 Overview of the modelling procedure with BASEMENT

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 discretised 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 into and out of the domain. Boundary conditions are defined on STRINGDEFs, i.e. on a selected sequence of successive vertices (with direction) located either inside or at the boundary of the computational mesh. The sequence of vertices along the stringdef gives the stringdef's direction with a left and right side. The upstream flow direction must be 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.

There exists three types of boundary conditions, the external (standard), internal and linked boundaries. The external boundaries are defined on the domain boundary, while the internal boundary is defined inside the domain. Linked boundary conditions connect two stringdefs inside or on the boundary of the domain. More informations about the type of boundaries and their features can be found in the Reference Manual. The "upstream_direction" is determined by placing yourself on the first node of the stringdef and looking into the direction of the second node of the nodestring. Then, determine whether "upstream" is on your left or right side.

STRINGDEFs can be defined on nodestrings, which are listed 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, sediment and tracer 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, the simulation works only for uniform sediments.

The sediment flow is defined as a specific bedload and/or suspended load 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. For the suspended load boundary fluxes, the suspended sediment concentration to be used at the boundary must be specified as either a constant or time series. The reference bed elevation has to be provided at inflow and outflow boundary conditions of type equilibrium.s

2.2.3.3 Tracer Transport

The presence of dissolved species in the flow can be defined as either boundary conditions, local sources or sinks and also as initial conditions. At present, the maximum number of transported species is 5. The fluxes of each specie can be defined as discharges (m^3/s) or, alternatively, the concentration [-] of each specie can be set according to user specified values.

Similarly to the hydrological and sediment data, the tracer discharges or target concentrations can either be set as constant or defined as a time series. For the case of fluxes prescribed as boundary discharges, these are distributed evenly along the boundary length or weighted according to the wet area of the boundary section. In the case of region-defined local sources, the total discharge is distributed evenly across the region's

area. In the case of a prescribed target concentration at boundaries or sources this value is uniformly applied to the entirety of the boundary length or region area, respectively.

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 and description.

Output	Description
Cell-centered	
water_surface	Water surface elevation [m]
water_depth	Water depth [m]
bottom_elevation	Bottom elevation [m]
friction_chezy	Dimensionless squared chezy friction coefficient [-]
delta_z	Change in bottom elevation of during the course of the simulation [m]
spec_discharge	Specific hydraulic discharge (q_x, q_y) [m^2/s]
flow_velocity	Flow velocity (u_x, u_y) [m/s]
turb_k	Turbulent kinetic energy (κ) [m^2/s^2]
turb_reynolds	Turbulent Reynolds stresses [Nm/m^2]
flow_velocity	Flow velocity (u_x, u_y) [m/s]
flow_curvature	Flow curvature (inverse of flow radius) [m^{-1}]
flow_radius	Flow radius [m]
theta	Non-dimensional effective bed shear stress for bedload transport [-]

Output	Description
theta_critical	Non-dimensional critical bed shear stress [-]
trsp_capacity	Bedload transport capacity ($q_{b,x}$, $q_{b,y}$) [m^2/s] as compact volume, no porosity
trsp_capacity_abs	Bedload transport capacity magnitude q_b [m^2/s] as compact volume, no porosity
suspended_conc	Suspended sediment concentration [-]
suspended_theta	Non-dimensional effective bed shear stress for suspended sediment transport [-]
bed_gradient	Local bed gradient ($\partial z/\partial x$, $\partial z/\partial y$) [-]
flood_tracking	Water front arrival time [s] Max. water depth [m] Max. flow velocity [m/s] Max. specific discharge [m^2/s] Max. bed shear stress [Pa]
tracer1-5	Concentration of tracer specie 1 [-] ... Concentration of tracer specie 5 [-]
aboveground_biomass	Above ground biomass of vegetation [-]
belowground_biomass	Above ground biomass of vegetation [-]
rooting_depth	Rooting depth of vegetation [m]
Nodestring	
ns_hyd_discharge	Hydraulic output variables on the Nodestrings
ns_mor_discharge	Morphologic output variables on the Nodestrings

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 “results.xdmf” (see Figure 2.1) for the cell centered outputs or in a text format (.csv) for the nodestring output. The software ParaView and QGIS enables to visualize the results stored in “results.xdmf”.

Grid Generation with BASEmesh

3.1 General

In order to provide a free and open source solution for the creation of computational meshes, the plugin BASEmesh for the open source geographic information (GIS) software QGIS was developed. The plugin utilises Jonathan R. Shewchuk's advanced mesh generator [Triangle](#) (Shewchuk, 1996) as its meshing algorithm.

BASEmesh version 2.x is compatible with BASEMENT v2.8 and v3.x, but requires QGIS version 3.10 or higher. For versions of BASEmesh compatible with QGIS v2.18 or versions lower than v3.10, please refer to the compatibility section on the [BASEmesh Website](#).

3.2 Installation

BASEmesh is available for installation through a custom plugin repository which is not included in QGIS upon installation. The BASEmesh plugin repository must be added to the QGIS plugin manager by the user prior to installation.

To install BASEmesh, follow these steps:

1. Start QGIS
2. Load the QGIS plugin manager by choosing *Manage and Install Plugins...* in the *Plugins* category of the QGIS toolbar
3. Select *Settings* from the left panel
4. Click on *Add...* and provide a descriptive name, e.g. 'BASEmesh Plugin Repository'
5. Specify the repository address: https://people.ee.ethz.ch/~basement/qgis_plugins/qgis_plugins.xml
6. Press OK to confirm; a new entry has been added to the list of plugin repositories (make sure the *Status* reports as *connected* before continuing)

7. Select *All* from the left panel of the plugin manager and search for ‘BASEmesh’
8. Choose the BASEmesh plugin (if several are available, choose the one with the highest version number) and press *Install Plugin*
9. Close the plugin manager. A new toolbar should have appeared and a *BASEmesh* entry added to the *Plugins* category of the QGIS toolbar

3.3 Mesh generation

The following section covers the basics of mesh generation using version 2.0 of the BASEmesh plugin. For in-depth parameter explanations and advanced use-cases, refer to the [BASEmesh Manual](#).

Mesh generation in BASEmesh v2.x is performed in two steps. First, a 2D quality mesh is generated using Triangle, which is then interpolated using one or more elevation sources. Elevation sources are either existing meshes containing elevation data (TIN), or raster data in the form of a digital elevation model (DEM). This interpolation can be performed for the mesh nodes (BASEMENT v2.8), the mesh elements (BASEMENT v3.x), or both, which allows use of the same computational grid for both environments.

3.3.1 Quality mesh generation

The quality meshing utility provides a QGIS interface to the Triangle advanced mesh generator. As Triangle is two-dimensional, the generated mesh will not contain any elevation information.

The following constraints are available to control the mesh generation process:

- *Break lines*: A map layer containing lines or line strings representing distinct interruptions of the surface slope (e.g. dyke crests, river side walls, ...) which will be preserved in the computational mesh. Note that you do not have to include break lines for node string definitions (see *String definitions* description below).
- *Dividing constraints*: An integer layer attribute used to split a break line before meshing. This is important when using inner boundaries in BASEMENT as the number of mesh elements at the upstream and downstream interface must be equal.
- *Constrained points*: Additional points to enforce during triangulation, such as a known measurement point.
- *Minimum angle constraint*: The minimum angle enforced for any mesh elements generated. This heavily affects the element count of the resulting mesh.
- *Maximum area constraint*: A global maximum area for any mesh elements generated. This will be overridden by any region-specific area constraints defined (see below).

In addition to the global mesh quality constraints, additional constraints may be defined for individual mesh regions. A region is any closed loop of break lines, the constraints are then applied by placing a point marker within a region.

These markers may specify up to three flags:

- *Hole marker*: Regions marked as holes will be carved out of the resulting mesh. This flag is mutually exclusive with the other flags.
- *MATID*: Specify the material ID for any mesh elements generated within this region.
- *Maximum area*: This allows overriding the global maximum area constraint for mesh elements in this region.

In BASEMENT an ordered list of neighbouring node IDs is called a *string definition* (aka. StringDef) or *node string*. In BASEmesh v2.x, their declaration is also part of the quality meshing utility.

They are defined through line strings in a separate map layer and will be preserved in the resulting mesh as break lines are:

- *String definitions layer*: A map layer containing lines defining the node strings.
- *String definition ID field*: The unique name attribute of a given string definition. Required for node string identification.
- *Include in 2DM node strings*: If checked, the node strings will be written into the 2DM mesh file using *NS* tags. Required for BASEMENT v3.x.
- *Write to sidecar file*: If checked, the node strings will be written into a separate text file. Required for BASEMENT v2.8.

Note that BASEMENT v3.x does not allow more than 200 nodes per node string; split your string definition lines if your meshing parameters generate meshes exceeding this limit.

3.3.2 Elevation mesh generation

The elevation meshing utility generates mesh geometries in the SMS 2DM format from existing 3D input geometries. It is provided to allow generation of TIN elevation data from geometries and is not necessary if you already have raster (DEM) elevation data for your quality mesh.

You can use the *BASEmesh/Converters/Convert legacy layer* utilities in the QGIS processing toolbox to create 3D geometries from 2D geometries with elevation attributes as used in previous versions of BASEmesh. Only layers containing elevation information will be displayed for this step.

Key parameters for the elevation meshing utility:

- *Line segments*: A map layer containing 3D lines or line strings constraining the generated output geometry.
- *Fixed points*: A map layer containing 3D points used to further constrain the triangulation.
- *Keep convex hull*: If selected, the convex hull of the input data is kept and used as the mesh boundary.
- *Shrink to segments*: If selected, only closed areas enclosed by break lines are included in the generated mesh.

Note that in BASEmesh v2.x, there is no more differentiation between the mesh domain (aka. mesh boundary polygon) and the mesh break lines layer. For behaviour similar to previous versions of BASEmesh, merge the mesh boundary polygon lines into the break lines layer and select the *Shrink to segments* option as your mesh domain.

3.3.3 Mesh interpolation

The interpolation step converts the flat quality mesh generated by Triangle into a suitable computational mesh for BASEMENT. For v2.8, this means adding elevation information to the mesh nodes, for v3.x, the elevation information is added for the mesh elements instead. This interpolation is done from one or more interpolation sources, i.e. elevation meshes (TIN) or raster data (DEM).

In basic mode, a single elevation source may be selected, though multiple elevation sources are allowed in advanced mode - refer to the Interpolation utility's help panel for details.

Be aware that the interpolation process can be time consuming for large meshes. While it is possible to interpolate both the mesh nodes and elements, this will also double the time required to complete the interpolation process.

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

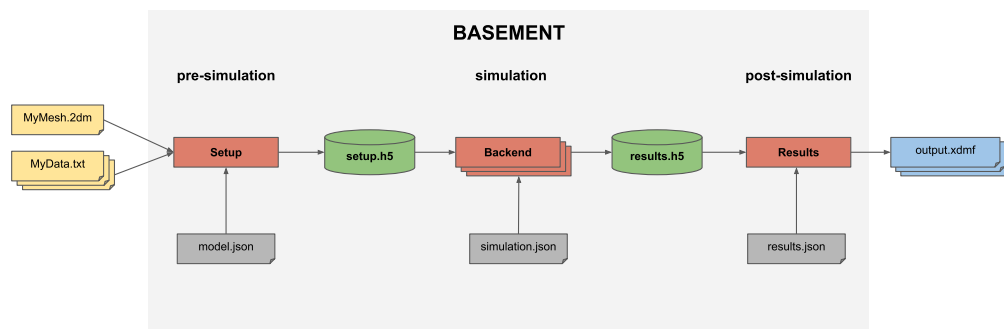


Figure 4.1 BASEMENT simulation workflow

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 or its path have to be specified. If a computational mesh of BASEMENT version 2.x is used, an elevation interpolation method has to be defined. If no interpolation method is specified, the default interpolation method “mean” is selected. In the STRINGDEF block, the stringdefs must be listed by their name and the upstream flow direction should be indicated as either left or right (see Section 2.2.2.3). The in the REGIONDEF block, regions can be defined by listing a region name and assigning cells to that region via the MatID from the .dm mesh file. Currently, each MatID should only be assigned to one region. Assigning an already assigned MatID to another region will overwrite the assignment to the previous region.

The hydraulics block contains the information about the initial conditions (dry, continue, region_defined), the parameters (CFL, minimum water depth, . . .), the boundary conditions, friction values, external sources and flood tracking. If the initial conditions are defined via regions, dry initial conditions are assigned for cells which do not belong to any regions from REGIONDEF or whose region is not specifically assigned initial conditions. The boundary conditions are defined by giving the corresponding STRINGDEF name and the required type (standard, linked or internal). The friction value of a cell is set to the default friction value unless specified otherwise via regions. Regions can further be used to specify external sources. The flood tracking feature will track the maximum values of the water depth, flow velocity, specific discharge, bed shear stress and the flood arrival time.

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 can be activated in order to influence the bedload transport direction. Further, gravitational transport processes can be activated.

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 hydraulic and sediment discharge, calculated at flow boundaries (nodestrings).

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 [BMv3NodestringResulty.py](#) is available for extracting the stringdefs results (discharge) stored in the results.h5 binary and converts them in a text format (.csv). The available outputs are listed and described in Table 4.1.

Table 4.1 Output of the post-processing python script *BMv3NodestringResulty.py*

Output	Description
Mean wse	mean water surface elevation [m]
Discharge	total normal water discharge Q [m ³ /s]
Wetted area	total wetted area of the edges belonging to the NS [m ²]
Mean bottom elevation	mean bed elevation of wetted edges [m]
Reference elevation	reference elevation (talweg) [m]
Wetted geometric length	wetted geometric length [m]
Total water volume stored in cells	total water volume stored in the cells belonging to the NS
Total cells conveyance	total conveyance of the cells belonging to the NS
Morphological flux	total normal morphological flux [m ³ /s] as compact volume, no porosity (output)
Bedload transport	total bed load transport capacity [m ³ /s] as compact volume, no porosity

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.

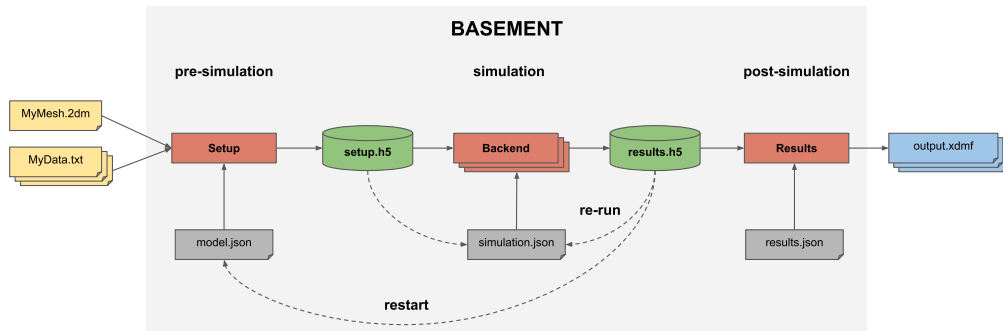


Figure 4.2 BASEMENT simulation workflow with restart and re-run processes

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.

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.

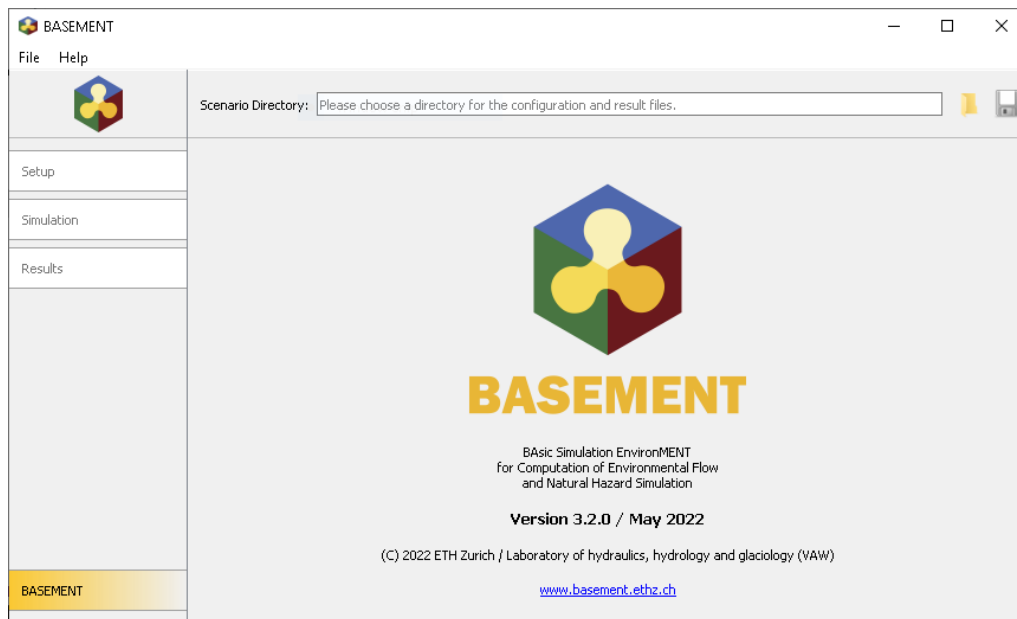


Figure 5.1 Welcome Screen

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 object), 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).

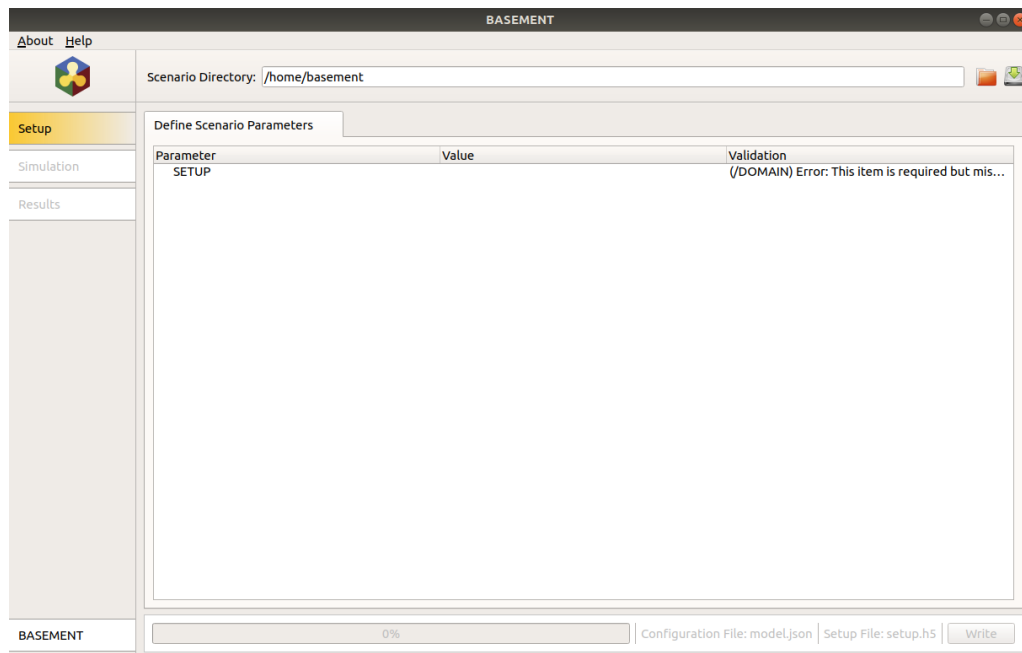


Figure 5.2 Setup Screen

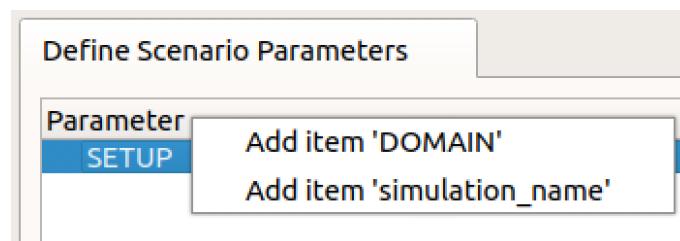


Figure 5.3 Adding JSON Items



Figure 5.4 File Name Editor

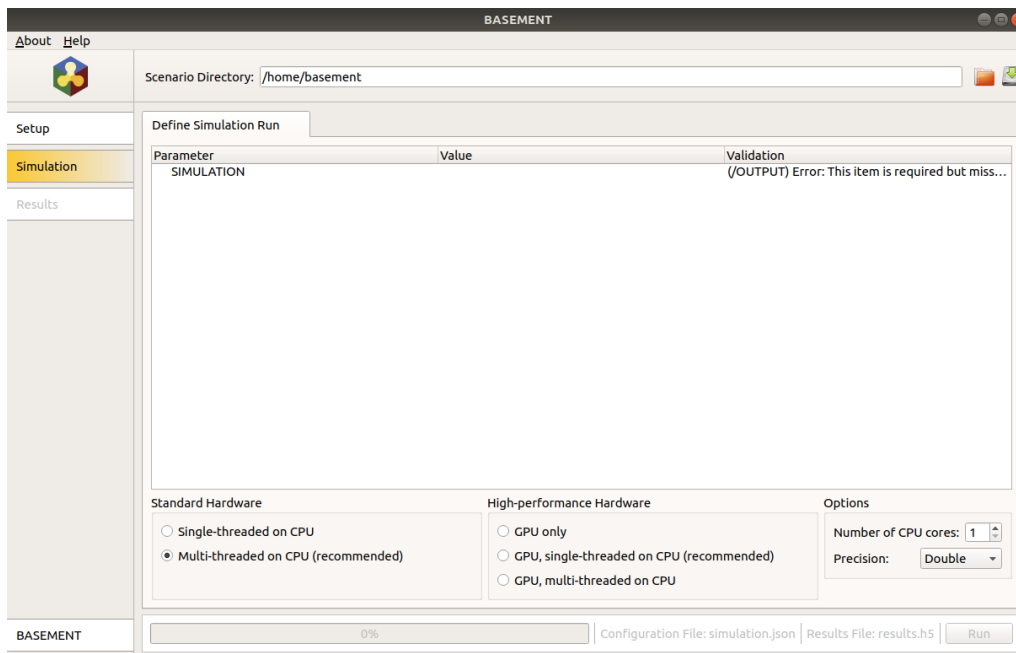


Figure 5.5 Simulation Screen

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.

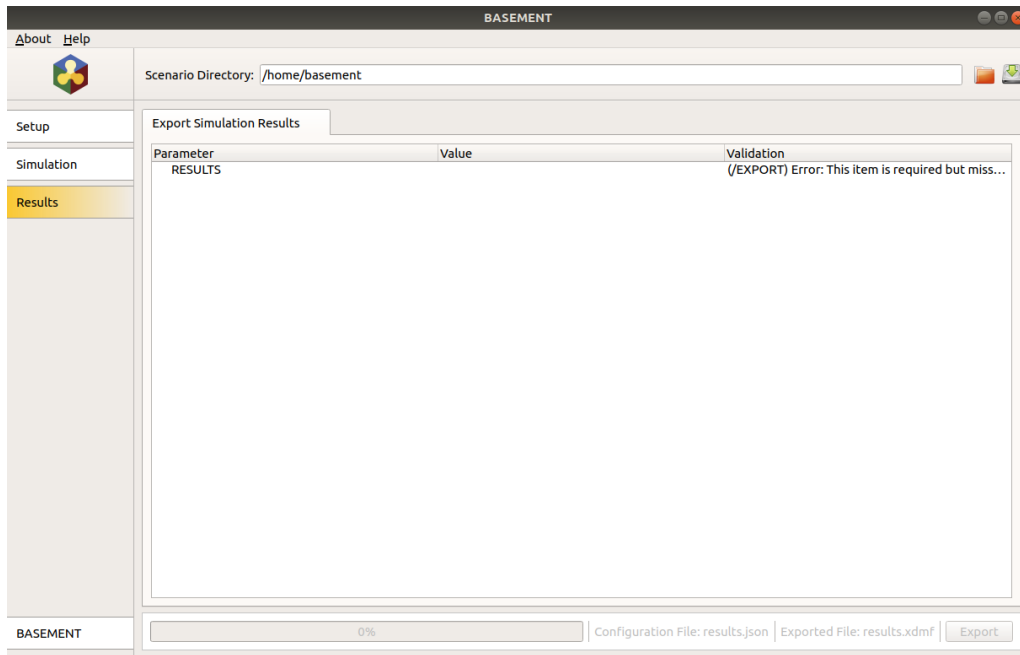


Figure 5.6 Results Screen

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 possibility of running on single precision:

```
$ ./BMv3_BASEplane_seq
```

```
$ ./BMv3_BASEplane_omp
```

```
$ ./BMv3_BASEplane_cuda
```

```
$ ./BMv3_BASEplane_cudaC
```

```
$ ./BMv3_BASEplane_cuda0
```

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)\BASEMENTv3.2” 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 3.2\bin\BMv3_BASEplane_setup.exe
-f F:\Project_1\model.json
-o F:\Project_1\mySim_run.h5
```

```
C:\Program Files\BASEMENT 3.2\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\BASEMENT3.2\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 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\BASEMENT3.2\bin\BMv3_BASEplane_setup.exe
-f F:\Project_1\model.json
-o F:\Project_1\mySim_run.h5
```

```
"C:\Program Files\BASEMENT3.2\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\BASEMENT3.2\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\BASEMENT3.2\bin\BMv3_BASEplane_setup.exe
-f F:\Project_2\model.json
-o F:\Project_2\mySim_run.h5
```

```
"C:\Program Files\BASEMENT3.2\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\BASEMENT3.2\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.

References

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

REFERENCE MANUAL

**VERSION 3.2
May 2022**



BASEMENT

Contents

1	Mathematical Models	3
1.1	Hydrodynamics	3
1.1.1	Introduction	3
1.1.2	Governing Equations	4
1.1.3	Closure Relations	4
1.1.3.1	Friction Terms	4
1.1.3.2	Turbulent Terms	5
1.1.3.3	Lateral Inflow/Outflow	7
1.1.4	Boundary Conditions	7
1.1.4.1	Standard Boundary Conditions	8
1.1.4.2	Linked Boundary Conditions	10
1.1.4.3	Internal Boundary Conditions	11
1.1.5	Flood Tracking	11
1.2	Morphodynamics	11
1.2.1	Introduction	11
1.2.2	Bedload Sediment Transport	12
1.2.2.1	Governing Equations for Uniform Sediment Transport	12
1.2.2.2	Threshold Conditions for Sediment Movement	12
1.2.2.3	Closure Relations for Bedload Transport	14
1.2.2.4	Correction of Bedload Direction	17
1.2.2.5	Fixed Bed Concept	18
1.2.2.6	Gravitational Transport	19
1.2.2.7	External Sources Terms	22
1.2.2.8	Boundary Conditions	24
1.2.2.9	Upstream Boundary Condition	24
1.2.2.10	Downstream Boundary Condition	25
1.2.2.11	Linked Boundary Condition	25
1.3	Suspended Sediment Transport	26
1.3.1	Governing Equations for Uniform Suspended Sediment Transport	26
1.3.2	Closures for Suspended Transport	26
1.3.2.1	Deposition rate	26
1.3.2.2	Erosion rate	27
1.3.2.3	Settling Velocities of Particles	27
1.3.3	External Source Terms	28
1.3.4	Boundary Conditions	29
1.3.4.1	Upstream Boundary Condition	29
1.3.4.2	Downstream Boundary Condition	29
1.4	Passive tracers	29
1.4.1	Introduction	29

1.4.2	Transport of passive species	29
1.4.2.1	Governing Equations for passive specie transport	29
1.4.2.2	External Sources Terms	30
1.4.2.3	Boundary Conditions	30
1.4.2.4	Upstream Boundary Condition	30
1.4.2.5	Downstream Boundary Condition	31
1.5	Riparian vegetation	31
1.5.1	Introduction	31
1.5.2	Description of Vegetation	32
1.5.3	Effect of Vegetation on Water Flow	33
1.5.4	Effects of Vegetation on Bedload Transport	33
1.5.4.1	Bottom Shear Stress	33
1.5.4.2	Critical Shear Stress	33
1.5.5	Effects of Bed Changes on Vegetation	33
1.5.5.1	Biomass Redistribution	33
1.5.5.2	Plant Burial	34
1.5.5.3	Plant Uprooting	34
2	Numerical Models	35
2.1	General View	35
2.2	Discretization	37
2.3	Numerical solution of Hydrodynamics	37
2.3.1	Vectorial Form of the Governing Equations	37
2.3.2	Spatial Discretisation	38
2.3.3	Flux Estimation	38
2.3.3.1	Rotational Invariance of the Shallow Water Equations	38
2.3.3.2	Computation of the Flux	39
2.3.3.3	The HLLC approximated Rieman Solver	39
2.3.4	Numerical Stability	40
2.3.5	Discretisation of Source terms	40
2.3.5.1	Bed Slope Source Term	40
2.3.5.2	Friction Source Term	40
2.3.5.3	External Source Term	41
2.3.6	Solution Procedure	42
2.4	Numerical solution of Morphodynamics	42
2.4.1	Numerical solution of the Exner equation	42
2.4.1.1	Fundamentals	42
2.4.1.2	Spatial discretization	43
2.4.1.3	Discretization of External Source Term	44
2.4.2	Solution procedure	44
2.5	Numerical solution of Advection-Diffusion equation	45
2.5.1	Numerical solution of the advective part	45
2.5.2	Numerical solution of the diffusive part	46
2.5.3	Discretization of external source terms	47
2.5.4	Solution procedure	47
3	References	49

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

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

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
T_x (T_y)	$[-]$	turbulent terms in x (y) direction .

The bed slope source terms

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

are evaluated as follows:

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

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:

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

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

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

1.1.3.1.2 Logarithmic Law

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

Chézy:

$$\begin{aligned} c_f &= 5.75 \log \left(12 \frac{R}{K_s} \right) & \text{for } R > K_s \\ c_f &= 5.75 \log (12) & \text{for } R < K_s, \end{aligned} \quad (1.5)$$

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).

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

1.1.3.2 Turbulent Terms

The turbulent and viscous stresses are considered under the eddy viscosity model, following the Boussinesq hypothesis, and can be written as

$$T_{x_i} = \frac{\partial}{\partial x_j} \left((\nu + \nu_t) \frac{\partial}{\partial x_j} h u_{x_i} \right)$$

where x_i stands for the x or y direction, ν and ν_t are the laminar and turbulent kinematic viscosities, respectively, u_{x_i} is the flow velocity and T_{x_i} are the commonly denominated Reynolds stresses. The turbulent viscosity is the defining parameter when employing this type of turbulence closure, with several closures being available in fluid mechanics literature. For SWE systems, the most common options for computing the eddy viscosity are the constant, mixing-length and κ - ϵ models.

1.1.3.2.1 Mixing-length model

The mixing-length model was derived by Ludwig Prandtl and is based on a characteristic length concept where a fluid retains some of its original characteristics (namely turbulence) before dispersing them into the surrounding fluid. In this model, the turbulent viscosity is locally derived by a length scale, the strain rate and the friction velocity as follows:

$$\nu_t = l_s^2 \sqrt{2S_{ij}S_{ij} + \frac{2.34\kappa}{u_f}}$$

where l_s is the characteristic length scale, $S_{ij} = (\partial_{x_j} u_i + \partial_{x_i} u_j) / 2$ is the strain rate, κ is the von Karman constant and $u_f = c_f |\vec{u}|$ is the friction velocity. The length scale can be defined as a constant or by using $l_s = 0.267\kappa h$ (ref).

1.1.3.2.2 κ - ϵ model

The κ - ϵ model is one of the most widely adopted models in hydraulics and general fluid mechanics. The turbulent kinetic energy (TKE) κ is introduced by means of an additional conservation equation, given by:

$$\frac{\partial(kh)}{\partial t} + \frac{\partial(khu_i)}{\partial x_i} - \frac{\partial}{\partial x_j} \frac{\nu_t}{\sigma_k} \frac{\partial kh}{\partial x_j} = hP_k - h\epsilon$$

where P_k is the TKE production rate and ϵ is its dissipation rate. The P_k term is locally defined, whereas the ϵ term is solved through another conservation equation, as:

$$\frac{\partial(\epsilon h)}{\partial t} + \frac{\partial(\epsilon hu_i)}{\partial x_i} - \frac{\partial}{\partial x_j} \frac{\nu_t}{\sigma_\epsilon} \frac{\partial \epsilon h}{\partial x_j} = hS_\epsilon$$

where S_ϵ is an aggregate net source of ϵ . In the Standard κ - ϵ model, the source terms for both κ and ϵ are defined as:

$$P_k = 2\nu_t S_{ij} S_{ij} + \frac{u_f^3}{c_f h}$$

$$S_\epsilon = 2c_{\epsilon_1} \frac{\epsilon}{\kappa} \nu_t S_{ij} S_{ij} + 3.6 \frac{c_{\epsilon_2} \sqrt{c_\mu} u_f^4}{h^2 c_f^{3/4}} - c_{\epsilon_2} \frac{\epsilon^2}{\kappa}$$

and the constants of the standard model are $c_\mu = 0.09$, $\sigma_k = 1.00$, $\sigma_\epsilon = 1.30$, $c_{\epsilon_1} = 1.44$ and $c_{\epsilon_2} = 1.92$. The turbulent viscosity is finally obtained, locally, as

$$\nu_t = c_\mu \frac{\kappa^2}{\epsilon}$$

1.1.3.3 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 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, three different types of boundary conditions can be defined:

- Standard boundary conditions: located at the domain boundary Γ_i
- Linked boundary conditions: located at the domain boundary Γ_i or inside the domain Ω
- Internal boundary conditions: located inside the domain Ω

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

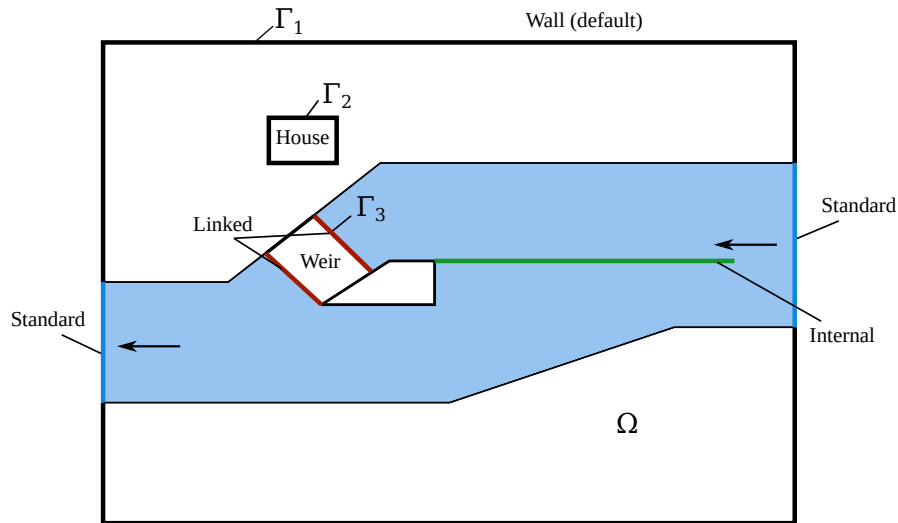


Figure 1.1 Modeling domain and types of boundary conditions available. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir. **Standard** or **linked** boundary conditions must be provided at Γ_1 , Γ_2 and Γ_3 while **internal**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

1.1.4.1 Standard Boundary Conditions

At the standard 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 of the domain are set as wall boundaries.

1.1.4.1.1 Wall Boundaries

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:

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

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

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

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.

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

$$h = \sqrt[3]{\frac{(Q/b)^2}{gFr^2}} \quad (1.9)$$

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:

$$h = wse - z_B \quad (1.10)$$

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_out*: 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_out_constant* and *weir_out_dynamic*: These boundary conditions establish a relation between the approaching discharge q constant and the water depth using the Poleni weir formula:

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

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:

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

where a and b must be specified by the user in the case of *weir_out_dynamic* (default values are $a = 0.611$ and $b = 0.075$).

- *hqrelation_out*: The discharge is determined as a function of the water surface elevation, thus a stage-discharge-relation has to be specified.
- *zhydrograph*: Sets a fixed water surface elevation (*wse*) at the boundary. The *wse* [m] at the boundary must be specified by the user. The depth is calculated as:

$$h = wse - z_B \quad (1.13)$$

where z_B is the bottom elevation at the boundary. The flow velocity is calculated with the Riemann solver (HLLC).

- *zero_gradient_out* (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:

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

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.*

1.1.4.2 Linked Boundary Conditions

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_linked_constant* and *weir_linked_dynamic*: Similar to the standard weir boundary, the weir height w has to be specified. No kinetic energy is considered.
- *hqrelation_linked*: The flux is calculated given a h-Q relation (see description of the h-Q relation for standard boundaries).
- *2way_hqrelation_linked*: 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.

- *zhydrograph_linked*: Sets a fixed water surface elevation (WSE) at the upstream boundary. The flux is calculated with the Riemann solver and used as inflow in the downstream boundary. Input of kinetic energy is neglected at the downstream boundary.
- *zhydrograph_linked_kinE*: Sets a fixed water surface elevation (WSE) at the upstream boundary. The flux is calculated with the Riemann solver and used as inflow in the downstream boundary. Input of kinetic energy is taken into account at the downstream boundary, using the flow depths of the cells adjacent to the boundary.

1.1.4.3 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_internal*: The wall conditions (eq. 1.7) are applied on both sides of the internal boundary.
- *dynamic_wall_internal*: The wall conditions are applied on the internal boundary until reaching a threshold value (time or water depth) after which the wall is removed.
- *hrelation_internal*: A stage-discharge 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, specific discharge and bed shear stress along the numerical simulation and over a selected domain area. 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 Bedload Sediment Transport

1.2.2.1 Governing Equations for Uniform Sediment Transport

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 conservation of sediment mass is ensured by the Exner equation (eq. 1.15), 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 :

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

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 bedload flux. The term S_s describes the exchange per unit width between the sediment and the suspended material (see Section 1.3). The Exner equation describes the bed evolution due to erosion or deposition processes, which results in changes of the bed level z_B .

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 bedload flux is much slower than the water flow velocity (Soares-Frazão and Zech, 2011).

1.2.2.2 Threshold Conditions for Sediment Movement

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

$$\theta = \frac{|\vec{\tau}_b|}{(\rho_s - \rho)gd} \quad (1.16)$$

where $vec\tau_b$ is the bed 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.

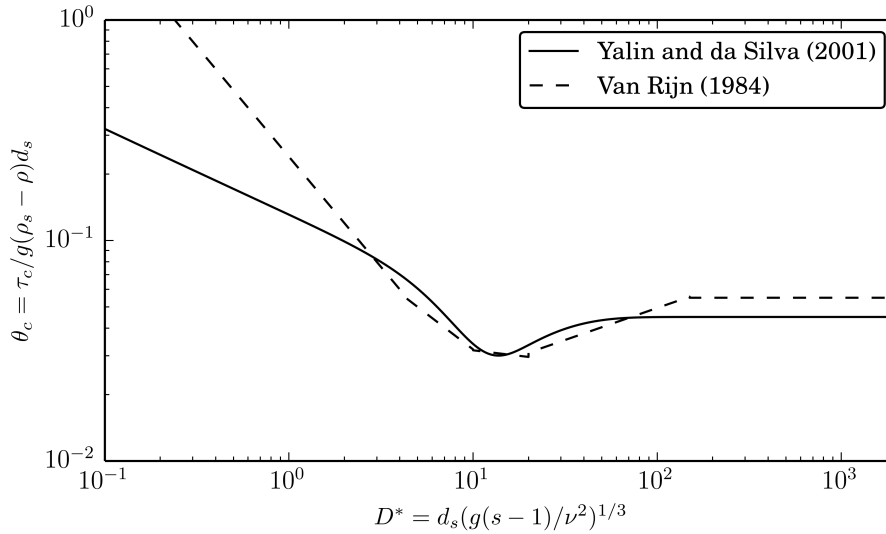


Figure 1.2 Modified Shields diagram for initiation of sediment motion

The bed shear stress $\vec{\tau}_b = \begin{pmatrix} \tau_{bx} \\ \tau_{by} \end{pmatrix}$ 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:

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

where $\vec{u} = \begin{pmatrix} u \\ v \end{pmatrix}$ is the flow velocity vector, ρ is the density of water and c_f is the dimensionless Chézy friction coefficient as defined in Section 1.1.3.1.

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 Shields parameter. According to the Shields' 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 plotted 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 (1984a):

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

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

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

1.2.2.2.1 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 θ_{cr} with the correction factors k_l and k_t for the local bed slope in the longitudinal and transversal flow direction. In the following, the critical Shields stress corrected for arbitrary bed slope δ is referred to as $\theta_{c,\delta}$, defined as:

$$\frac{\theta_{c,\delta}}{\theta_{cr}} = k_l k_t = k \tag{1.20}$$

The correction factor k_l and k_t are calculated as suggested by van Rijn (1989):

$$k_l = \cos \delta_l \left(1 - \frac{\tan \delta_l}{\tan \gamma} \right) \tag{1.21}$$

$$k_t = \cos \delta_t \sqrt{1 - \frac{\tan^2 \delta_t}{\tan^2 \gamma}} \tag{1.22}$$

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

Other formulations are also available, as for example the one proposed by Chen et al. (2010):

$$k = \frac{1}{\tan \gamma} \left(\cos^2 \left(\frac{\pi}{2} - \delta_l \right) - 1 + \frac{1 + \tan^2 \gamma}{(1 + \tan^2 \delta_l + \tan^2 \delta_t)} \right)^{0.5} + \cos \left(\frac{\pi}{2} - \delta_l \right) \tag{1.23}$$

1.2.2.3 Closure Relations for Bedload Transport

In order to solve system (eq. 1.1) and equation (eq. 1.15) 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 discharge. Let us now introduce the dimensionless bedload transport rate Φ also known as the Einstein bedload number, first introduced by Hans Albert Einstein in 1950, and given by

$$\Phi = \frac{q_B}{\sqrt{(s-1)gd^3}} \quad (1.24)$$

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 ($\theta - \theta_{cr}$). The critical Shields stress θ_{cr} is defined so as to fit experimental or field data and provide a threshold for which the bedload transport rate is too low to be of interest. The Shields parameter, takes the following form

$$\theta = \frac{h\sqrt{S_{fx}^2 + S_{fy}^2}}{(s-1)d} \quad (1.25)$$

where h is the water depth, S_{fx} and S_{fy} the friction slope in x- and y-direction respectively, $s = \rho_s/\rho_w$, and d is the grain size diameter. Note that Eq. 1.16 and Eq. 1.25 are equivalent.

In what follows, we describe the bedload transport formulas that are implemented to calculate the transport capacity $q_B = |\vec{q}_B|$, where the specific bedload flux vector $\vec{q}_B = (q_{B_x}, q_{B_y})$ generally has the same direction as the water flow.

For practical purposes, the bedload transport formula can be calibrated by an additional pre-factor (*factor*). The bedload transport capacity is obtained from the closure relation scaled by this pre-factor.

1.2.2.3.1 Meyer-Peter and Müller (1948)

The bedload transport formula of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) defines the specific bedload transport rate q_B as:

$$q_B = \alpha(\theta - \theta_{cr})^m \sqrt{(s-1)gd^3} \quad (1.26)$$

Herein, α denotes the bedload coefficient (originally $\alpha = 8$), m the bedload exponent (originally $m = 1.5$), 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 were 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 bedload coefficient α , the exponent m and the critical Shields parameter θ_{cr} can be adapted by the user in the MPM-like formula.

1.2.2.3.2 Grass Formula

The Grass formula (Grass, 1981) proposes a simple bedload transport formula, where q_b is a function of the flow velocity u and a dimensional constant α and does not require the evaluation of the Shields stress:

$$q_B = \alpha(u - u_c)^m \cdot \sqrt{(s - 1)gd^3} \quad (1.27)$$

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, u_c is the critical velocity and the exponent m is usually set to $m = 3$. The threshold condition for incipient motion of grains is typically 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.

1.2.2.3.3 Engelund and Hansen (1972)

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

$$q_B = 0.05\sqrt{(s - 1)gd^3} \cdot c_f^2\theta^{2.5} \quad (1.28)$$

where d denotes the median sediment size of the bed material, c_f the dimensionless Chézy friction coefficient and θ is the dimensionless bed shear stress (see eq. 1.25). The Engelund and Hansen formula for bedload transport does not consider the critical shear stress as threshold condition for incipient motion.

1.2.2.3.4 Smart & Jäggi (1983)

Smart and Jaeggi (1983) developed a bedload transport formula for steep channels using their own experimental results and the results of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948). The specific bedload transport rate q_B is defined as:

$$q_B = \frac{\alpha}{(s - 1)} \left(\frac{d_{90}}{d_{30}} \right)^{0.2} J^{0.6} |\vec{q}| (J - J_{cr}) \quad (1.29)$$

where s is the sediment density coefficient ($s = \rho_s/\rho$), $|\vec{q}|$ is the magnitude of the specific discharge and d_{30} and d_{90} are the characteristic grain size diameters, i.e. 30 % resp. 90 % (by weight) of the bed material are smaller. The energy slope J and the critical slope for the initiation of the bedload transport J_{cr} calculated as

$$J = \frac{\theta(s - 1)d_m}{h} \quad (1.30)$$

$$J_{cr} = \frac{\theta_{cr}(s - 1)d_m}{h} \quad (1.31)$$

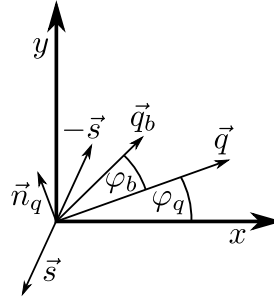


Figure 1.3 Bed load transport deviation angle φ_b from the flow direction \vec{q} due to the lateral bed slope \vec{s} (Vonwiller, 2017)

where θ is the dimensionless bed shear stress (see eq. 1.25), θ_{cr} the critical dimensionless bed shear stress, d_m the mean grain size diameter and h the water depth. Smart and Jaeggi (1983) recommend values of $\alpha = 4$ and $\theta_{cr} = 0.05$. The scope of application is for bed slopes $0.005 \leq J \leq 0.2$ (Smart and Jaeggi, 1983).

1.2.2.4 Correction of Bedload Direction

The 2D projection of the solid discharge along x and y is obtained through standard procedures, that are 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 reaches.

1.2.2.4.1 Lateral Bed Slope Effect

Empirical bedload 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 bedload direction differs from the flow direction due to gravity acting on the bed material. Figure 1.3 illustrates the deviation of the bedload transport direction due to lateral bed slope in a Cartesian coordinate system.

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

$$\tan \varphi_b = -f(\theta) \cdot \vec{s} \cdot \vec{n}_q \quad \text{for } \vec{s} \cdot \vec{n}_q < 0 \quad (1.32)$$

$$f(\theta) = N_l \left(\frac{\theta_{cr}}{\theta} \right)^{M_l} \quad (1.33)$$

where φ_b = bedload direction with respect to the flow vector \vec{q} , N_l = lateral transport factor ($0.75 \leq N_l \leq 2.63$), M_l = lateral transport exponent (typically $M_l = 0.5$), $\vec{s} = \left(\frac{\partial z_B}{\partial x}, \frac{\partial z_B}{\partial y} \right)$ 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 bedload transport under the influence of lateral bed slope is written as:

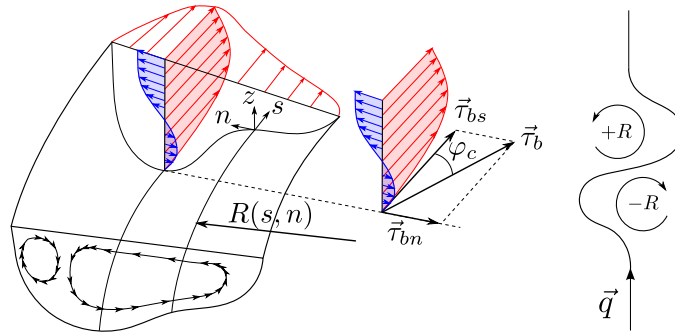


Figure 1.4 Effect of spiral motion in river bend on bed shear stress $\vec{\tau}_b$ with deviation angle from main flow direction φ_c (Vonwiller, 2017)

$$\frac{q_{B_y}}{q_{B_x}} = \tan(\varphi_b + \varphi_q) \quad (1.34)$$

1.2.2.4.2 Curvature Effect

Curvature in rivers may cause deviation of the bedload direction from the depth averaged flow direction. Due to three dimensional spiral flow motion, the bedload direction tends to point towards the inner side of the curve, while the flow direction points towards the outer side (Figure 1.4). 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

$$\tan \varphi_c = \frac{|\vec{\tau}_{bn}|}{|\vec{\tau}_{bs}|} = -N_* \frac{h}{R} \quad (1.35)$$

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 to $N_* \approx 11$ for laboratory channels (Rozovskii, 1961).

1.2.2.5 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 1.5). The fixed bed elevation can either be assigned via regions or via a separate .2dm mesh file. When the fixed bed elevation is specified via regions, the fixed bed elevation must be provided relative to the initial bottom elevation z_B with $z_{rel} \leq 0$. When the fixed bed elevation is specified via a mesh, the elevation in the separate .2dm mesh file must correspond to the absolute fixed bed elevation z_{fix}

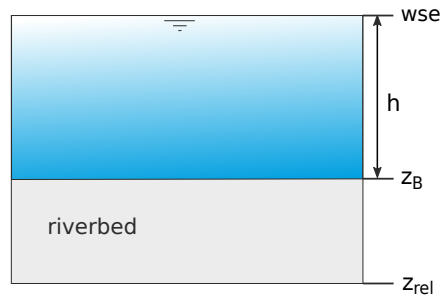


Figure 1.5 Fixed bed concept and definition

[m]. Moreover, the fixed bed mesh file must have the exact same topology as the original computational mesh. In case the specified mesh only has elevation information on the nodes, the elevation is interpolated with the same method as specified in the INTERPOLATION block (default: mean). If the fixed bed elevation of the fixed bed mesh exceeds the bottom elevation of the computational mesh, the fixed bed elevation is defined at the elevation of the computational mesh.

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.

1.2.2.6 Gravitational Transport

Gravitational induced riverbank or sidewall failures are significant aspects concerning erosion and transport modelling. Such processes may play an important role in many situations, such as meandering streams, river widenings or failures of erodible embankment structures due to overtopping waters. Such slope failure processes take place mostly discontinuous and can deliver significant contributions to the total sum of transported material. The modes of slope failures can differ largely (falls, topples, slides, etc.) and depend on the soil material, the degree of soil compaction and the pore pressures within the soil matrix. Here, a simplified, geometric approach is applied to be able to consider some aspects of this purely gravitational induced transport. The main idea of the implemented geometrical approach is to assume that a slope failure takes place if the local bed slope γ becomes steeper than a critical slope γ_{cr} (Figure 1.6).

$$q_{B,grav} = \begin{cases} 0 & \text{if } (\gamma \leq \gamma_{cr}) \\ f(\gamma, \gamma_{cr}) & \text{if } (\gamma > \gamma_{cr}) \end{cases} \quad (1.36)$$

The sliding material is moved from the sediment element with higher elevation to the lower situated element until the stable condition: $\gamma \leq \gamma_{cr}$ is reached. Two characteristic critical slope angles are defined in this approach to have some flexibility in modelling the complex geotechnical aspects. The critical angles can be characterized as:

- critical angle for dry or partially saturated bank material γ_{dry} , which may greatly exceed the material's angle of repose (up to nearly vertical walls) due to negative pore pressures,
- critical angle for fully saturated and over flown material γ_{wet} which is in the range of the material's angle of repose

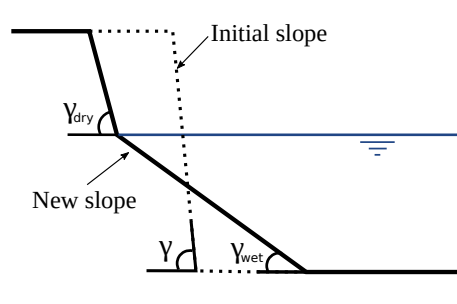


Figure 1.6 Critical failure angles for slope collapse

1.2.2.6.1 Calculation Procedure

The flux due to gravitational transport $q_{B,grav}$ is calculated with the following procedure, by looping over each element of the computational grid:

1. In a first step, the local bed slope γ_i is calculated with respect to each neighbouring element i , where z is the bed elevation of the main element, z_i is the bed elevation of the neighbour element i and d_i is the distance between the element centers.

$$\gamma_i = \arctan\left(\frac{z - z_i}{d_i}\right) \quad (1.37)$$

2. For local bed slopes γ_i exceeding the critical slope γ_{cr} , the new bed elevations z_{new} and $z_{i,new}$ are determined such that the stable condition $\gamma_i = \gamma_{cr}$ is reached for all neighbouring cells i . The critical angle γ_{cr} is selected according to eq. 1.38, where h is the water depth in the main element and h_{min} is the user-specified minimum water depth.

$$\gamma_{cr} = \begin{cases} \gamma_{wet} & \text{if } h \geq h_{min} \\ \gamma_{dry} & \text{if } h < h_{min} \end{cases} \quad (1.38)$$

3. If the calculated bed elevation change of the main element $\delta_z = z - z_{new}$ is smaller than the user-specified parameter min_bed_change (default: 0.001 m) $\delta_{z,min}$, no gravitational transport occurs to avoid oscillatory behaviour and to reduce the computational effort. If the minimum bed elevation change $\delta_{z,min}$ is exceeded, the specific gravitational flux $q_{B,grav,i}$ [m²/s] to each neighbour element i is calculated from the bed elevation change in element i according to eq. 1.39, where A_i is the area of element i , and l_i is the length of the edge connecting the main element to its i^{th} neighbour element. If the calculated bed elevation change of the main element $\delta_z = z - z_{new}$ is larger than the user-defined maximum bed elevation change $\delta_{z,max}$, the gravitational flux is limited, such that $\delta_z = \delta_{z,max}$. The maximum bed elevation change $\delta_{z,max}$ is calculated by eq. 1.40, where $r_{b,max}$ is the user-specified parameter $max_bed_change_rate$ and Δt is the current update time step.

$$q_{B,grav,i} = \begin{cases} 0 & \text{if } \delta_z < \delta_{z,min} \\ \frac{(z_{i,new} - z_i) \cdot A_i}{l_i} & \text{if } \delta_z \geq \delta_{z,min} \\ \frac{(z_{i,new} - z_i) \cdot A_i}{l_i} \cdot \frac{\delta_{z,max}}{\delta_z} & \text{if } \delta_z \geq \delta_{z,max} \end{cases} \quad (1.39)$$

$$\delta_{z,max} = r_{b,max} \cdot \Delta t \quad (1.40)$$

4. If a non-erodible fixed bed elevation z_{fix} is specified, the gravitational transport flux is corrected the same way as the bedload transport flux (see Section 1.2.2.5).
5. Finally, the balancing of the gravitational fluxes and the determination of the new bed elevations z is achieved by solving the Exner equation using the same numerical approaches as outlined for the bed load transport. This procedure ensures that fixed bed elevations are taken into account and the mass continuity is fulfilled.

1.2.2.6.2 Time Scale of the Gravitational Transport Process

Since the sediment movement due to gravitational transport during one update time step is limited to adjacent elements, it may take many update time steps to reach a stable condition on a larger scale, e.g. a bank slope spanning over multiple elements. The time scale until a globally stable condition is reached, is influenced by the update time step (`update_time`), the maximum bed change rate (`max_bed_change_rate`) and the grid resolution. The parameter `update_time` (default: 0.0 s) determines at which frequency the gravitational transport procedure (steps 1-5 above) is executed. Generally, a smaller update time step reduces the time scale until a globally stable condition is reached. The default behaviour is to set the update time step value to 0.0 seconds, which results in the gravitational transport procedure being executed at the same time step as determined from the hydraulic CFL-criterion (see Section 2.3.4).

Furthermore, the speed of the gravitational transport process can be limited with the parameter `max_bed_change_rate` (default: 1.0 m/s). This parameter represents a maximum rate at which the bed elevation of a cell can be lowered due to gravitational transport and determines the maximum bed elevation change during one update time step. Generally, a smaller value may increase the time scale until a globally stable condition is reached.

Since sediment movement due to gravitational transport is limited to adjacent elements, also the grid resolution effects the time scale until a globally stable condition is reached. A finer grid resolution (smaller elements) increases the necessary number of update cycles to reach a stable slope over a specific length. However, a finer grid resolution may also decrease the hydraulic time step and therefore may increase the frequency at which the gravitational transport procedure is executed.

1.2.2.6.3 Bed slope at Stable Condition

The implemented approach for modelling gravitational transport processes ensures that the local bed slope does not exceed the user-specified critical angle. Due to the spatial discretization with constant bed elevations within an element, the local bed slope is calculated between two element centers. On a larger scale (e.g. a bank slope spanning over multiple elements), the bed slope may deviate from the user-specified critical angle after reaching stable conditions. The stable bed slope over multiple elements, generally exceeds the critical bed slope.

To illustrate this effect, a simple test case was simulated. The rectangular computational domain is initially split into two parts: the left side with a bed elevation of 2 meters and

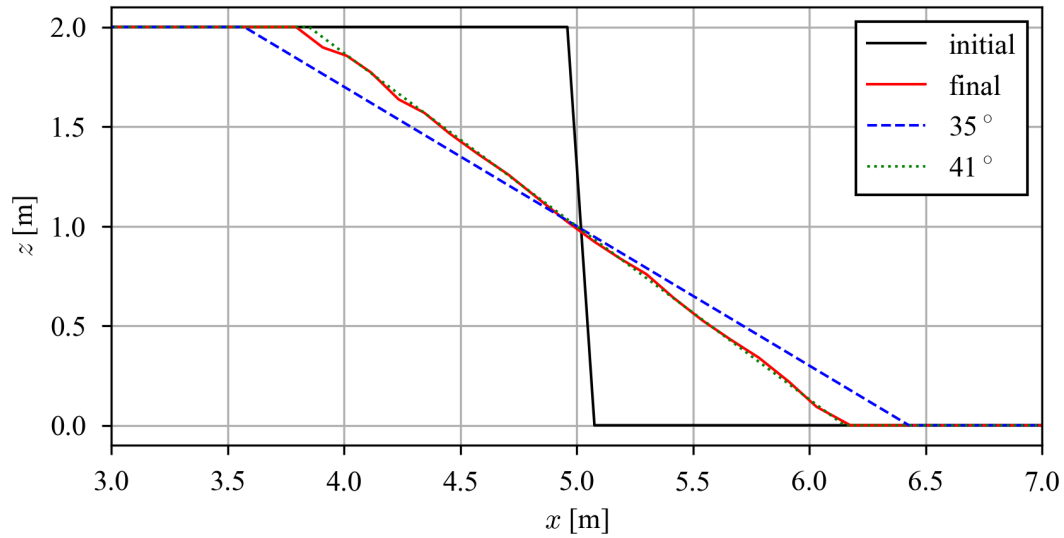


Figure 1.7 Initial and final bed elevation profiles along the centerline are compared to profiles with angles of 35° and 41° . The slope of the bed profile at stable conditions (final) exceeds the critical angle of $\gamma_{dry} = 35^\circ$.

the right side with a bed elevation of 0 meters. The domain is completely dry and the critical angle for dry material is set to $\gamma_{dry} = 35^\circ$. The simulation only considers only gravitational transport and is stopped after a stable condition is reached. The initial and final bed elevation profile along the centerline are illustrated in Figure 1.7. The initial profile exhibits the nearly vertical bed step. The final profile at stable conditions exhibits a slope of approximately 41° , which exceeds the critical angle of $\gamma_{dry} = 35^\circ$. The reason for this deviation on a larger scale is that the distance which is considered for the calculation of the slope is not a straight line, but a line connecting the element centers. This is illustrated in Figure Figure 1.8. Calculating the large scale slope considering the length of the green line results in a slope of approximately 41° , while considering the length of the red line results in a slope of approx. 35° .

1.2.2.7 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.

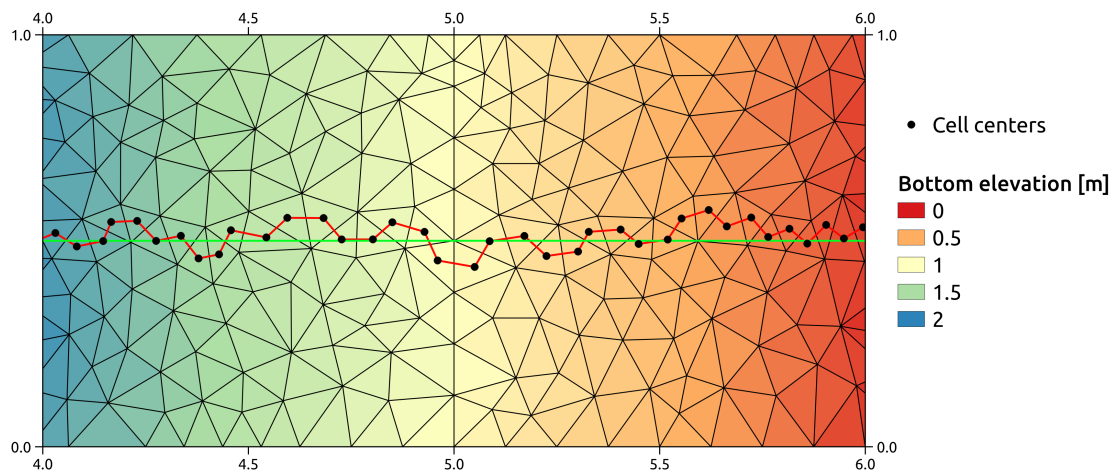


Figure 1.8 The red line connects the element centers and represents the distance, which is taken into account for the **local slope** calculation and thus for the gravitational transport. The green line represents the direct distance, which is taken into account for the **large scale slope**. The slope along the red line corresponds to 35° , while the slope along the green line corresponds to 41° .

Therefore, the “Available” behaviour aims to avoid this situation. The “Infinity” behaviour abstracts all available sediment volume.

1.2.2.8 Boundary Conditions

After the specification of the *closure relations* for the sediment transport, the system of governing equations (eq. 1.1) and (eq. 1.15) 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 be co-located with 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.

1.2.2.9 Upstream Boundary Condition

- *equilibrium_in*: After erosion or deposition up to a user specified reference bed elevation (*reference_bed_elevation*) this upstream boundary condition grants a equilibrium condition, i.e. 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.
- *sedimentograph*: based on a sediment hydrograph describing the bedload inflow as function of time (constant or variable). The bedload 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 bedload input and is specified separately as own parameter value. The volumetric flow rate is either distributed using a geometrical weighting (*sedimentograph*), using wetted area weighting (*sedimentograph_warea*) or using wetted conveyance weighting (*sedimentograph_conveyance*). **Note:** When using the pre-factor (*factor*) described in Section 1.2.2.3, it is automatically applied to the volumetric flow rate at the boundary for these types of boundary conditions, i.e. the sediment hydrograph is scaled by the pre-factor.
- *transport_capacity*: the sediment inflow is defined by calculating the equilibrium transport capacity according to the hydraulic state at the boundary. The bedload is defined as a compact volumetric flow rate (without porosity) $Q_b [m^3/s]$. The volumetric flow rate is either distributed using a geometrical weighting (*transport_capacity*), using wetted area weighting (*transport_capacity_warea*) or using wetted conveyance weighting (*transport_capacity_conveyance*). **Note:** When using the pre-factor (*factor*) described in Section 1.2.2.3, the pre-factor is implicitly included in the volumetric flow rate at the boundary for this type of boundary condition, i.e. the transport capacity at the boundary is scaled by the pre-factor. Additionally, an independent scaling factor can be specified (*boundary_factor*), only applying to these types of the boundaries.

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 .

$$q_b = \frac{Q_b}{L_n} \quad \left[\frac{m^3}{s \cdot m} \right] \quad (1.41)$$

2. Wetted area weighting

$$q_b = \frac{Q_b}{A_{w,tot}} \cdot h \quad \left[\frac{m^3}{s \cdot m^2} \right] \quad (1.42)$$

3. Conveyance weighting

$$q_b = \frac{Q_b}{K_{tot}} h \sqrt{c_f h} \quad \left[\frac{m^3}{s \cdot m} \right] \quad (1.43)$$

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

1.2.2.10 Downstream Boundary Condition

One downstream boundary condition is available:

- *equilibrium_out*: After erosion or deposition up to a user specified reference bed elevation (*reference_bed_elevation*) this downstream boundary condition grants a equilibrium condition, i.e. all sediment entering the last computational cell will leave the cell over the downstream boundary. This leads to a constant bed elevation at the boundary condition.

1.2.2.11 Linked Boundary Condition

One linked boundary condition is available:

- *equilibrium_linked*: At the upstream boundary, erosion or deposition is possible up to a user specified reference bed elevation (*reference_bed_elevation*). After reaching the reference elevation, this boundary condition grants a equilibrium condition, i.e. all sediment leaving the computational cells on the upstream side is entering at the downstream boundary with a lag of one timestep. This leads to a constant bed elevation at the upstream boundary.

1.3 Suspended Sediment Transport

1.3.1 Governing Equations for Uniform Suspended Sediment Transport

Similarly to bedload, the governing equations are also derived under shallow water conditions ensuring mass conservation extends to the suspended sediment phase. In a Cartesian reference system $(x; y; z)$ in which the z axis is vertical and the $x - y$ plane is horizontal, the conservation of suspended sediment mass is ensured by an advection-diffusion equation with source terms, describing the bed interaction and elevation changes arising from resuspension and deposition.

$$\frac{\partial}{\partial t} C_s h + \frac{\partial}{\partial x_i} \left(C_s h u_i - h D_{s_{ij}} \frac{\partial C_s}{\partial x_j} \right) = S_s + Sl_s$$

where C_s is the concentration of suspended sediment, $D_{s_{ij}}$ is its diffusivity (tensor), Sl_s are local sources and S_s aggregates the source terms that parameterize vertical exchanges with the bed.

1.3.2 Closures for Suspended Transport

For suspended sediment transport, the source term S_s represents the exchange with the bed and is calculated through the difference between the deposition rate q_d and the resuspension rate q_e .

$$S_s = q_e - q_d$$

1.3.2.1 Deposition rate

The deposition rate is expressed as the a sink flux:

$$q_d = w_s \alpha_s C_s$$

where w_s is the settling velocity and α_s is an adaptation coefficient. The adaptation coefficient can be determined through two distinct approaches, the first being provided by Lin (1984) as

$$\alpha_s = m \left(3.25 + 0.55 \ln \left(\frac{w_s}{\kappa u_*} \right) \right)$$

where κ is the von Karman constant and m is a tuning parameter (default value 1.0). The the second is based on the critical shear stress approach of Xu (1998)

$$\alpha_s = \begin{cases} \left(1 - \frac{\tau}{\tau_{c,d}} \right) & \tau < \tau_{c,d} \\ 0 & \tau \geq \tau_{c,d} \end{cases}$$

with

$$\tau_{c,d} = \frac{\rho_s - \rho}{\rho_s} \frac{ghw_s}{mU}$$

and where m is a calibration parameter which has been suggested to take a value of 0.0018.

1.3.2.2 Erosion rate

The erosion (or resuspension) rate, q_e , is given by

$$q_e = w_s \beta_s C_r$$

where w_s is the settling velocity of particles (see Section 1.3.2.3), β_s is a calibration constant and C_r is a reference concentration which can be determined by multiple options available in the literature. According to van Rijn (1984b), the reference concentration can be calculated as

$$C_r = a \frac{d_g}{b} \frac{T_g(\theta_c)^c}{D^{*d}}$$

where:

T_g is the dimensionless characteristic number for the bottom shear stress, b is the reference height above the mean bed bottom, D^* is the dimensionless diameter and a , c and d are calibration constants with default values $(a, b, c, d) = (0.015, 0.05, 1.5, 0.3)$. Another approach is the one of Zyserman and Fredsøe (1994), calculated as

$$C_r = \frac{a(\theta_s - \theta_c)^c}{1 + b(\theta_s - \theta_c)^d}$$

where a , b , c and d are calibration constants with default values $(a, b, c, d) = (0.331, 0.72, 1.75, 1.75)$.

1.3.2.3 Settling Velocities of Particles

The settling velocity w_s of sediment particles is an important parameter when determining suspended load. Many different empirical or semi-empirical formulas have been suggested in literature, with the following being implemented:

1.3.2.3.1 van Rijn

The sink rate can be determined according to the grain diameter after van Rijn (1984b):

$$w_s = \frac{(s-1)gd^2}{18\nu} \quad \text{for } 0.001 < d \leq 0.1 \text{ mm}$$

$$w_s = \frac{10\nu}{d} \left(\sqrt{1 + \frac{0.01(s-1)gd^3}{\nu^3}} - 1 \right) \quad \text{for } 0.1 < d \leq 1 \text{ mm}$$

$$w_s = 1.1\sqrt{(s-1)gd} \text{ for } d \geq 1mm$$

where d is the diameter of the grain, ν is the kinematic viscosity and $s = \rho_S/\rho$ is the specific density.

1.3.2.3.2 Wu and Wang

Another approach for the computation of the sink velocity is the one of Wu et al. (2000):

$$w = \frac{M\nu}{Nd} \left[\sqrt{\frac{1}{4} + \left(\frac{4N}{3M^2}(D^*)^3\right)^{1/n}} - \frac{1}{2} \right]^n$$

where:

$$M = 53.5e^{-0.65S_p}$$

$$N = 5.65e^{-2.5S_p}$$

$$n = 0.7 + 0.9S_p$$

S_p is the Corey shape factor, with a value for natural sediments of about 0.7 (0.3 - 0.9).

1.3.2.3.3 Zhang

The Zhang formula (Zhang, 1961) is based on many laboratory data and was developed for naturally worn sediment particles. It can be used in a wide range of sediment sizes in the laminar as well turbulent settling regions:

$$w_s = \sqrt{\left(13.95\frac{\nu}{d}\right)^2 + 1.09(s-1)gd} - 13.95\frac{\nu}{d}$$

1.3.3 External Source Terms

The source term Sl_s 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] or by an imposed concentration [-]. 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)
- Concentration: This sink type allows to impose a specified concentration.

Addition of sediment 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.

1.3.4 Boundary Conditions

For the suspended sediment transport only external boundaries that allow sediment flowing into or out of the domain can be specified. Boundary conditions of suspended transport type can be co-located with hydraulic or bedload boundary conditions.

1.3.4.1 Upstream Boundary Condition

Two upstream boundary conditions are available:

- *discharge_in* and *discharge_in_warea*: based on a suspended sediment discharge inflow, either as a constant or a function of time, the prescribed volumetric flow rate [m^3/s] is imposed at the boundary. The volumetric flow rate is either distributed using a geometrical weighting or a wet-area weighting.
- *concentration_in*: the suspended sediment inflow is defined by forcing a target concentration. The suspended sediment input rate is thus given by the target concentration paired with the total hydrodynamic mass flux.

1.3.4.2 Downstream Boundary Condition

- *zero_gradient_out*: this downstream boundary allows the free outflow of any tracer quantities in the flow. **Note:** If this condition is not prescribed, a wall condition is assumed and the tracer quantities will be retained (no outflow).

1.4 Passive tracers

1.4.1 Introduction

A multitude of dissolved species are present in environmental flows. In the context of hydraulic and environmental engineering, numerical modelling of scalar transport becomes a relevant tool mostly because of its versatility. In terms of advective phenomena, the most common applications include

- Pollutant fate and transport
- Accumulation or depletion of nutrients
- Calculation of water residence times
- Flow visualization

1.4.2 Transport of passive species

1.4.2.1 Governing Equations for passive specie transport

The governing equations are obtained under the shallow water framework and impose mass conservation for both fluid and dissolved phases.

In a Cartesian frame of reference $(x; y; z)$ in which the z axis is vertical and the horizontal lies in the $x - y$ plane, the system of governing equations is formed by (eq. 1.1) for hydrodynamics and is coupled with multiple equations for the conservation of the total tracer masses. The conservation of each tracer mass is ensured by the scalar continuity equation (eq. 1.44), which is tightly coupled to the shallow water equations. This equation allows to describe the evolution of the specie concentration as:

$$\frac{\partial}{\partial t} C_k h + \frac{\partial}{\partial x_i} \left(C_k h u_i - h D_{kij} \frac{\partial C_k}{\partial x_j} \right) = Sl_k \quad (1.44)$$

where C_k is the concentration of specie k , D_{kij} is it's diffusion tensor and Sl_k is the local source term, specifying additional sources or sinks of the specie k .

1.4.2.2 External Sources Terms

The source term Sl_k conveys an input or output (sink) that occurs locally on the computational domain over elements limited by regions. It can be specified as total volumetric flux [m^3/s] or by an imposed concentration [-]. Different approaches define the behaviour of external sources if it imposes negative fluxes (sink):

- Exact: The specified volume is added or extracted (non conservative)
- Available: The specified volume to extract is limited by the available tracer volume (conservative)
- Infinity: All available tracer volume will be extracted (conservative)
- Concentration: This sink type allows to impose a specified tracer concentration.

Additionally, there is the option of forcing a target concentration C_k^f homogeneously across all cells defined by the region.

1.4.2.3 Boundary Conditions

The system of governing equations (eq. 1.1) and (eq. 1.44) can be solved within the modeling domain described in Figure 1.1, provided that boundary conditions (hydrodynamical and tracer boundary conditions) are specified at the domain boundary Γ . For the tracer transport only *external boundaries* that allow tracer flowing into or out of the domain can be specified. A tracer boundary condition should be co-located with a hydraulic boundary condition. Otherwise, the boundary will behave as a wall and tracer transport will not occur.

1.4.2.4 Upstream Boundary Condition

Two upstream boundary conditions are available:

- *discharge_in* and *discharge_in_warea*: based on a tracer discharge inflow, either as a constant or a function of time, the prescribed volumetric flow rate Q_k [m^3/s] is imposed at the boundary. The volumetric flow rate is either distributed using a geometrical weighting or a wet-area weighting, and the specific tracer discharge q_k is thus given by:

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

$$q_k = \frac{Q_k}{L_n} \quad \left[\frac{m^3}{s \cdot m} \right]$$

2. Wetted-area weighting

$$q_k = \frac{Q_k}{A_{w,tot}} \cdot h \quad \left[\frac{m^3}{s \cdot m} \right]$$

- *concentration_in*: the tracer inflow is defined by forcing a target tracer concentration C_k^f . The volumetric flow rate is thus given by the target concentration paired with the total hydrodynamic mass flux q through that boundary as $q_k = q\phi_k^f$.

Note: If the hydrodynamical mass flow at the boundary is not inward directed then no tracer flux is imposed.

1.4.2.5 Downstream Boundary Condition

One downstream boundary condition is available:

- *zero_gradient_out*: this downstream boundary allows the free outflow of any tracer quantities in the flow. **Note:** If this condition is not prescribed, a wall condition is assumed and the tracer quantities will be retained (no outflow).

1.5 Riparian vegetation

1.5.1 Introduction

Riparian vegetation is known to play an important role in mediating river morphodynamic processes at various spatial and temporal scales. Predicting river morphology has to account for the feedbacks between plants, flow, and sediment transport. On one hand, vegetation can modify the flow resistance and the shear stresses acting on the riverbed, thus influencing the overall flow pattern and rate of sediment transport. On the other hand, erosion and deposition processes may cause plant mortality through uprooting and burial during floods. Including vegetation into river morphodynamic simulations has potential applications for

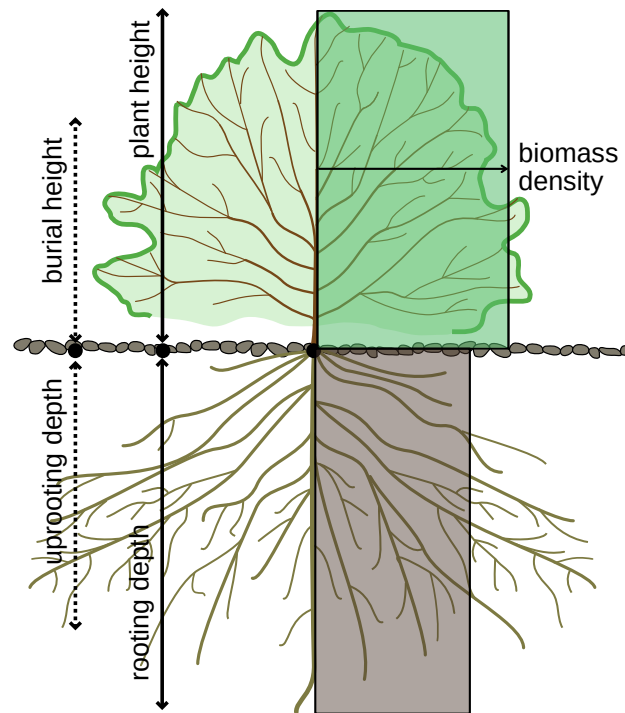


Figure 1.9 Schematic representation of vegetation in the model. The vegetation state is described by an aboveground, belowground biomass, and a rooting depth. The other variables (uprooting depth, burial height, and plant height) are derived through specific functions and input parameters. Adapted from Caponi et al. (2020)

- estimating sedimentation and erosion processes
- restoration projects
- riparian forests dynamics
- flood hazard mapping

1.5.2 Description of Vegetation

Vegetation is described by a dimensionless aboveground biomass density, B_c (subscript c stands for canopy), belowground density, B_r (subscript r stands for roots) and a rooting depth, D_r (see Figure 1.9). The sum of B_c and B_r should ideally be 1 at maximum, while there is no specific limit for the rooting depth. The model accounts also for the vegetation height, H , which is derived as $H = aB_c^b$, where a and b are constant parameters. B_c and B_r are considered to distribute linearly along the main vertical axis of the plant. The uprooting depth, D_{upr} , namely the depth at which uprooting occurs, is defined as $\beta_{upr}D_r$, with β_{upr} a constant input parameter that decreases the maximum erosion that vegetation can withstand. The burial height, H_{bur} , represents the effective plant height when the plant is submerged (due to bending) and is defined as $H_{bur} = \beta_{bur}H$, with β_{bur} a constant parameter (see Section 1.5.5).

1.5.3 Effect of Vegetation on Water Flow

The aboveground vegetation is assumed to change the bed roughness. This is included by modifying the Strickler's coefficient k_{str} [$m^{1/3}/s$] (Bertoldi et al., 2014), such as

$$k_{str}(t) = k_{s,g} + (k_{s,v} - k_{s,g})B_c(t) \quad (1.45)$$

where $k_{s,g}$ represents the roughness of the bare bed, which depends on the sediment grain size, while $k_{s,v}$ ($< k_{s,g}$) is the roughness of a completely vegetated bed assumed to vary with species-specific canopy characteristics. The Strickler's coefficient can change during the simulation as B_c changes (see Section 1.5.5) (Caponi et al., 2020).

1.5.4 Effects of Vegetation on Bedload Transport

1.5.4.1 Bottom Shear Stress

The presence of vegetation is also known to affect the shear stresses acting on the bed surface and responsible for sediment transport. The reduction of bed shear stress is included in the model by multiplying the total shear stress by a factor $\gamma < 1$ and computing the sediment flux using a reduced dimensionless bed shear stress (Shields parameter), $\gamma\theta$. The parameter γ ranges between 0 and 1 and it is chosen according to $\gamma = k_{str}(t)/k_{s,g}$, with k_{str} evaluated as in eq. 1.45, (Caponi and Siviglia, 2018).

1.5.4.2 Critical Shear Stress

The role of root-enhanced riverbed cohesion is taken into account by increasing the critical Shields parameter (Bertoldi et al., 2014). Assuming an MPM-like formula (eq. 1.26), the critical Shields parameter θ_{cr} is defined as

$$\theta_{cr}(t) = \theta_{cr,g} + (\theta_{cr,v} - \theta_{cr,g})B_r(t) \quad (1.46)$$

in which $\theta_{cr,g}$ and $\theta_{cr,v}$ ($> \theta_{cr,g}$) represent the values used for bare bed and completely vegetated riverbed, respectively (Caponi and Siviglia, 2018).

1.5.5 Effects of Bed Changes on Vegetation

Bed level change causes three effects on vegetation in the model: uprooting, burial, and biomass redistribution.

1.5.5.1 Biomass Redistribution

As soon the bed level changes, the portion of vegetation above and below ground changes as well. The model assumes that the total biomass remains constant during a simulation, unless uprooting occurs. This means that in case of a positive bed level change, $\Delta z_B > 0$ (deposition), B_c will decrease by $\Delta z_B(B_c/H_{bur})$ and B_r will increase by the same amount, where H_{bur} is a fraction of the plant height. On the contrary, in case of bed level erosion, B_c will increase by $\Delta z_B(B_r/D_r)$ and B_r will decrease by the same amount (Caponi et al.,

2020). Changes in B_c and B_r during the simulation will change the effects on flow and sediment transport associated with these values following eq. 1.46 and eq. 1.45.

1.5.5.2 Plant Burial

Plant burial is the mechanism by which a plant get covered by sediments, that is, when the bed level increases in a cell until reaching the burial plant height H_{bur} . This value takes into account the bending of the plant when submerged, which reduces the effective height of the plant. In case the bed level change reaches H_{bur} , B_c will go to zero, causing the k_{str} value to equal $k_{s,g}$. In case the bed level decreases again during the simulation, B_c can increase as well (Caponi et al., 2020). Plants can in fact resist well sedimentation processes, thanks to the high flexibility of the stems that prevents breakage.

1.5.5.3 Plant Uprooting

Plant uprooting occurs when the pulling forces applied on the plant by the water flow equal the resisting forces of the plant, which are given by the root system anchoring. We consider that this can occur only when part of the plant roots are already exposed to the flow, that is, when the bed level has decreased during the simulation (type II of uprooting, following the conceptual model of Edmaier et al. (2018)). Therefore, the uprooting is modelled by defining a critical depth at which the plant is removed. This depth is currently defined as a percentage of the rooting depth as $D_{cr} = \beta_{upr} D_r$, where β_{upr} is a parameter that modulates the resistance of the plant and depends on soil characteristics and plant species. When uprooting occurs, B_c and B_r are set to zero and vegetation cannot influence flow and sediment transport anymore during the simulation.

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.

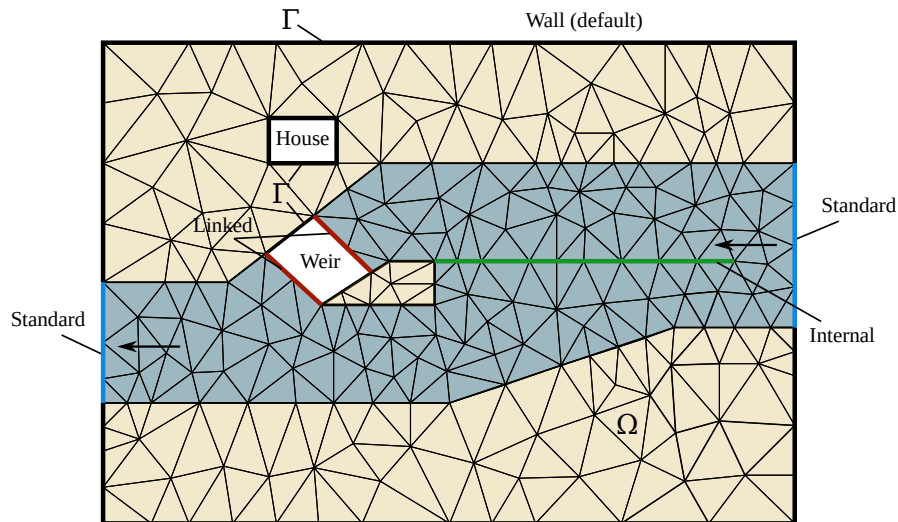


Figure 2.1 Modeling domain, types of boundary conditions and computational mesh. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir. External boundary conditions must be provided at Γ_1 , Γ_2 and Γ_3 while internal boundary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

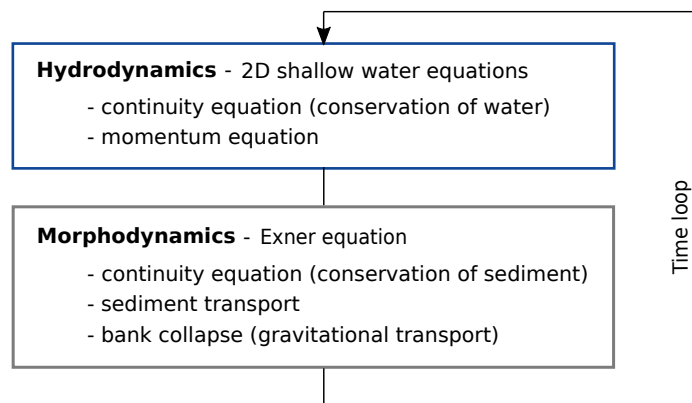


Figure 2.2 Overview of the numerical model

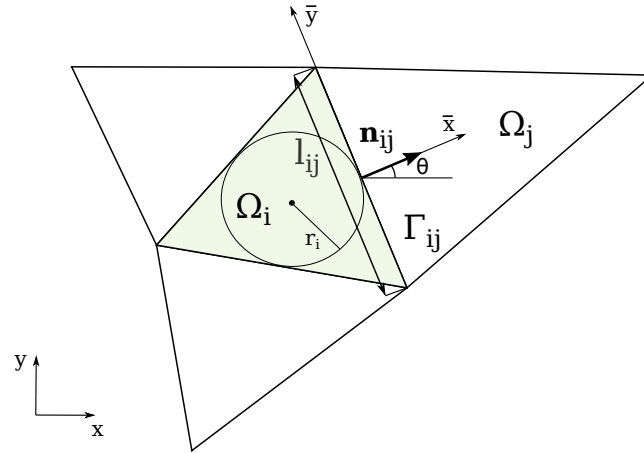


Figure 2.3 Element (shaded triangle) of unstructured triangular mesh and used notation

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 \mathbf{U}_i^n and the numerical solution sought at time $t^{n+1} = t^n + \Delta t$, is denoted by \mathbf{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:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}_x}{\partial x} + \frac{\partial \mathbf{F}_y}{\partial y} = \mathbf{S} \quad (2.1)$$

where the vector of unknowns is

$$\mathbf{U} = \begin{pmatrix} H \\ q_x \\ q_y \end{pmatrix} \quad (2.2)$$

the vector fluxes are

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

and the vector of source terms is

$$\mathbf{S} = \begin{pmatrix} S_h \\ gHS_x \\ gHS_y \end{pmatrix}. \quad (2.4)$$

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

$$\mathbf{U}_i^{n+1} = \mathbf{U}_i^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^3 l_{ij} [\mathbf{F}_{ij}] + \Delta t \mathbf{S}_i. \quad (2.5)$$

2.3.3 Flux Estimation

2.3.3.1 Rotational Invariance of the Shallow Water Equations

The flux \mathbf{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):

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

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

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

being

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

2.3.3.2 Computation of the Flux

The flux \mathbf{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 \mathbf{U} is transformed into the local coordinate system (\bar{x}, \bar{y}) (see Figure 2.3) at the edge with the operation $\mathbf{T}(\theta)\mathbf{U}$.
- 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 $\mathbf{F}[\mathbf{T}(\theta)\mathbf{U}]$ is defined.
- The flux vector, formulated in the local coordinate system is transformed back to the global coordinates (Cartesian) with $\mathbf{T}^{-1}\mathbf{F}[\mathbf{T}(\theta)\mathbf{U}]$. 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 Riemann 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:

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

The wave speed velocities are estimated as:

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

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

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

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

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

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

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

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

The expression of the states $\mathbf{U}_{*i}, \mathbf{U}_{*j}$ 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:

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

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)

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

where \mathcal{A} represents the advective operator

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

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

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

$$\left. \begin{array}{l} ODEs : \frac{d\mathbf{U}}{dt} = \mathcal{S}(\mathbf{U}) \\ ICs : \mathbf{U}(x, y, 0) = \mathbf{U}_i^n \end{array} \right\} \xrightarrow{\Delta t} \bar{\mathbf{U}}_i \quad \text{IVP1} ,$$

$$\left. \begin{array}{l} PDEs : \mathcal{A}(\mathbf{U}) = 0 \\ ICs : \mathbf{U}(x, y, 0) = \bar{\mathbf{U}}_i \end{array} \right\} \xrightarrow{\Delta t} \mathbf{U}_i^{n+1} \quad \text{IVP2} ,$$

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 $\bar{\mathbf{U}}_i$. IVP2 is then integrated by a time step Δt , with initial condition given by the solution of IVP1 $\bar{\mathbf{U}}_i$. The solution of IVP2 \mathbf{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:

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

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

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

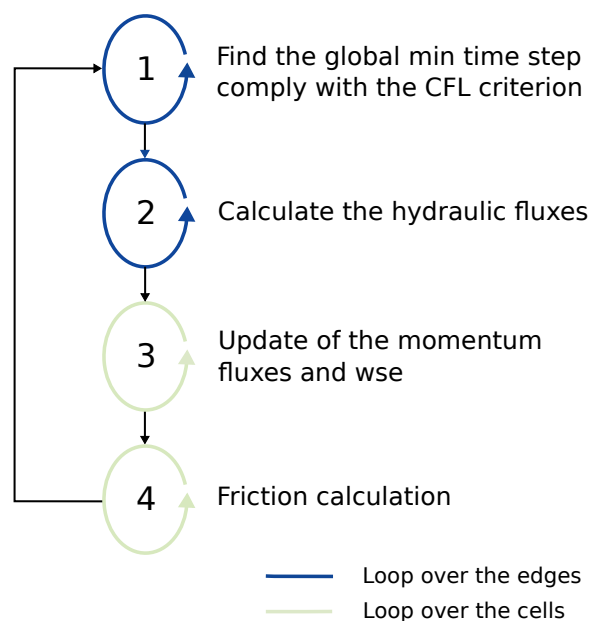


Figure 2.4 Numerical solution procedure of hydrodynamic simulation for each time step Δt

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-momentum 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). This approach makes the assumption that the bed load flux is much slower than the water flow velocity (Soares-Frazão and Zech, 2011).

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

$$z_{B_i}^{n+1} = z_{B_i}^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^3 [q_{B_{ij} \cdot l_{ij}}] + \Delta t \mathbf{S}_i . \quad (2.18)$$

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 1.2.2.4.1)
 - calculation of the local curvature of the flow field, for the spiral flow correction (see section Section 1.2.2.4.2)

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.: $q_{B_{i,n}} = q_{B_{i,x}} \cdot n_{ij,x} + q_{B_{i,y}} \cdot n_{ij,y}$ and $q_{B_{j,n}} = q_{B_{j,x}} \cdot n_{ij,x} + q_{B_{j,y}} \cdot n_{ij,y}$ 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:

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

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

where $u_n = u \cdot n_{ij,x} + v \cdot n_{ij,y}$, $c = \sqrt{gh}$ and $a_2 = \frac{\partial q_{b,n}}{\partial q_n}$ 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

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

and

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

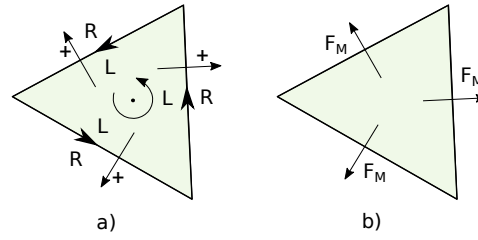


Figure 2.5 a) Sign convention for the edge direction: counterclockwise b) Positive morphological flux direction at edges: from left (L) to right (R)

- Flux calculation:

$$q_{Bij}^{HLL} = \begin{cases} q_{Bi,n} & \text{if } S^- \geq 0, \\ \frac{q_{Bi,n}S^+ - q_{Bj,n}S^- + S^-S^+(z_{Bj} - z_{Bi})}{S^+ - S^-} & \text{if } S^- < 0 < S^+, \\ q_{Bj,n} & \text{if } S^+ \leq 0. \end{cases} \quad (2.23)$$

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:

$$\begin{aligned} \text{Exact:} & \quad S_{b,i} = \delta_i \\ \text{Available:} & \quad S_{b,i} = \delta_i & \text{if } \delta_i \cdot \Delta t > 0 \\ & \quad S_{b,i} = \max(\delta_i, -(z_{Fix} - z_i)) & \text{if } \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & \quad S_{b,i} = \delta_i & \text{if } \delta_i \cdot \Delta t > 0 \\ & \quad S_{b,i} = -(z_{Fix} - z_i) & \text{if } \delta_i \cdot \Delta t < 0 \end{aligned} \quad (2.24)$$

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.

$$z_i^{t+1} = z_i^t + S_{b,i} \cdot \Delta t \quad (2.25)$$

2.4.2 Solution procedure

The numerical solution procedure of BASEMENT explains how the discretised Exner equation (eq. 1.15) 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

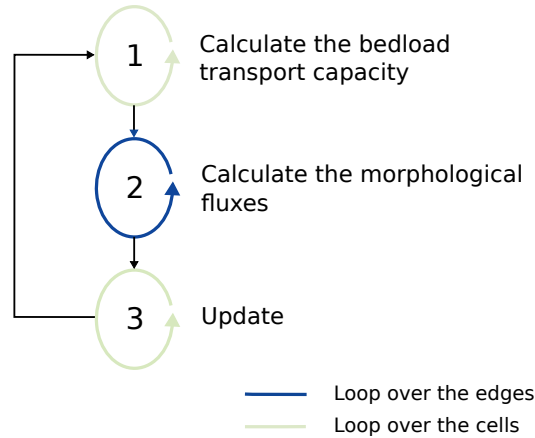


Figure 2.6 Numerical solution procedure of morphodynamic simulation for each time step Δt

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.

2.5 Numerical solution of Advection-Diffusion equation

2.5.1 Numerical solution of the advective part

The scalar advection equation assures that scalar masses are conserved in the flow column when moving with the surrounding fluid. The same cell-centered finite volume approach used for the SWE is employed in scalar advection, namely the HLLC approximate Riemann solver. In order to discretize the scalar advection equation, the same unstructured mesh adopted for the hydrodynamic and morphodynamic parts is used, as is the same finite volume approach. As a consequence, the scalar concentration ϕ_s is defined at the element center and is equally distributed over the element. This numerical approach is applied to turbulent kinetic energy quantities (κ, ϵ), suspended sediment and tracers.

By integrating the scalar advection equation

$$\frac{\partial}{\partial t} \phi_k h + \frac{\partial}{\partial x_i} \left(\phi_k h u_i - h D_{s_{ij}} \frac{\partial \phi_k}{\partial x_j} \right) = S_{\phi_k} \quad (2.26)$$

in the control volume $V_i = [\Omega_i] \times [t^n, t^{n+1}]$ for a generic quantity defined by ϕ_k , we obtain:

$$q_{\phi_k i}^{n+1} = q_{\phi_k i}^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^3 \left[f_{\phi_k, ij} \cdot l_{ij} \right] + \Delta t \mathbf{S}_{\phi_k, i} \quad (2.27)$$

where f_{Sij} is the intercell scalar advective flux. The scalar advective fluxes at the cell interface are defined by:

$$f_{\phi_k, ij} = \frac{q_{\phi_k i}}{h} q_m \quad \text{if } q_m > 0 \quad (2.28)$$

$$f_{\phi_k, ij} = \frac{q_{\phi_k j}}{h} q_m \quad \text{if } q_m < 0 \quad (2.29)$$

where q_m is the hydrodynamic mass flux. This approach significantly reduces the numerical effort involved in the computation of the numerical fluxes for each species, without sacrificing accuracy or stability.

2.5.2 Numerical solution of the diffusive part

The diffusion equation ensures that quantities are conserved in the flow column due when turbulent or molecular exchanges originate some form of mixing. By integrating the scalar diffusion equation

$$\frac{\partial}{\partial t} \phi_k h - \frac{\partial}{\partial x_i} \left(h D_{s_{ij}} \frac{\partial \phi_k}{\partial x_j} \right) = 0 \quad (2.30)$$

in the control volume $V_i = [\Omega_i] \times [t^n, t^{n+1}]$ we obtain:

$$q_{\phi_k i}^{n+1} = q_{\phi_k i}^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^3 \left[d_{\phi_k, ij} \cdot l_{ij} \right] \quad (2.31)$$

where $d_{\phi_k, ij}$ is the intercell scalar diffusive flux. To compute the solution of the diffusive terms, the SVT solver Vanzo et al. (2016) is employed. It involves the augmentation of the existing system with a set of new conservation quantities and equations for each diffusive specie ϕ_k . The role of these new variables is to allow a relaxation of the diffusive part, such as

$$\lim_{\zeta \rightarrow 0} \psi_x^{\phi_k} = \partial_x \phi_k, \quad \lim_{\zeta \rightarrow 0} \psi_y^{\phi_k} = \partial_y \phi_k \quad (2.32)$$

where ψ denotes a relaxation variable, subject to the following relations

$$\partial_t \psi_x^{\phi_k} - \partial_x \frac{\phi_k}{\zeta} = -\frac{\psi_x^{\phi_k}}{\zeta}, \quad \partial_t \psi_y^{\phi_k} - \partial_y \frac{\phi_k}{\zeta} = -\frac{\psi_y^{\phi_k}}{\zeta} \quad (2.33)$$

which are formally denoted as the relaxation sub-system. The main purpose of this relaxation is to preserve the hyperbolicity of the numerical scheme, as demonstrated by Vanzo et al. (2016). To construct the diffusive numerical fluxes, the following Riemann problem is considered along some edge normal as

$$\begin{cases} \partial_t \Phi_k + \partial_\xi D_{n_{ij}} = \mathbf{0}, & \xi \in \mathbb{R}, t > 0, \\ \Phi_k(\xi, 0) = \begin{cases} \Phi_k^n & \text{if } \xi < 0, \\ \Phi_k^j & \text{if } \xi > 0, \end{cases} \end{cases} \quad (2.34)$$

where Φ_k is the conserved variables vector and D_n is the diffusive numerical flux vector. The structure of this Riemann problem is composed of three unique waves (from a total of six). One of these is always a stationary contact discontinuity and the two remaining waves are symmetrical, with the same propagation speed in opposite directions. The problem thus becomes characterized by a single intermediate state Φ_k^* where the fluxes are directly evaluated. The exact expression for the intermediate state Φ_k^* and numerical $D(\Phi_k^*)_n$ can be found in Vanzo et al. (2016).

2.5.3 Discretization of external source terms

The source term S_{ϕ_k} describes a local input or removal of scalar 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:

$$\begin{aligned} \text{Exact:} & \quad S_{\phi_k,i} = \delta_i \\ \text{Available:} & \quad S_{\phi_k,i} = \delta_i && \text{if } \delta_{\phi_k} \cdot \Delta t > 0 \\ & \quad S_{\phi_k,i} = \max(\delta_i, -q_{\phi_k,i}) && \text{if } \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & \quad S_{\phi_k,i} = \delta_i && \text{if } \delta_i \cdot \Delta t > 0 \\ & \quad S_{\phi_k,i} = -q_{\phi_k,i} && \text{if } \delta_i \cdot \Delta t < 0 \end{aligned} \quad (2.35)$$

The external source volume is then added to the initial value of element i through a first-order Euler approach.

$$q_{\phi_k,i}^{t+1} = q_{\phi_k,i}^t + S_{\phi_k,i} \cdot \Delta t \quad (2.36)$$

2.5.4 Solution procedure

The numerical solution for all modules involving scalar advection and diffusive terms – turbulence, suspended sediment and tracers – is obtained as follows:

1. Loop over the cell interfaces and compute the advective flux at each interface:
 - Retrieve the hydrodynamic fluxes F_{ij} at the interface between cells i and j and extract the first component of the flux vector (mass fluxes) to the variable q_m .
 - For each specie, perform the advective flux calculation through the simplified HLLC solver described above
2. Loop over the cell interfaces and compute the diffusive flux at each interface:

- Retrieve the hydrodynamic and scalar quantities \mathbf{Q}_h and Φ_k at the interface between cells i and j perform the flux calculation using the SVT solver
3. Define the diffusion specific timestep and update the global minimum time step Δt
4. Loop over the cells and update the conserved quantities with the fluxes at each of its interfaces:
 - Retrieve and add the advective fluxes $f_{\phi ij}$ and diffusive fluxes $d_{\phi ij}$ at each of the three interfaces.
 - For each specie, perform the update as prescribed in Equations 2.27, 2.31, and 2.36.
5. Add the external source terms

3

References

- Bertoldi, W., Siviglia, A., Tettamanti, S., Toffolon, M., Vetsch, D. and Francalanci, S. (2014). [Mechanisms of vegetation uprooting by flow in alluvial non-cohesive sediment](#). *Geophysical Research Letters*, 41(20): 7167–7175.
- Bezzola, G.R. (2002). Fließwiderstand und Sohlenstabilität natürlicher Gerinne [PhD thesis]: Eidgenössische Technische Hochschule Zürich.
- Caponi, F. and Siviglia, A. (2018). [Numerical modeling of plant root controls on gravel bed river morphodynamics](#). *Geophysical Research Letters*, 45(17): 9013–9023.
- Caponi, F., Vetsch, D.F. and Siviglia, A. (2020). [A model study of the combined effect of above and below ground plant traits on the ecomorphodynamics of gravel bars](#). *Scientific Reports*, 10(1): 1–14.
- Chen, X., Ma, J. and Dey, S. (2010). Sediment transport on arbitrary slopes: Simplified model. *Journal of Hydraulic Engineering-ASCE*, 136(5): 311–317.
- Duran, A., Liang, Q. and Marche, F. (2013). On the well-balanced numerical discretization of shallow water equations on unstructured meshes. *Journal of Computational Physics*, 235: 565–586.
- Edmaier, K., Crouzy, B. and Perona, P. (2018). [Feedbacks between the riparian salicaceae and hydrogeomorphic processes a quantitative review](#). *Earth-Science Reviews*, 176(August 2017): 147–165.
- Engelund, F. (1974). Flow and bed topography in channel bends. *Journal of the Hydraulics Division ASCE*, 100(11): 1631–1648.
- Engelund, F. and Hansen, E. (1972). A monograph on sediment transport in alluvial streams. *Teknisk Forlag, Copenhagen*.
- Exner, F.M. (1925). Ueber die wechselwirkung zwischen wasser und geschiebe in fluessen. Akademie der Wissenschaften, Mathematische Naturwissenschaft Abt. IIa, Wien, Austria.
- Grass, A.J. (1981). Sediment transport by waves and currents. *University College, London, Dept. of Civil Engineering*, London, UK.
- Ikeda, S. (1982). Lateral Bed-Load Transport on Side Slopes. *Journal of the Hydraulics Division-Asce*, 108(11): 1369–1373.
- Lin, B. (1984). Current Study of Unsteady Transport of Sediment in China. *Proceedings of Japan-China Bilateral Seminar on River Hydraulics and Engineering Experiences*,

- Proceedings of Japan-China Bilateral Seminar on River Hydraulics; Engineering Experiences, Tokyo-Kyoto –Sapporo.*, Tokyo-Kyoto-Sapporo.
- Malcherek, A. (2001). Sedimenttransport und Morphodynamik. Vorlesungsskript der Universität der Bundeswehr München, München.
- Meyer-Peter, E. and Müller, R. (1948). Formulas for Bed-Load Transport, 2nd Meeting IAHR, Stockholm, Sweden.
- Rozovskii, I.L. (1961). Flow of Water in Bends of Open Channels. *Academy of Science of the Ukrainian S.S.R, Institute of Hydrology; Hydraulic Engineering*,.
- Shields, A. (1936). Anwendungen der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegungen. Mitteilung der Preussischen Versuchsanstalt für Wasserbau und Schiffbau. Berlin, Deutschland.
- Smart, G.M. and Jaeggi, M.N.R. (1983). Sediment Transport on Steep Slopes. *VAW-Mitteilung* 64, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW). Zürich, ETH Zürich.
- Soares-Frazão, S. and Zech, Y. (2011). HLLC scheme with novel wave-speed estimators appropriate for two-dimensional shallow-water flow on erodible bed. *International Journal for Numerical Methods in Fluids*, 66.
- Talmon, A.M., Struiksma, N. and van Mierlo, M.C.L.M. (1995). Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes. *Journal of Hydraulic Research*, 33(4): 495–517.
- Toro, S., E. F. (1994). Restoration of the contact surface in the HLL-Riemann solver. *Shock Waves*, 4: 25–34.
- Toro, E.F. (2009). Riemann Solvers and Numerical Methods for Fluid Dynamics. *Springer-Verlag*, Berlin.
- Toro, E.F. (2001). Shock-Capturing Methods for Free-Surface Shallow Flows. *John Wiley*, Chichester, New York.
- van Rijn, L.C. (1989). Handbook Sediment Transport by Current and Waves. *Delft Hydraulics Laboratory*, Delft, The Netherlands.
- van Rijn, L.C. (1984a). Sediment Transport, Part I: Bed Load Transport. *Journal of Hydraulic Engineering, ASCE*, 110(10): 1431–1456.
- van Rijn, L.C. (1984b). Sediment Transport, Part II: Suspended Load Transport. *Journal of Hydraulic Engineering, ASCE*, 110(11): 1613–1641.
- Vanzo, D., Siviglia, A. and Toro, E.F. (2016). Pollutant transport by shallow water equations on unstructured meshes: Hyperbolization of the model and numerical solution via a novel flux splitting scheme. *Journal of Computational Physics*, 321: 1–20.
- Vonwiller, L. (2017). Numerical Modeling of Morphological Response of Gravel-Bed Rivers to Sediment Supply. *VAW-Mitteilung* 246, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW). Zürich, ETH Zürich.
- Wu, W., Wang, S.S.Y. and Jia, Y. (2000). Non-Uniform Sediment Transport in Alluvial Rivers. *Journal of Hydraulic Research*, 38(6): 427–434.
- Xu, Y. (1998). Numerical Modeling of Suspended Sediment Transport in Rivers [PhD thesis]: Mitteilung 98, Institut für Wasserbau, Universität Stuttgart.
- Yalin, M. and Silva, A. da (2001). Fluvial processes. *International Association of Hydraulic Engineering; Research (IAHR)*, Delft, The Netherlands.
- Zhang, R.J. (1961). River Dynamics. *Industry Press*, Beijing, China.
- Zyserman, J.A. and Fredsøe, J. (1994). Data Analysis of Bed Concentration of Suspended Sediment. *Journal of Hydraulic Engineering, ASCE*, 120(9): 1021–1042.

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

TUTORIALS & TEST CASES

**VERSION 3.2
May 2022**



BASEMENT

Contents

1	Tutorials	3
1.1	Hydrodynamics and sediment transport at the river Flaz	3
1.1.1	Introduction	3
1.1.2	Computational Mesh	3
1.1.3	Hydraulics	3
1.1.3.1	Setup the Configuration File model.json	4
1.1.3.2	Setup the Configuration File simulation.json	7
1.1.3.3	Set up the Configuration File results.json	7
1.1.3.4	Steady Flow Simulation	7
1.1.3.5	Model Calibration	7
1.1.3.6	Unsteady Flow Simulation	8
1.1.4	Morphology	10
1.1.4.1	Setup the Configuration File model.json	10
1.1.4.2	Setup the Configuration File simulation.json	13
1.1.4.3	Results	14
1.1.5	Passive tracers	14
1.1.5.1	Setup the Configuration File model.json	14
1.1.5.2	Setup the Configuration File simulation.json	16
1.1.5.3	Set up the Configuration File results.json	17
1.2	Vegetation dynamics and bedload transport	17
1.2.1	Introduction	17
1.2.2	Computational Mesh	18
1.2.3	Morphology with Vegetation	18
1.2.3.1	Setup the Configuration File model.json	18
1.2.3.2	Setup the Configuration File simulation.json	20
1.2.3.3	Set up the Configuration File results.json	21
1.2.3.4	Results	22
1.3	Post-Processing	22
1.3.1	ParaView	22
1.3.2	Extract Data from Result File	22
2	Test cases	25
2.1	Introduction and Backends	25
2.1.1	Introduction	25
2.1.2	Backends	25
2.2	Circular dam break	26
2.2.1	Description	26
2.2.2	Geometry and Initial Conditions	26

2.2.3	Results	27
2.2.4	Performance	30
2.2.4.1	Ubuntu	30
2.2.4.2	Windows	33
2.3	Conical Dune	35
2.3.1	Description	35
2.3.2	Geometry and Initial Conditions	35
2.3.3	Results	36
2.4	Dam-break flow in a L-shaped channel with a mobile-bed	39
2.4.1	Description	39
2.4.2	Geometry and initial conditions	39
2.4.3	Results	39
2.4.4	Performance	41
2.4.4.1	Ubuntu	41
2.4.4.2	Windows	43
3	References	45

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 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.

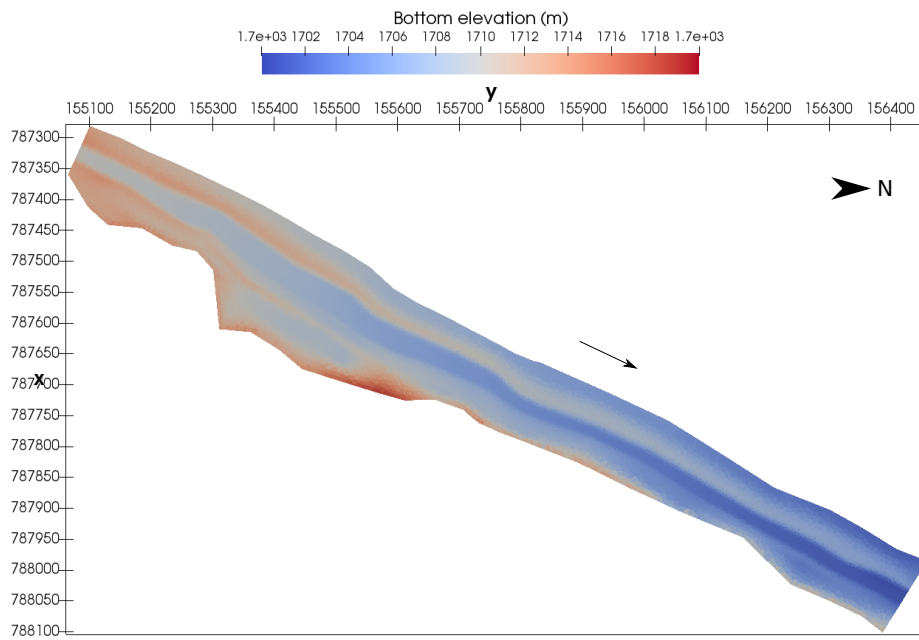


Figure 1.1 Planar view of the initial bottom elevation of the river Flaz

1.1.3.1 Setup 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": {...},
          "TURBULENCE": {...},
          "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 path 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, TURBULENCE parameters, 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},
      ...
    ]
  }

"TURBULENCE": {
  "INITIAL": {
    "type": "zero"
  },
  "PARAMETER": {
    "turbulence_start": 0,
  },
  "REYNOLDS_STRESS": {
    "closure_model": "mix_length",
    "constants": {
      "turb_visc_max": 0.05
    }
  }
}

"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 Setup 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",
      "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": "xmdf"}
    ]
  }
}
```

1.1.3.4 Steady Flow Simulation

The simulation results are stored inside the results.h5 binary. By calling the python script BMv3NodestringResults.py available on the [BASEMENT Website](#), 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).

1.1.3.5 Model Calibration

The calibration of the friction value is done by comparing the water surface elevation between BASEMENT version 3 and version 2.8 at a cross section located in the middle of

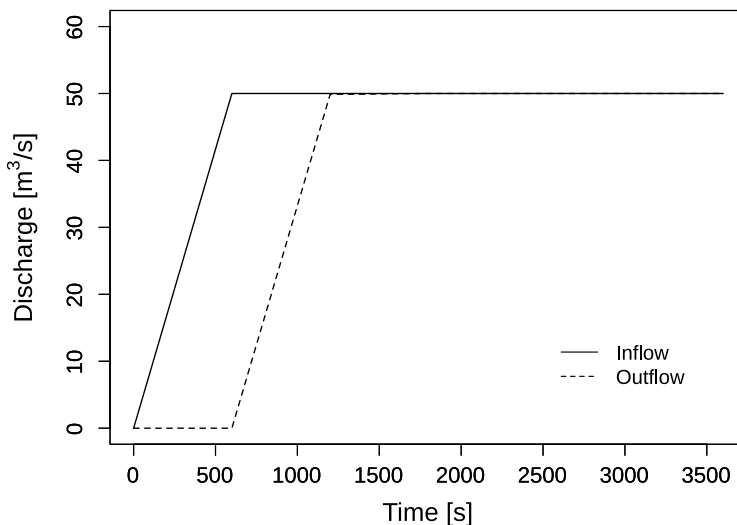


Figure 1.2 Inflow and outflow hydrograph at boundaries

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 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 hydrograph. The initial block:

```
"INITIAL": {
    "type": "continue",
    "file": "../run/Flaz_steady_state_results.h5",
    "time": 3000.0
}
```

The run 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": {
```

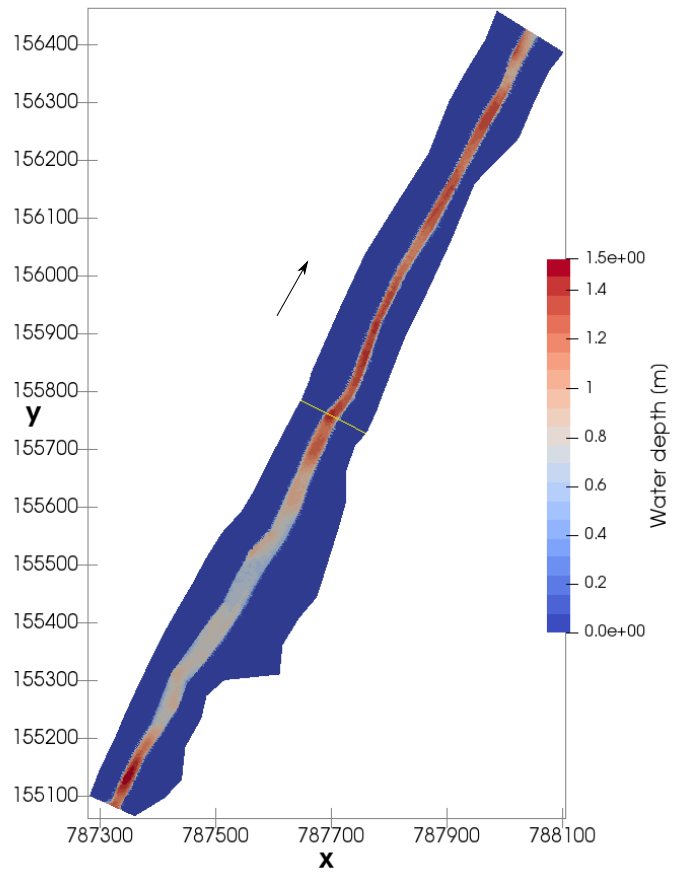


Figure 1.3 Water depth at the end of the steady flow simulation ($t=3600$ s) with the cross section location (yellow line)

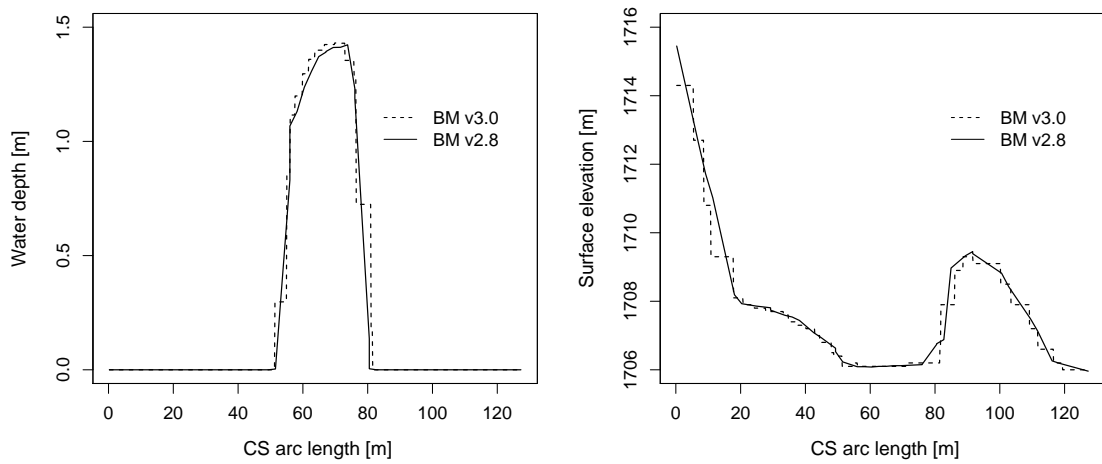


Figure 1.4 Cross sectional view of the water depth and surface elevation facing the opposite flow direction at the end of the steady flow simulation ($t=3600$ s)

```

    "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 with the numerical simulation.

1.1.4 Morphology

1.1.4.1 Setup 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 and the morphological boundary conditions are defined. 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. Additionally, lateral transport due to local slope bed slope is considered with a default value of 1.5 (see Reference Manual).

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

An additional suspended load block can be defined as well. The erosion and deposition laws are chosen and the morphological boundary conditions are defined. The boundary condition is defined as an input concentration at the inflow boundary. The outflow boundary is a simple zero-gradient outflow.

```
"SUSLOAD": {
    "PARAMETER": {
        "suspended_diffusivity": [0.1],
    },
    "BOUNDARY": {
        "STANDARD": [
```

```

    {
      "name": "inflow_SUS",
      "string_name": "Inflow",
      "type": "concentration_in",
      "data1": 0.0001
    },
    {
      "name": "outflow_SUS",
      "string_name": "Outflow",
      "type": "zero_gradient_out"
    }
  ]
},
"INITIAL": {
  "type": "zero"
},
"SETTLING_VELOCITY": {
  "closure_model": "van_rijn"
},
"SHEAR_PARTITION": {
  "default_friction_susp": 67.0
},
"EROSION_RATE": {
  "closure_model": "van_rijn",
  "constants": {
    "critical_shields": 0.125
  }
},
"DEPOSITION_RATE": {
  "closure_model": "lin",
  "constants": {
    "param_m": 1.0
  }
}
}

```

1.1.4.2 Setup the Configuration File simulation.json

The simulation time defined in the simulation.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"
  ]
}

```

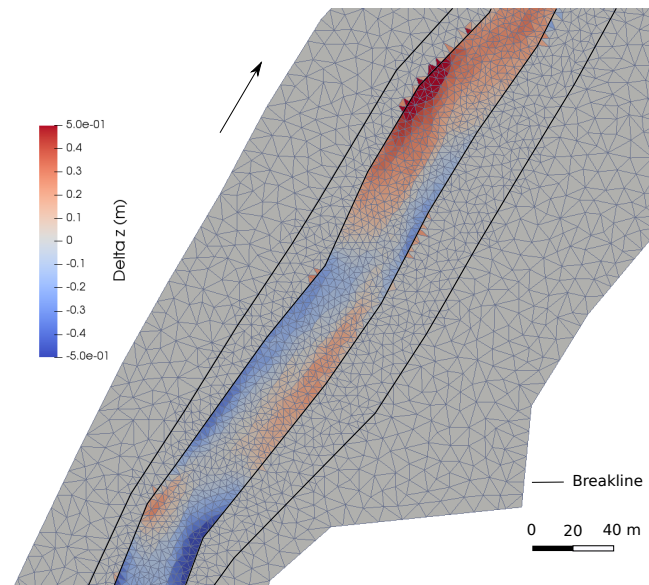


Figure 1.5 Planar view of the widening part of the river Flaz with the change in bed elevation (Δz) due to the flood event at the end of the morphodynamic simulation ($t=84'000$ s)

}

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).

1.1.5 Passive tracers

1.1.5.1 Setup the Configuration File model.json

This section shows how the flow simulation could be augmented with scalar advection with a TRACERS block. A maximum of 5 tracers are presently supported. Additionally, the block tracers is defined inside the model.json file with the following structure:

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

```
{
  "SETUP":{
    "simulation_name":"Flaz_tracers",
    "DOMAIN": {
      "PHYSICAL_PROPERTIES": {...},
      "BASEPLANE_2D": {
        "GEOMETRY": {...},
        "TRACERS": {
          "PARAMETER": {...},
          "BOUNDARY": {...},
          "INITIAL": {...},

```

```

        "SOURCE": {...}
      }
    }
  }
}

```

The TRACERS block contains the subsections PARAMETER, BOUNDARY and INITIAL:

```

"PARAMETER": {
  "tracers_start": 0.0,
  "num_tracers": 3,
}

"BOUNDARY":{
  "STANDARD": [
    { "name": "tracer_inflow",
      "string_name": "Inflow",
      "type": "discharge_in",
      "tracer1_file": "Inflow_tracer1.txt",
      "tracer2_file": "Inflow_tracer2.txt",
      "tracer3_file": "Inflow_tracer3.txt"},
    { "name": "Outflow",
      "string_name": "Outflow",
      "type": "zero_gradient_out"}
  ]
}

```

The tracer discharge series are of the same format of the hydrograph: two columns with time (first col.) and imposed quantity (discharge or concentration) (second col.). To specify constant values use “tracerX” followed by the intended value, instead of “tracerX_file”.

```

"INITIAL":{
  "type": "zero"
}

"INITIAL":{
  "type": "uniform",
  "tracers": [0.0,0.25,0.5]
}

"INITIAL":{
  "type": "region_defined",
  "regions": [
    {"region_name": "one",
      "tracers": [0.0,0.1,0.2]},
    {"region_name": "two",
      "tracers": [0.4,0.3,0.2]}
  ]
}

```

The initial conditions are prescribed in array format with the “tracers” keyword. The supported types of initial conditions with this input method are “uniform” and “region_defined”. The remaining options are “zero”, with no additional inputs, and “continue” accepting “file” and “time” parameters.

A source block within the tracers block would look like:

```
"SOURCE": [
  { "name": "total_exact1",
    "type": "total",
    "data1_file": "./scalars1.dat",
    "data2_file": "./scalars2.dat",
    "data3_file": "./scalars3.dat",
    "data4_file": "./scalars4.dat",
    "data5_file": "./scalars5.dat",
    "region_name": "one",
    "sink": "exact" }
]
```

And, as in the boundaries case, to specify constant values use “dataX” followed by the intended value, instead of “dataX_file”.

1.1.5.2 Setup 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",
      "bottom_elevation",
      "spec_discharge",
      "water_depth",
      "tracer1",
      "tracer2",
      "tracer3"
    ]
  }
}
```

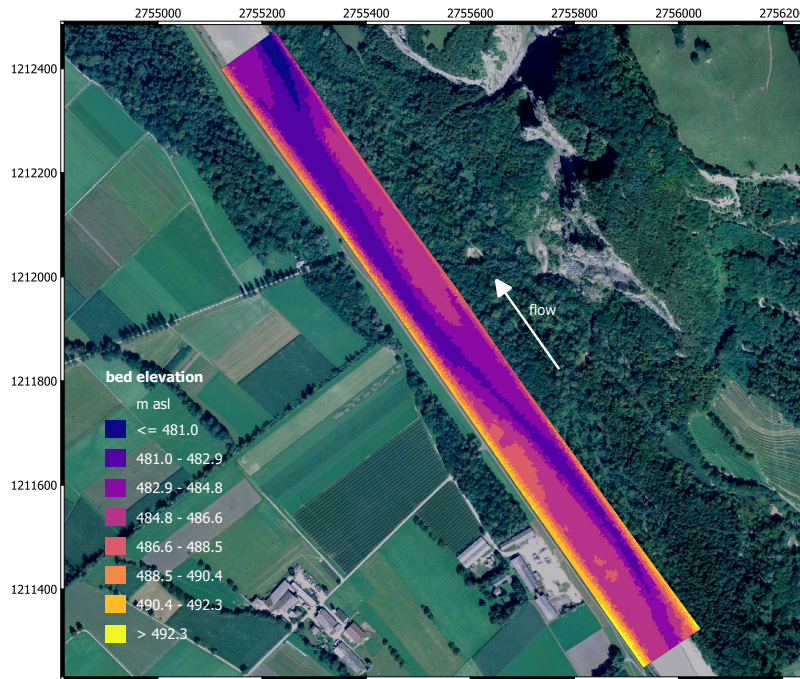


Figure 1.6 Planar view of the initial bottom elevation of the Alpine Rhine river

1.1.5.3 Set up the Configuration File results.json

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

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

1.2 Vegetation dynamics and bedload transport

1.2.1 Introduction

The aim of this tutorial is to show the specific setup of the configuration files for numerical simulations with BASEMENT that include vegetation and bed load transport. For this purpose, the model is applied to a 1 km-long reach of the Alpine Rhine River located at the boundary between Switzerland and Lichtenstein. This particular river reach is characterized by an alternating sequence of gravel bars, which are hotspot for riparian vegetation growth. This tutorial presents the simulation of the flood event of 2005.

1.2.2 Computational Mesh

The computational mesh of the Alpine Rhine river was created ad-hoc to show the main model functionalities with the vegetation module activated and for application with BASEMENT version 3. The mesh has 9799 number of cells with 5149 vertices. The MATID was defined on the gravel bars, the main channel, and the banks to differentiate the bed properties. Figure 1.6 shows the bed elevation of the river used in the simulation.

1.2.3 Morphology with Vegetation

The simulation in the tutorial includes a steady-state hydrodynamic simulation and an unsteady morphodynamic simulation with vegetation. The first one is used to get the initial conditions for the hydraulic variables. The unsteady simulation

The setup of the configuration files follows the same procedure seen in the Flaz tutorial for hydraulics and morphology (Section 1.1.3.1 and Section 1.1.4.1). Here only the vegetation part is shown in detail.

1.2.3.1 Setup the Configuration File model.json

The model is set up with the blocks HYDRAULICS, MORPHOLOGY, and VEGETATION activated. The structure of the VEGETATION block in the file model.json is:

```
{
  "SETUP": {
    "simulation_name": "tutorial_morpho_veg_flood",
    "DOMAIN": {
      "PHYSICAL_PROPERTIES": {...},
      "BASEPLANE_2D": {
        "GEOMETRY": {...},
        "HYDRAULICS": {...},
        "MORPHOLOGY": {...},
        "VEGETATION": {
          "INITIAL": {},
          "PARAMETERS": {}
        }
      }
    }
  }
}
```

The blocks INITIAL and PARAMETERS are both mandatory. The initial conditions for vegetation can be set up using a restart file from a previous simulation (as for the hydraulics) or with input values for the aboveground, belowground biomass, and the rooting depth. In the latter case, the structure is:

```
"INITIAL": {
  "type": "region_defined",
```



```

"regions": [
  {
    "aboveground_biomass": 0.4,
    "belowground_biomass": 0.6,
    "rooting_depth": 1.5,
    "region_name": "bar_up"
  },
  {
    "aboveground_biomass": 0.8,
    "belowground_biomass": 0.2,
    "rooting_depth": 0.5,
    "region_name": "bar_dw"
  },
  {
    "aboveground_biomass": 0.0,
    "belowground_biomass": 0.0,
    "rooting_depth": 0.0,
    "region_name": "channel"
  },
  ...
]
}

```

In this tutorial the vegetation was placed only in the gravel bars and using different characteristics for each of the bar (Figure 1.7). It is important that the sum of the aboveground and belowground biomass equal 1 at maximum. The biomass values are dimensionless, while the rooting depth is expressed in meter.

A number of parameters are needed to run simulation with vegetation. These are all collected in the block PARAMETERS, which has the following elements:

```

"PARAMETER": {
  "burial_factor": 1,
  "plant_height_exp": 1,
  "plant_height_fact": 1,
  "uprooting_factor": 1,
  "veg_strickler_fact": 15,
  "veg_theta_critical_fact": 0.02
}

```

The parameters that are mandatory are the Strickler coefficient, the critical Shield parameter valid for completely vegetated bed, and the parameters for calculating the plant height starting from the aboveground biomass (“plant_height_exp” and “plant_height_fact”). The others are by default set to 1. It is important to note that vegetation should be used in combination with a “MPM_like” formula for bedload transport and a “strickler” type friction closure for the hydrodynamics.

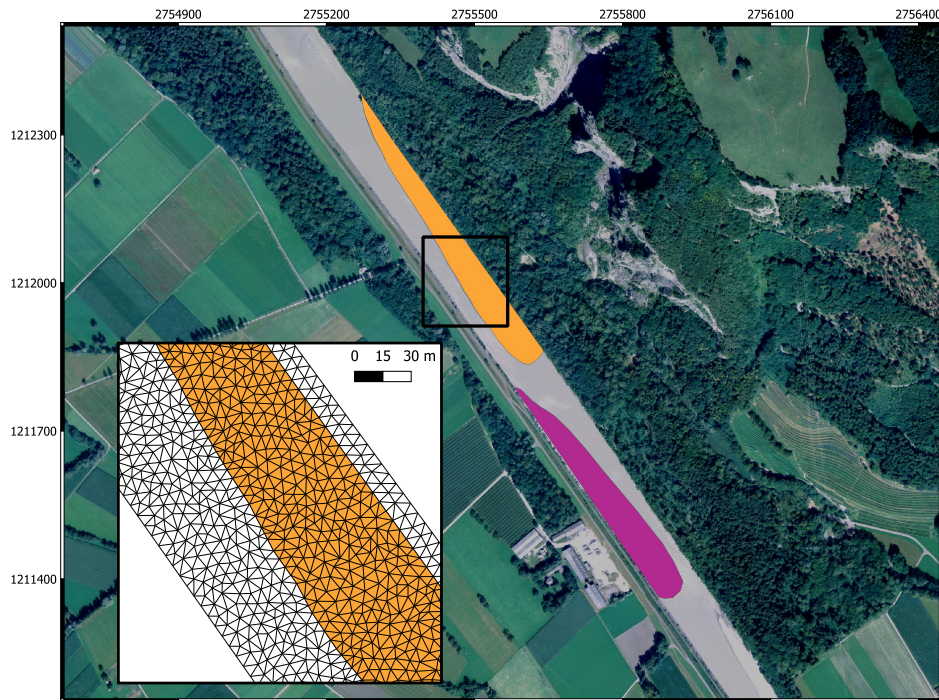


Figure 1.7 Initial location of vegetation on the two bars and an extract of the computational mesh used.

1.2.3.2 Setup 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": {
    "OUTPUT": [
      "bottom_elevation",
      "flow_velocity",
      "friction_chezy",
      "water_surface",
      "delta_z",
      "water_depth",
      "theta_critical",
      "trsp_capacity",
      "aboveground_biomass",
      "belowground_biomass",
      "rooting_depth"
    ],
    "TIME": {
      "end": 111600.0,
      "out": 11160.0,
      "start": 0.0
    },
    "TIMESTEP": {
```

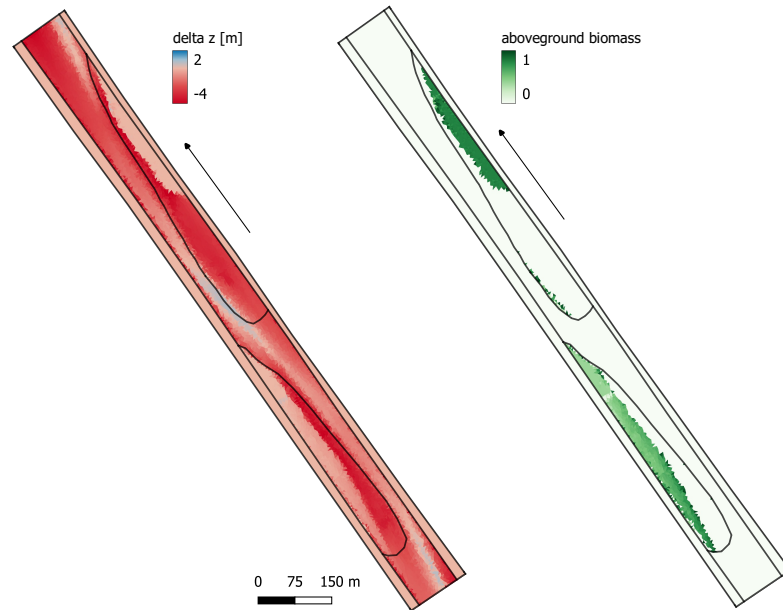


Figure 1.8 Results for the bed elevation and the aboveground biomass after the flood (at $t=111600$ s). Breaklines are highlighted in black.

```

    "init": 0.02,
    "minimum": 0.0001
  }
}
}

```

There are three additional available outputs for vegetation: the aboveground biomass, the belowground biomass, and the rooting depth.

1.2.3.3 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": "xmdf"}
    ]
  }
}

```

1.2.3.4 Results

An example of the results of the simulation of the 2005 flood in the Alpine Rhine river considering vegetation is shown in Figure 1.8. Vegetation is removed in most parts of the bars as a result of uprooting, while the aboveground biomass of surviving vegetation changed because of erosion and deposition processes, which modify biomass redistribution.

1.3 Post-Processing

BASEMENT version 3.x simulation results are generated inside the scenario directory and stored in binary format “.h5”. These results can be converted into a 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” available on the [BASEMENT Website](#).

1.3.1 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 aware, 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).

1.3.2 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 [m³/s], the mean water surface elevation (wse) [m], the wetted area [m²], the mean bottom elevation [m], reference elevation (talweg) [m], wetted geometric length [m], total water volume stored in cells of the stringdef [m³], total conveyance of cells [m³/s], the morphological flux [m³/s] and the bedload transport capacity [m³/s].

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 assess the performance and accuracy of the simulations with BASEMENT version 3. 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. The different backends are: 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 and graphic processing units (GPU) with a compute unified device architecture (CUDA) with single and double precision. The features of the GPU card are shown in Table 2.1.

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

Card	K20	P100	RTX 2080Ti	GTX 1080 Ti	GTX 1070 Ti	GTX 1050 Ti
Memory [GB]	5	12	11	11	8	4
Architecture	Kepler	Pascal	Turing	Pascal	Pascal	Pascal
Bandwidth [GB/s]	208	549	616	484	256	112
CUDA cores	2496	3584	4352	3584	2432	768

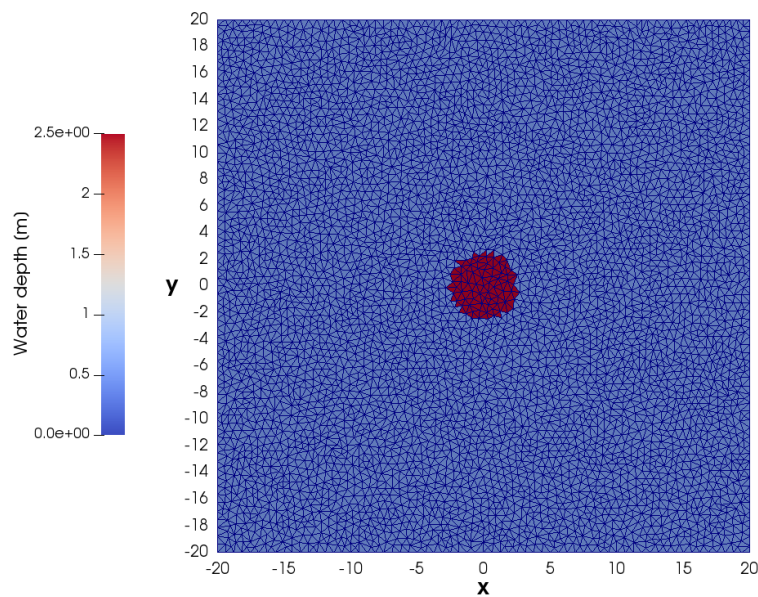


Figure 2.1 Computational domain of the circular dam break (10k cells) with initial water depth.

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 (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.

$$e_X = \frac{|X_{BM} - X_{ref}|}{X_{ref}} \quad (2.1)$$

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 calculated 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.

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

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

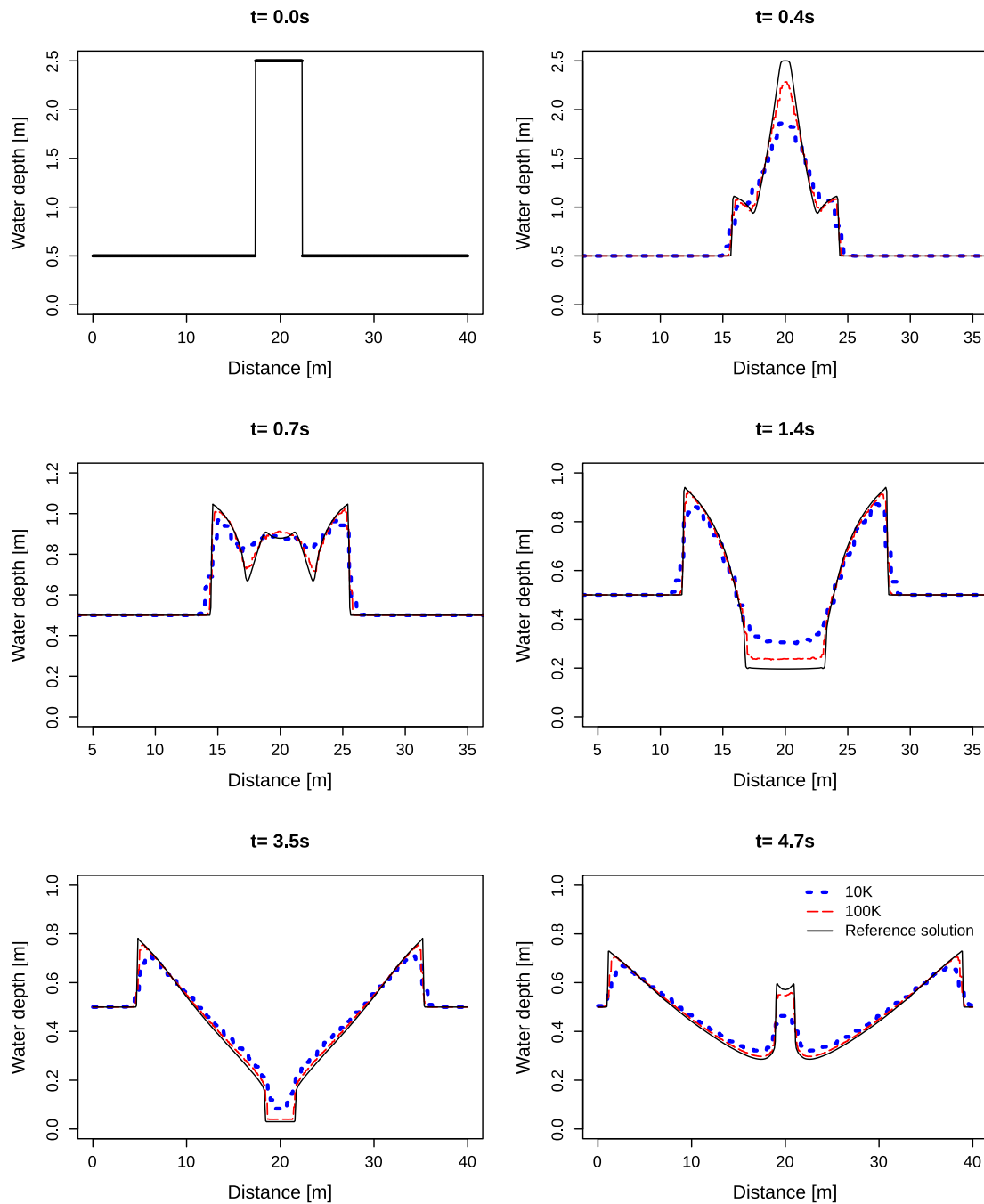


Figure 2.2 Snapshots of the water depth evolution along the reference cross-section. Comparison between BASEMENT simulations with a computational grid of 10k cells, 100k cells and the reference solution of Toro (2001).

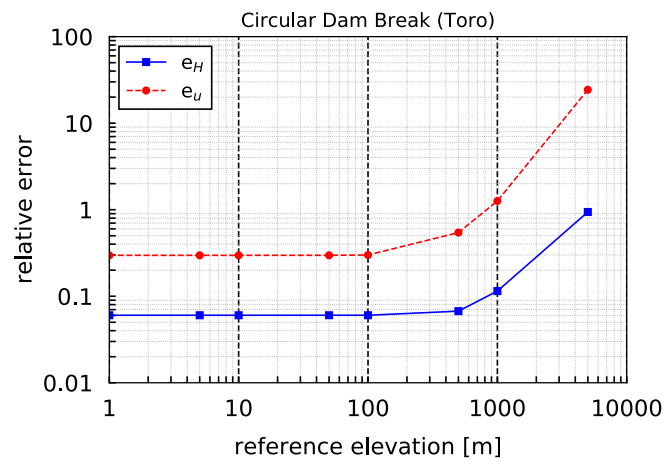


Figure 2.3 Relative error compared to the reference solution of Toro (2001)

2.2.4 Performance

The performance is evaluated in terms of effective computation time and in terms of speedup S . The latter is a measure of parallelization efficiency. The speedup S is calculated as the division of the sequential runtime T_1 (of each mesh size respectively) by the runtime with a certain number of cores T_N or a specific GPU card.

2.2.4.1 Ubuntu

Tables 2.4, 2.5 and 2.6 contain the execution time and speedup of all the simulations performed on different backends under Linux. The backends belong to two categories, either in Central Processor Units (CPU) or Graphics Processor Units (GPU). The CPU run simulations exclusively with double precision, while GPU can perform simulations with 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	0.16	0.19 (1.49x)	0.11 (2.46x)	0.07 (3.33x)	0.04 (4.18x)	0.03 (5.31x)
50k	1.88	1.08 (1.73x)	0.57 (3.29x)	0.33 (5.70x)	0.20 (9.31x)	0.15 (12.68x)
100k	5.44	3.06 (1.77x)	1.62 (3.35x)	0.89 (6.12x)	0.52 (10.4x)	0.35 (15.47x)
500k	63.63	34.49 (1.85x)	17.71 (3.59x)	9.28 (6.86x)	5.06 (12.57x)	3.07 (20.72x)
1000k	190.39	101.66 (1.87x)	51.83 (3.67x)	26.98 (7.06x)	14.36 (13.26x)	8.75 (21.77x)

Table 2.4 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Ubuntu 16.04 (Intel Xeon E5-2667 v3 @ 3.20GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double
10k	0.16	0.19 (1.49x)	0.11 (2.46x)	0.07 (3.33x)	0.04 (4.18x) 0.03 (5.31x)
50k	1.88	1.08 (1.73x)	0.57 (3.29x)	0.33 (5.70x)	0.20 (9.31x) 0.15 (12.68x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double
100k	5.44	3.06 (1.77x)	1.62 (3.35x)	0.89 (6.12x)	0.52 0.35 (10.4x) (15.47x)
500k	63.63	34.49 (1.85x)	17.71 (3.59x)	9.28 (6.86x)	5.06 3.07 (12.57x) (20.72x)
1000k	190.39	101.66 (1.87x)	51.83 (3.67x)	26.98 (7.06x)	14.36 8.75 (13.26x) (21.77x)

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

Mesh size	Xeon 1 Double	RTX 2080Ti Single	RTX 2080Ti Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
10k	0.16	0.04 (4.41x)	0.04 (4.10x)	0.06 (2.86x)	0.05 (2.99x)	0.04 (3.85x)	0.04 (4.04x)
50k	1.88	0.15 (12.18x)	0.19 (9.74x)	0.24 (7.90x)	0.27 (7.01x)	0.18 (10.5x)	0.18 (10.53x)
100k	5.44	0.30 (18.01x)	0.37 (14.65x)	0.51 (10.61x)	0.59 (9.23x)	0.36 (15.28x)	0.37 (14.67x)
500k	63.63	1.66 (38.37x)	2.57 (24.72x)	3.42 (18.61x)	4.67 (13.61x)	2.13 (29.84x)	2.52 (25.28x)
1000k	190.39	3.63 (52.48x)	6.45 (29.54x)	8.63 (22.05x)	12.45 (15.29x)	5.03 (37.87x)	6.28 (30.33x)

Table 2.6 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	GTX 1050Ti Single	GTX 1050Ti Double	GTX 1070Ti Single	GTX 1070Ti Double	GTX 1080Ti Single	GTX 1080Ti Double
10k	0.16	0.04 (3.98x)	0.05 (2.93x)	0.03 (4.42x)	0.04 (4.00x)	0.04 (4.26x)	0.04 (4.05x)
50k	1.88	0.20 (9.28x)	0.34 (5.53x)	0.13 (11.1x)	0.21 (8.78x)	0.16 (11.81x)	0.19 (9.68x)

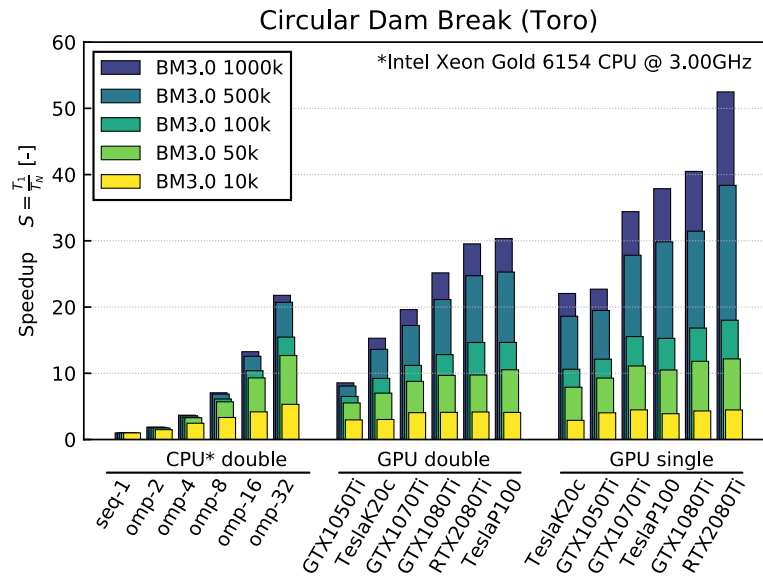


Figure 2.4 Speedup for CPU (double precision) and GPU (single and double precision) backends for the circular dam break test case.

Mesh size	Xeon 1 Double	GTX 1050Ti	GTX 1050Ti	GTX 1070Ti	GTX 1070Ti	GTX 1080Ti	GTX 1080Ti
		Single	Double	Single	Double	Single	Double
100k	5.44	0.45 (12.13x)	0.84 (6.5x)	0.30 (15.54x)	0.49 (11.19x)	0.21 (16.83x)	0.42 (12.82x)
500k	63.63	3.27 (19.48x)	7.88 (8.08x)	1.96 (27.82x)	3.70 (17.21x)	2.02 (31.45x)	3.01 (21.14x)
1000k	190.39	8.55 (22.70x)	22.26 (8.55x)	5.53 (34.40x)	9.71 (19.61x)	4.70 (40.48x)	7.57 (25.16x)

Figure 2.4 shows the speedup achieved by the different backends. The sequential and OpenMP backends were run on processors of type Intel Xeon Gold 6154 (3.00GHz) with two sockets and with 18 cores per socket. The largest speedups are obtained for certain GPU cards using single precision. But also by using the GPU backend with double precision, the simulation time can be reduced significantly compared to sequential computation. It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem. Further, it can be observed that the speedup greatly depends on the problem size. For smaller mesh, the speedup obtained by increasing the number of cores or by using GPU cards can be limited. 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 with Intel Xeon

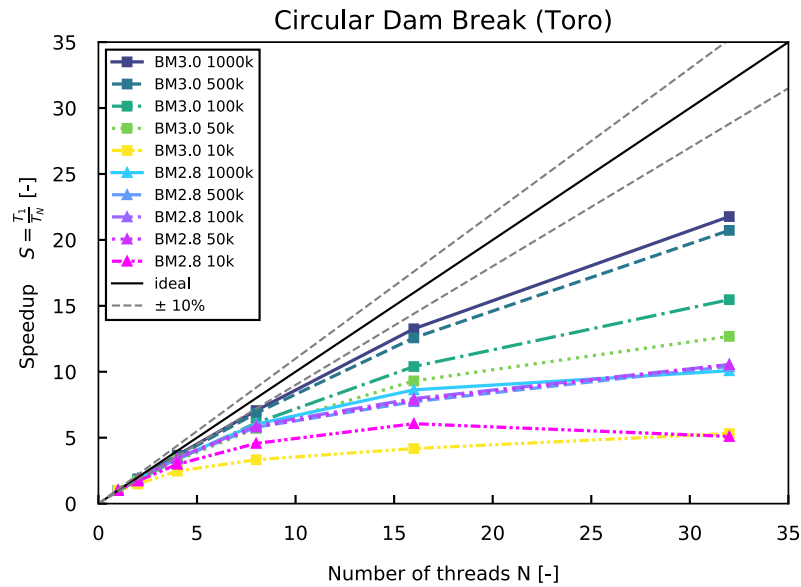


Figure 2.5 Speedup of the computational time $[T_N]$ using different number of threads (CPU) compared to the time of the sequential backend Xeon1 $[T_1]$ for the circular dam break

Gold 6154 (3.00GHz) processors. 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 2.7 contains the execution time and speedup of all the simulations performed on different backends under Windows. The simulations were run on Prozessor Intel Xeon E-2174G (3.80GHz) processors with 4 cores and 2 threads per core (8 logical cores using HyperThreading). The performance scales adequately up to 4 cores. The use of 8 logical usings (HyperThreading) does not results in a significant improvement of performance compared to using 4 physical cores.

Table 2.7 Computational time (s) and speedup (in parentheses) of the circular dam break simulations for CPU simulations under Windows 10 (Intel Xeon E-2174G, 3.80GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
10k	0.23	0.14 (1.67x)	0.08 (3.0x)	0.09 (2.49x)
50k	2.80	1.58 (1.77x)	0.98 (2.84x)	0.81 (3.44x)
100k	8.08	4.73 (1.71x)	3.16 (2.56x)	2.58 (3.13x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
500k	95.01	51.78 (1.83x)	30.55 (3.11x)	23.62 (4.02x)
1000k	275.02	149.84 (1.84x)	90.00 (3.06x)	67.25 (4.09x)

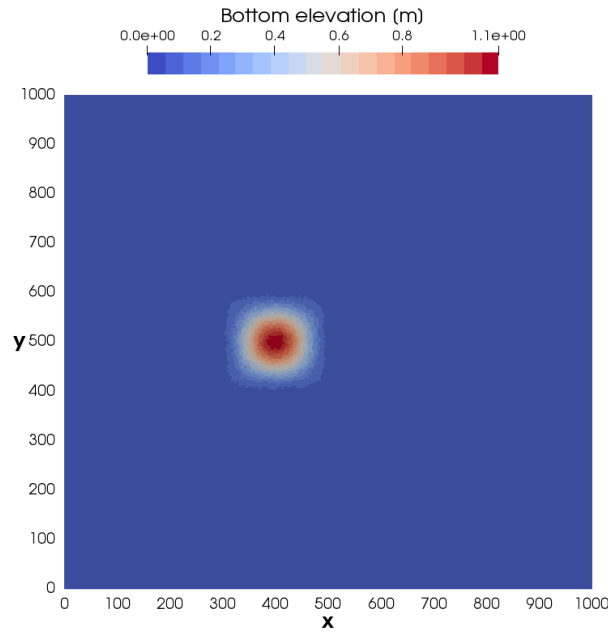


Figure 2.6 Initial bottom elevation of the conical dune, maximum elevation of 1.1 m at $[x=400, y=500]$.

2.3 Conical Dune

2.3.1 Description

The conical dune test proposed by Hudson and Sweby (2005) is used to assess the accuracy 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 2.6):

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

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

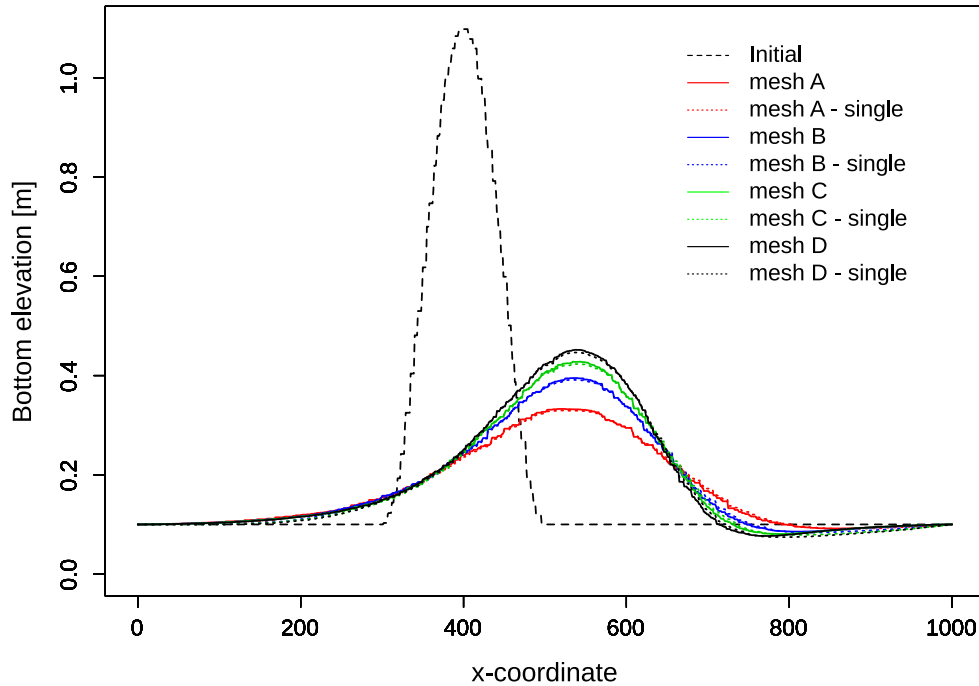


Figure 2.7 Longitudinal bottom elevation profile at $y=500$ m for initial conditions and after 100h of simulation for the meshes A, B, C and D with double and single precision

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 $\alpha_{s,ref} = 21.787^\circ$.

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

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 2.7 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 2.8 summarizes the results obtained from the numerical simulations at $t=100$ h for

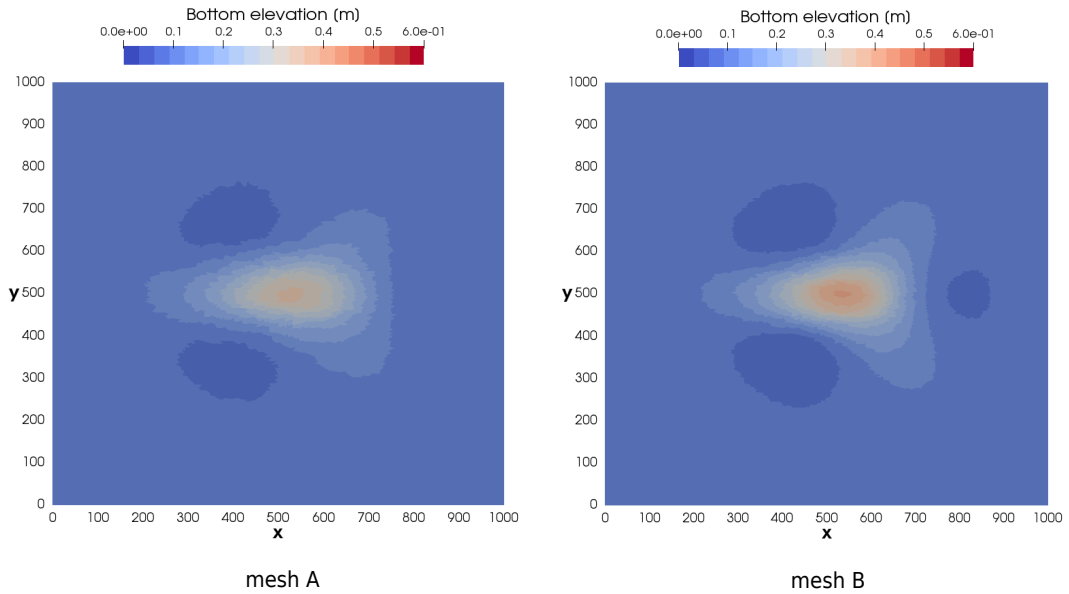


Figure 2.8 Planar view of the bottom elevation after 100 hours of simulation for the meshes A and B.

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 2.8 and Figure 2.9). 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 2.8. 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 2.8 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 2.8). The results are more accurate for finer meshes (mesh C and mesh D, Figure 2.7), 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 2.8 and Figure 2.9 by a well defined star shaped sediment transport and a spread angle that becomes closer to the value proposed by de Vriend (1987).

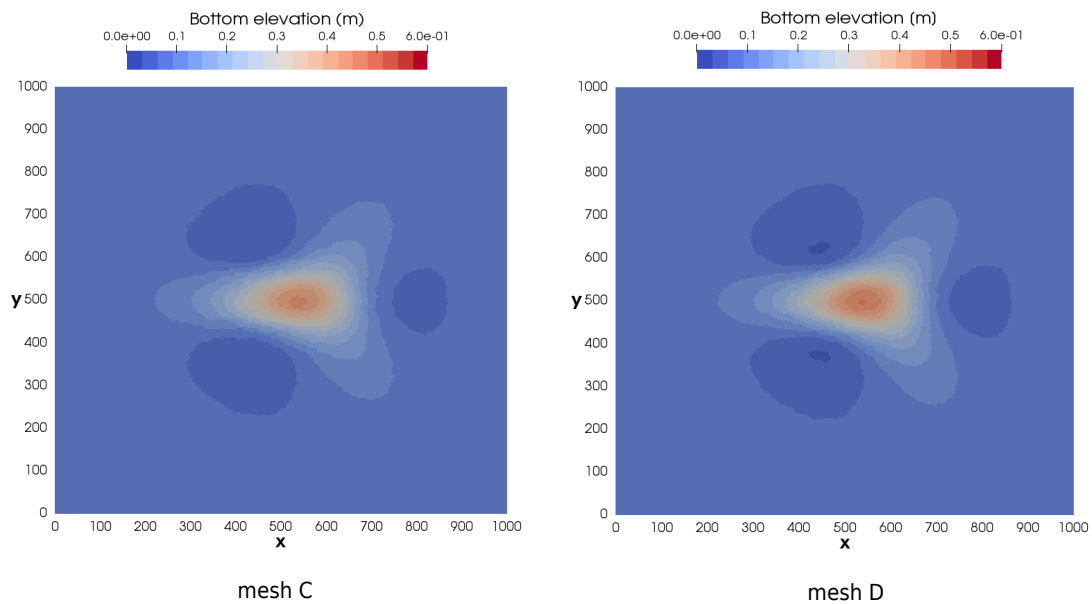


Figure 2.9 Planar view of the bottom elevation after 100 hours of simulation for the meshes C and D.

2.4 Dam-break flow in a L-shaped channel with a mobile-bed

2.4.1 Description

This test case is based on the experiments described in Palumbo et al. (2008) and is a frequently used benchmark test case in literature (e.g. Siviglia et al. (2013), Soares-Frazão and Zech (2011)).

2.4.2 Geometry and initial conditions

This test case consist of a domain with a non-symmetrical sudden enlargement. The dimensions of the domain as illustrated in Figure 2.10. The sediment bed is composed of coarse uniform sand with grain size diameter of $d_s = 1.82$ mm. The sediment porosity is $p = 0.47$ and the sediment density $\rho_s = 2680$ kg/m³. The Manning friction coefficient is set to $n = 0.0167$ s/m^{1/3}. The initial bed level is at an elevation of 0.1 m over the whole domain. The initial water depth upstream (left) of the dam is set to 0.25 m. The dam at is located at $x = 3.0$ m. At time $t = 0$ seconds, he dam is removed instantaneously, resulting in wave propagation and sediment transport.

The computational domain is discretised by unstructured triangular cells. Four different sized computational grids were generated, resulting in grids with 27,000 cells (27k), 54,000 cells (54k), 108,000 cells (108k), 216,000 cells (216k). Wall boundary conditions are applied at the domain side walls. At the outflow boundary (right), a free-outflow boundary condition was applied. The sediment transport is calculated using the MPM_like formula with a pre-factor of 3.97 and an exponent of 1.5. The simulation lasts 12 seconds.

2.4.3 Results

The simulated bed elevations at $t = 12$ s are compared to the experimental results from Palumbo et al. (2008) in Figure 2.11. Overall, the simulated bed elevations are in acceptable agreement with experimental data. The scour in cross section CS1 ($x = 4.1$ m) is matched well, while the deposition around $y = 0.3$ m is underestimated. At cross-section CS2, the numerical results correspond well with the experimental data. In particular at location CS1, the observed deviations may be attributed to distinct 3D flow effects that are not captured by the 2D depth-averaged model (Siviglia et al. 2013, Xia et al. 2010).

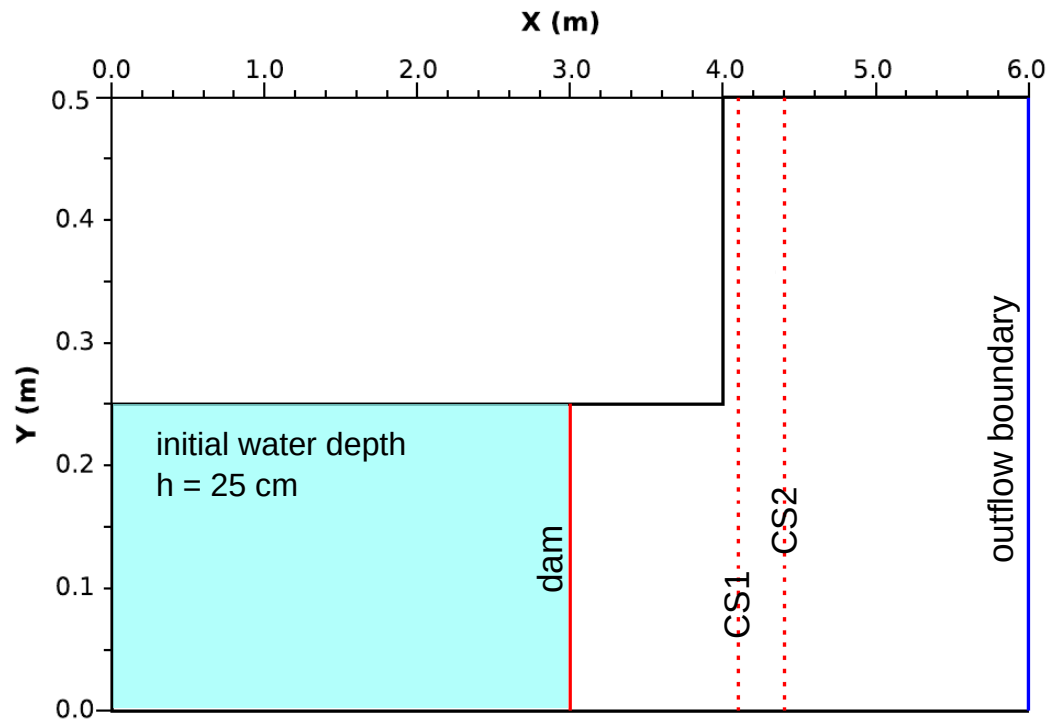


Figure 2.10 The numerical test setup for the dam-break flow in a L-shaped channel with a mobile-bed. Experimental and numerical bed elevations are compared along cross-sections CS1 and CS2. Modified from Siviglia et al. (2013).

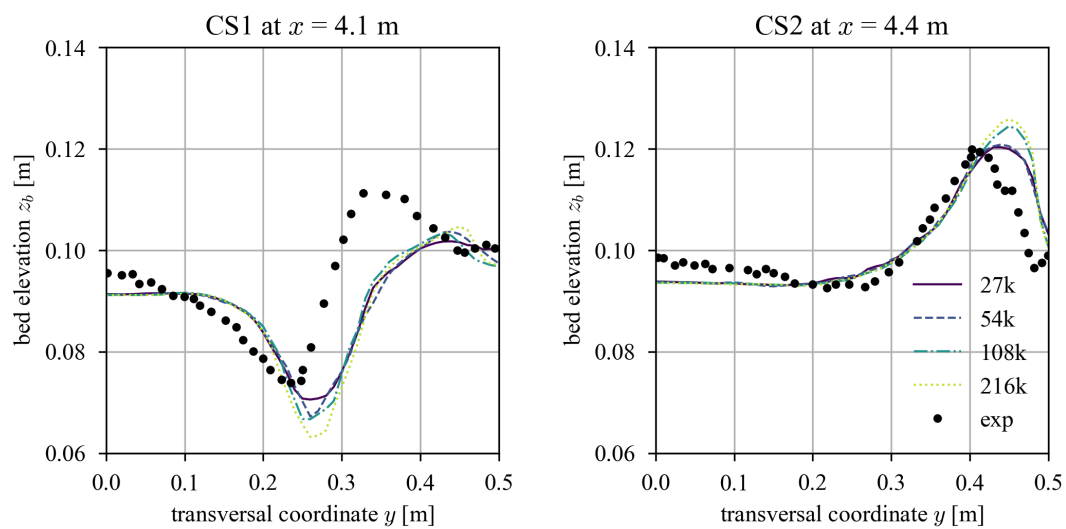


Figure 2.11 Experimental and numerical bed elevation are compared at cross-sections CS1 and CS2.

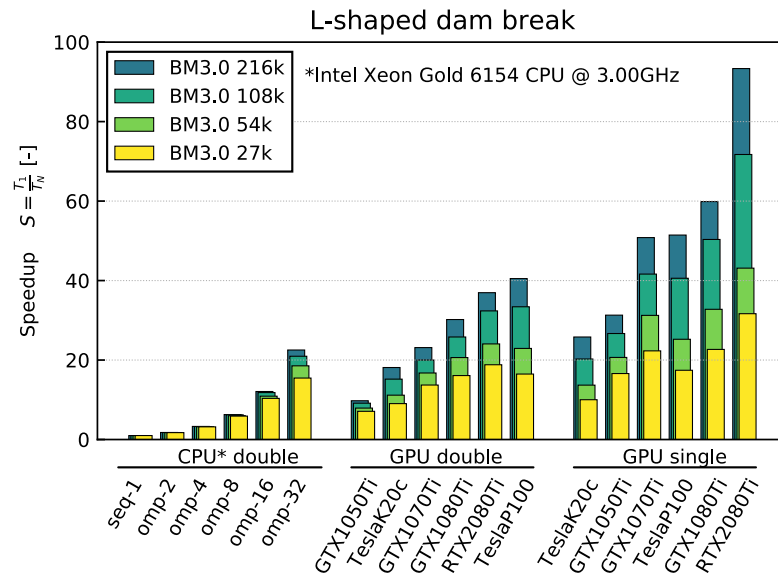


Figure 2.12 Speedup of the computational time $[T_N]$ for CPU (double) and GPU (single and double) compared to the time of the sequential backend Xeon1 $[T_1]$ for the L-shaped dam break test case.

2.4.4 Performance

2.4.4.1 Ubuntu

Simulations of this test case were performed on CPU- and GPU-backends. The largest execution times are obtained by using the sequential backend. By using the OpenMP-backend, the computation time can be reduced almost linearly with the number of cores. Also by using GPU-backends the computation time can be reduced in comparison to sequential computation, whereas the increase in performance depends on the GPU-card and the precision (single or double). The best performance using double precision is obtained with the card Tesla P100, while the RTX 2080Ti outperformed other cards when using single precision (see Tables 2.9, 2.10 and 2.11 or Figure 2.12). It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem.

Table 2.9 Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for CPU simulations (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
30k	43.8	25.2 (1.7x)	13.7 (3.2x)	7.4 (5.9x)	4.2 (10.4x)	2.8 (15.5x)
60k	97.7	56.1 (1.7x)	30.4 (3.2x)	16.3 (6.0x)	9.0 (10.9x)	5.3 (18.5x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
90k	357.3	202.7 (1.8x)	109.3 (3.3x)	57.5 (6.2x)	3.2 (11.8x)	17.0 (21.0x)
120k	1096.3	618.5 (1.8x)	332.6 (3.3x)	174.9 (6.3x)	90.7 (12.1x)	48.7 (22.5x)

Table 2.10 Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for GPU simulations

Mesh size	Xeon 1 Double	RTX 2080Ti Single	RTX 2080Ti Double	Tesla K20 Single	Tesla K20 Double	Tesla P100 Single	Tesla P100 Double
30k	43.8	1.4 (31.7x)	2.3 (18.8x)	4.4 (10.0x)	4.8 (9.0x)	2.5 (17.4x)	2.7 (16.5x)
60k	97.7	2.3 (43.1x)	4.1 (24.1)	7.1 (13.7x)	8.8 (11.2x)	3.9 (25.2x)	4.3 (22.9x)
90k	357.3	5.0 (71.7x)	11.0 (32.4x)	17.6 (20.3x)	23.5 (15.2x)	8.8 (40.6x)	10.7 (33.4x)
120k	1096.3	11.7 (93.3x)	29.7 (37.0x)	42.5 (25.8x)	60.5 (18.1x)	21.3 (51.4x)	27.1 (40.5x)

Table 2.11 Computational time (s) and speedup S (inside brackets) of the L-shaped 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
30k	43.8	2.6 (16.6x)	6.2 (7.1x)	2.0 (22.3x)	3.2 (13.7x)	1.9 (22.7x)	2.7 (16.1x)
60k	97.7	4.7 (20.7x)	12.4 (7.9x)	3.1 (31.2x)	5.8 (16.7x)	3.0 (32.8x)	4.7 (20.69x)
90k	357.3	13.4 (26.7x)	39.1 (9.1x)	8.6 (41.6x)	17.9 (20.0x)	7.1 (50.3x)	13.8 (25.8x)
120k	1096.3	35.0 (31.3x)	112.4 (9.8x)	21.6 (50.8x)	47.4 (23.1x)	18.3 (59.9x)	36.3 (30.2x)

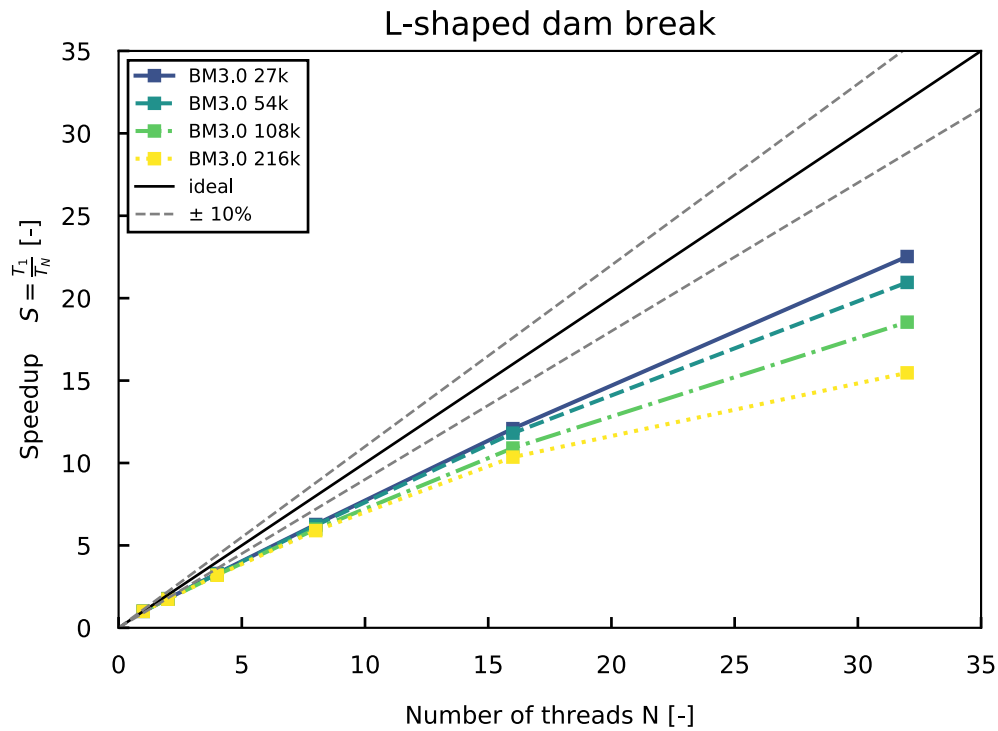


Figure 2.13 Speedup of the L-shaped dam break test case performed on CPU for an increasing number of threads and different mesh sizes

In Figure 2.13, the speedup of the OpenMP-backend is illustrated for different mesh sizes on an Intel Xeon Gold 6154 (3.00GHz) processor on an Ubuntu system with 36 cores. The speedup of scales almost linearly up to 32 cores for this test case, indicating a good scaling behaviour.

2.4.4.2 Windows

Tables 2.12 contains the execution time and speedup of the simulations performed on different backends under Windows. The simulations were run on Prozessor Intel Xeon E-2174G (3.80GHz) processors with 4 cores and 2 threads per core (8 logical cores using HyperThreading). The performance scales adequately up to 4 cores. The use of 8 logical usings (HyperThreading) does not results in a significant improvement of performance compared to using 4 physical cores.

Table 2.12 Computational time (s) and speedup (in parentheses) for CPU simulations of L-shaped dam break with a mobile bed under Windows 10 (Intel Xeon E-2174G, 3.80GHz)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
27k	70.0	38.3 (1.83x)	25.6 (2.73x)	16.8 (4.18x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
54k	158.8	87.3 (1.82x)	58.1 (2.73x)	37.5 (4.23x)
108k	578.5	319.6 (1.81x)	212.3 (2.72x)	137.7 (4.20x)
216k	1770.6	986.0 (1.80x)	680.9 (2.60x)	427.8 (4.14x)

References

- de Vriend, H.J. (1987). 2DH mathematical modelling of morphological evolutions in shallow water. *Coastal engineering*, 11(1): 1–27.
- Hudson, J. and Sweby, P.K. (2005). A high-resolution scheme for the equations governing 2D bed-load sediment transport. *International Journal for Numerical Methods in Fluids*, 47: 1085–1091.
- Palumbo, A., Soares Frazao, S., Goutière, L., Pianese, D. and Zech, Y. (2008). Dam-break flow on mobile bed in a channel with a sudden enlargement. *Proceedings of the river flow 2008 conference*.
- Siviglia, A., Stecca, G., Vanzo, D., Zolezzi, G. and Toro, E.F. (2013). Numerical modelling of two-dimensional morphodynamics with applications to river bars and bifurcations. *Advances in Water Resources*, 52: 243–260.
- Soares-Frazão, S. and Zech, Y. (2011). HLLC scheme with novel wave-speed estimators appropriate for two-dimensional shallow-water flow on erodible bed. *International Journal for Numerical Methods in Fluids*, 66.
- Toro, E.F. (2001). Shock-Capturing Methods for Free-Surface Shallow Flows. *John Wiley*, Chichester, New York.
- Vanzo, D., Siviglia, A. and Toro, E.F. (2016). Pollutant transport by shallow water equations on unstructured meshes: Hyperbolization of the model and numerical solution via a novel flux splitting scheme. *Journal of Computational Physics*, 321: 1–20.

**BASIC SIMULATION ENVIRONMENT
FOR SIMULATION OF ENVIRONMENTAL FLOW
AND NATURAL HAZARD SIMULATION**

APPENDIX

**VERSION 3.2
May 2022**



BASEMENT

Third Party Software

1.1 Third party software copyright notices

Abseil

Copyright The Abseil Authors.

License: Apache 2.0

Brotli

Copyright (c) 2009, 2010, 2013-2016 by the Brotli Authors.

License: MIT

Bzip2

This program, "bzip2", the associated library "libbzip2", and all documentation, are copyright (C) 1996-2019 Julian R Seward. All rights reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

1. Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
2. The origin of this software must not be misrepresented; you must not claim that you wrote the original software. If you use this software in a product, an acknowledgment in the product documentation would be appreciated but is not required.
3. Altered source versions must be plainly marked as such, and must not be misrepresented as being the original software.
4. The name of the author may not be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE AUTHOR ``AS IS'' AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE AUTHOR BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

Julian Seward, jseward@acm.org
bzip2/libbzip2 version 1.0.8 of 13 July 2019

Double-conversion

Copyright 2006-2011, the V8 project authors. All rights reserved.

License: BSD 2.0

Egl-registry

Copyright (c) 2008-2018 The Khronos Group Inc.
Copyright (c) 2013-2017 The Khronos Group Inc.
Copyright (c) 2013-2017 The Khronos Group Inc.
Copyright (c) 2007-2016 The Khronos Group Inc.

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and/or associated documentation files (the "Materials"), to deal in the Materials without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Materials, and to permit persons to whom the Materials are furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Materials.

THE MATERIALS ARE PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE MATERIALS OR THE USE OR OTHER DEALINGS IN THE MATERIALS.

Freetype

The FreeType 2 font engine is copyrighted work and cannot be used legally without a software license. In order to make this project usable to a vast majority of developers, we distribute it under two mutually exclusive open-source licenses.

This means that *you* must choose *one* of the two licenses described below, then obey all its terms and conditions when using FreeType 2 in any of your projects or products.

- The FreeType License, found in the file `FTL.TXT', which is similar to the original BSD license *with* an advertising clause that forces you to explicitly cite the FreeType project in your product's documentation. All details are in the license file. This license is suited to products which don't use the GNU General Public License.

Note that this license is compatible to the GNU General Public License version 3, but not version 2.

- The GNU General Public License version 2, found in `GPLv2.TXT' (any later version can be used also), for programs which already use the GPL. Note that the FTL is incompatible with GPLv2 due to its advertisement clause.

The contributed BDF and PCF drivers come with a license similar to that of the X Window System. It is compatible to the above two licenses (see file src/bdf/README and src/pcf/README). The same holds for the files `fthash.c' and `fthash.h'; their code was part of the BDF driver in earlier FreeType versions.

The gzip module uses the zlib license (see src/gzip/zlib.h) which too is compatible to the above two licenses.

The MD5 checksum support (only used for debugging in development builds) is in the public domain.

Glibc-queue

Copyright (C) 1991-2015 Free Software Foundation, Inc.

The GNU C Library is free software; you can redistribute it and/or modify it under the terms of the GNU Lesser General Public License as published by the Free Software Foundation; either version 2.1 of the License, or (at your option) any later version.

The GNU C Library is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU Lesser General Public License for more details.

You should have received a copy of the GNU Lesser General Public License along with the GNU C Library; if not, write to the Free Software Foundation, Inc., 51 Franklin St, Fifth Floor, Boston, MA 02110-1301 USA

* All code incorporated from 4.4 BSD is distributed under the following license:

Copyright (C) 1991 Regents of the University of California.
All rights reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

1. Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
2. Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.
3. [This condition was removed.]
4. Neither the name of the University nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE REGENTS AND CONTRIBUTORS ``AS IS'' AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE REGENTS OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

Google Test

Copyright 2008, Google Inc.

All rights reserved.

License: BSD 2.0

Harfbuzz

HarfBuzz is licensed under the so-called "Old MIT" license. Details follow.
For parts of HarfBuzz that are licensed under different licenses see individual
files names COPYING in subdirectories where applicable.

Copyright © 2010,2011,2012,2013,2014,2015,2016,2017,2018,2019,2020 Google, Inc.
Copyright © 2018,2019,2020 Ebrahim Byagowi
Copyright © 2019,2020 Facebook, Inc.
Copyright © 2012 Mozilla Foundation
Copyright © 2011 Codethink Limited
Copyright © 2008,2010 Nokia Corporation and/or its subsidiary(-ies)
Copyright © 2009 Keith Stribley
Copyright © 2009 Martin Hosken and SIL International
Copyright © 2007 Chris Wilson
Copyright © 2006 Behdad Esfahbod
Copyright © 2005 David Turner
Copyright © 2004,2007,2008,2009,2010 Red Hat, Inc.
Copyright © 1998-2004 David Turner and Werner Lemberg

For full copyright notices consult the individual files in the package.

Permission is hereby granted, without written agreement and without
license or royalty fees, to use, copy, modify, and distribute this
software and its documentation for any purpose, provided that the
above copyright notice and the following two paragraphs appear in
all copies of this software.

IN NO EVENT SHALL THE COPYRIGHT HOLDER BE LIABLE TO ANY PARTY FOR
DIRECT, INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES
ARISING OUT OF THE USE OF THIS SOFTWARE AND ITS DOCUMENTATION, EVEN
IF THE COPYRIGHT HOLDER HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH
DAMAGE.

THE COPYRIGHT HOLDER SPECIFICALLY DISCLAIMS ANY WARRANTIES, INCLUDING,
BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND
FITNESS FOR A PARTICULAR PURPOSE. THE SOFTWARE PROVIDED HEREUNDER IS
ON AN "AS IS" BASIS, AND THE COPYRIGHT HOLDER HAS NO OBLIGATION TO
PROVIDE MAINTENANCE, SUPPORT, UPDATES, ENHANCEMENTS, OR MODIFICATIONS.

HDF5

Copyright Notice and License Terms for
HDF5 (Hierarchical Data Format 5) Software Library and Utilities

HDF5 (Hierarchical Data Format 5) Software Library and Utilities
Copyright 2006 by The HDF Group.

NCSA HDF5 (Hierarchical Data Format 5) Software Library and Utilities
Copyright 1998-2006 by The Board of Trustees of the University of Illinois.

All rights reserved.

Redistribution and use in source and binary forms, with or without
modification, are permitted for any purpose (including commercial purposes)
provided that the following conditions are met:

1. Redistributions of source code must retain the above copyright notice, this list of conditions, and the following disclaimer.
2. Redistributions in binary form must reproduce the above copyright notice, this list of conditions, and the following disclaimer in the documentation and/or materials provided with the distribution.
3. Neither the name of The HDF Group, the name of the University, nor the name of any Contributor may be used to endorse or promote products derived from this software without specific prior written permission from The HDF Group, the University, or the Contributor, respectively.

DISCLAIMER:

THIS SOFTWARE IS PROVIDED BY THE HDF GROUP AND THE CONTRIBUTORS "AS IS" WITH NO WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED. IN NO EVENT SHALL THE HDF GROUP OR THE CONTRIBUTORS BE LIABLE FOR ANY DAMAGES SUFFERED BY THE USERS ARISING OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

You are under no obligation whatsoever to provide any bug fixes, patches, or upgrades to the features, functionality or performance of the source code ("Enhancements") to anyone; however, if you choose to make your Enhancements available either publicly, or directly to The HDF Group, without imposing a separate written license agreement for such Enhancements, then you hereby grant the following license: a non-exclusive, royalty-free perpetual license to install, use, modify, prepare derivative works, incorporate into other computer software, distribute, and sublicense such enhancements or derivative works thereof, in binary and source code form.

 Limited portions of HDF5 were developed by Lawrence Berkeley National Laboratory (LBNL). LBNL's Copyright Notice and Licensing Terms can be found here: COPYING_LBNL_HDF5 file in this directory or at http://support.hdfgroup.org/ftp/HDF5/releases/COPYING_LBNL_HDF5.

 Contributors: National Center for Supercomputing Applications (NCSA) at the University of Illinois, Fortner Software, Unidata Program Center (netCDF), The Independent JPEG Group (JPEG), Jean-loup Gailly and Mark Adler (gzip), and Digital Equipment Corporation (DEC).

 Portions of HDF5 were developed with support from the Lawrence Berkeley National Laboratory (LBNL) and the United States Department of Energy under Prime Contract No. DE-AC02-05CH11231.

 Portions of HDF5 were developed with support from the University of California, Lawrence Livermore National Laboratory (UC LLNL). The following statement applies to those portions of the product and must be retained in any redistribution of source code, binaries, documentation, and/or accompanying materials:

This work was partially produced at the University of California, Lawrence Livermore National Laboratory (UC LLNL) under contract no. W-7405-ENG-48 (Contract 48) between the U.S. Department of Energy (DOE) and The Regents of the University of California (University) for the operation of UC LLNL.

DISCLAIMER:

THIS WORK WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY AN AGENCY OF THE UNITED STATES GOVERNMENT. NEITHER THE UNITED STATES GOVERNMENT NOR THE UNIVERSITY OF CALIFORNIA NOR ANY OF THEIR EMPLOYEES, MAKES ANY

WARRANTY, EXPRESS OR IMPLIED, OR ASSUMES ANY LIABILITY OR RESPONSIBILITY FOR THE ACCURACY, COMPLETENESS, OR USEFULNESS OF ANY INFORMATION, APPARATUS, PRODUCT, OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS USE WOULD NOT INFRINGE PRIVATELY- OWNED RIGHTS. REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCTS, PROCESS, OR SERVICE BY TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY THE UNITED STATES GOVERNMENT OR THE UNIVERSITY OF CALIFORNIA. THE VIEWS AND OPINIONS OF AUTHORS EXPRESSED HEREIN DO NOT NECESSARILY STATE OR REFLECT THOSE OF THE UNITED STATES GOVERNMENT OR THE UNIVERSITY OF CALIFORNIA, AND SHALL NOT BE USED FOR ADVERTISING OR PRODUCT ENDORSEMENT PURPOSES.

HDF5 is available with the SZIP compression library but SZIP is not part of HDF5 and has separate copyright and license terms. See SZIP Compression in HDF Products (www.hdfgroup.org/doc_resource/SZIP/) for further details.

HighFive

License: BSL 1.0

JSON for Modern C++

Copyright (c) 2013-2020 Niels Lohmann

License: MIT

Libjpeg-turbo

libjpeg-turbo Licenses

=====

libjpeg-turbo is covered by three compatible BSD-style open source licenses:

- The IJG (Independent JPEG Group) License, which is listed in README.ijg

This license applies to the libjpeg API library and associated programs (any code inherited from libjpeg, and any modifications to that code.)

- The Modified (3-clause) BSD License, which is listed below

This license covers the TurboJPEG API library and associated programs, as well as the build system.

- The [zlib License](<https://opensource.org/licenses/Zlib>)

This license is a subset of the other two, and it covers the libjpeg-turbo SIMD extensions.

Complying with the libjpeg-turbo Licenses

=====

This section provides a roll-up of the libjpeg-turbo licensing terms, to the best of our understanding.

1. If you are distributing a modified version of the libjpeg-turbo source, then:
 1. You cannot alter or remove any existing copyright or license notices from the source.

- ```

Origin
- Clause 1 of the IJG License
- Clause 1 of the Modified BSD License
- Clauses 1 and 3 of the zlib License

```
2. You must add your own copyright notice to the header of each source file you modified, so others can tell that you modified that file (if there is not an existing copyright header in that file, then you can simply add a notice stating that you modified the file.)

```

Origin
- Clause 1 of the IJG License
- Clause 2 of the zlib License

```
  3. You must include the IJG README file, and you must not alter any of the copyright or license text in that file.

```

Origin
- Clause 1 of the IJG License

```
2. If you are distributing only libjpeg-turbo binaries without the source, or if you are distributing an application that statically links with libjpeg-turbo, then:
    1. Your product documentation must include a message stating:

This software is based in part on the work of the Independent JPEG Group.

```

Origin
- Clause 2 of the IJG license

```
    2. If your binary distribution includes or uses the TurboJPEG API, then your product documentation must include the text of the Modified BSD License (see below.)

```

Origin
- Clause 2 of the Modified BSD License

```
  3. You cannot use the name of the IJG or The libjpeg-turbo Project or the contributors thereof in advertising, publicity, etc.

```

Origin
- IJG License
- Clause 3 of the Modified BSD License

```
  4. The IJG and The libjpeg-turbo Project do not warrant libjpeg-turbo to be free of defects, nor do we accept any liability for undesirable consequences resulting from your use of the software.

```

Origin
- IJG License
- Modified BSD License
- zlib License

```

The Modified (3-clause) BSD License  
 =====

Copyright (C)2009-2020 D. R. Commander. All Rights Reserved.  
 Copyright (C)2015 Viktor Szathm ry. All Rights Reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

- Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
- Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.

- Neither the name of the libjpeg-turbo Project nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS "AS IS", AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT HOLDERS OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

#### Why Three Licenses?

=====

The zlib License could have been used instead of the Modified (3-clause) BSD License, and since the IJG License effectively subsumes the distribution conditions of the zlib License, this would have effectively placed libjpeg-turbo binary distributions under the IJG License. However, the IJG License specifically refers to the Independent JPEG Group and does not extend attribution and endorsement protections to other entities. Thus, it was desirable to choose a license that granted us the same protections for new code that were granted to the IJG for code derived from their software.

#### Libpng

##### COPYRIGHT NOTICE, DISCLAIMER, and LICENSE

=====

##### PNG Reference Library License version 2

-----

- \* Copyright (c) 1995-2019 The PNG Reference Library Authors.
- \* Copyright (c) 2018-2019 Cosmin Truta.
- \* Copyright (c) 2000-2002, 2004, 2006-2018 Glenn Randers-Pehrson.
- \* Copyright (c) 1996-1997 Andreas Dilger.
- \* Copyright (c) 1995-1996 Guy Eric Schalnat, Group 42, Inc.

The software is supplied "as is", without warranty of any kind, express or implied, including, without limitation, the warranties of merchantability, fitness for a particular purpose, title, and non-infringement. In no event shall the Copyright owners, or anyone distributing the software, be liable for any damages or other liability, whether in contract, tort or otherwise, arising from, out of, or in connection with the software, or the use or other dealings in the software, even if advised of the possibility of such damage.

Permission is hereby granted to use, copy, modify, and distribute this software, or portions hereof, for any purpose, without fee, subject to the following restrictions:

1. The origin of this software must not be misrepresented; you must not claim that you wrote the original software. If you use this software in a product, an acknowledgment in the product documentation would be appreciated, but is not required.
2. Altered source versions must be plainly marked as such, and must not be misrepresented as being the original software.
3. This Copyright notice may not be removed or altered from any source or altered source distribution.

PNG Reference Library License version 1 (for libpng 0.5 through 1.6.35)

-----

libpng versions 1.0.7, July 1, 2000, through 1.6.35, July 15, 2018 are Copyright (c) 2000-2002, 2004, 2006-2018 Glenn Randers-Pehrson, are derived from libpng-1.0.6, and are distributed according to the same disclaimer and license as libpng-1.0.6 with the following individuals added to the list of Contributing Authors:

Simon-Pierre Cadieux  
 Eric S. Raymond  
 Mans Rullgard  
 Cosmin Truta  
 Gilles Vollant  
 James Yu  
 Mandar Sahastrabuddhe  
 Google Inc.  
 Vadim Barkov

and with the following additions to the disclaimer:

There is no warranty against interference with your enjoyment of the library or against infringement. There is no warranty that our efforts or the library will fulfill any of your particular purposes or needs. This library is provided with all faults, and the entire risk of satisfactory quality, performance, accuracy, and effort is with the user.

Some files in the "contrib" directory and some configure-generated files that are distributed with libpng have other copyright owners, and are released under other open source licenses.

libpng versions 0.97, January 1998, through 1.0.6, March 20, 2000, are Copyright (c) 1998-2000 Glenn Randers-Pehrson, are derived from libpng-0.96, and are distributed according to the same disclaimer and license as libpng-0.96, with the following individuals added to the list of Contributing Authors:

Tom Lane  
 Glenn Randers-Pehrson  
 Willem van Schaik

libpng versions 0.89, June 1996, through 0.96, May 1997, are Copyright (c) 1996-1997 Andreas Dilger, are derived from libpng-0.88, and are distributed according to the same disclaimer and license as libpng-0.88, with the following individuals added to the list of Contributing Authors:

John Bowler  
 Kevin Bracey  
 Sam Bushell  
 Magnus Holmgren  
 Greg Roelofs  
 Tom Tanner

Some files in the "scripts" directory have other copyright owners, but are released under this license.

libpng versions 0.5, May 1995, through 0.88, January 1996, are Copyright (c) 1995-1996 Guy Eric Schalnat, Group 42, Inc.

For the purposes of this copyright and license, "Contributing Authors" is defined as the following set of individuals:

Andreas Dilger  
 Dave Martindale  
 Guy Eric Schalnat  
 Paul Schmidt  
 Tim Wegner



The PNG Reference Library is supplied "AS IS". The Contributing Authors and Group 42, Inc. disclaim all warranties, expressed or implied, including, without limitation, the warranties of merchantability and of fitness for any purpose. The Contributing Authors and Group 42, Inc. assume no liability for direct, indirect, incidental, special, exemplary, or consequential damages, which may result from the use of the PNG Reference Library, even if advised of the possibility of such damage.

Permission is hereby granted to use, copy, modify, and distribute this source code, or portions hereof, for any purpose, without fee, subject to the following restrictions:

1. The origin of this source code must not be misrepresented.
2. Altered versions must be plainly marked as such and must not be misrepresented as being the original source.
3. This Copyright notice may not be removed or altered from any source or altered source distribution.

The Contributing Authors and Group 42, Inc. specifically permit, without fee, and encourage the use of this source code as a component to supporting the PNG file format in commercial products. If you use this source code in a product, acknowledgment is not required but would be appreciated.

## OP2

Copyright (c) 2011, Gihan Mudalige, Istvan Reguly, Mike Giles, and others. Please see the AUTHORS file in the main source directory for details. All rights reserved.

License: BSD 2.0

## OpenMesh

Copyright (c) 2001-2015, RWTH-Aachen University

Department of Computer Graphics and Multimedia

All rights reserved.

[www.openmesh.org](http://www.openmesh.org)

License: BSD 2.0

## PCRE2

### PCRE2 LICENCE

-----

PCRE2 is a library of functions to support regular expressions whose syntax and semantics are as close as possible to those of the Perl 5 language.

Releases 10.00 and above of PCRE2 are distributed under the terms of the "BSD" licence, as specified below, with one exemption for certain binary redistributions. The documentation for PCRE2, supplied in the "doc" directory, is distributed under the same terms as the software itself. The data in the testdata directory is not copyrighted and is in the public domain.

The basic library functions are written in C and are freestanding. Also 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 the library is built.

THE BASIC LIBRARY FUNCTIONS  
-----

Written by: Philip Hazel  
Email local part: ph10  
Email domain: cam.ac.uk

University of Cambridge Computing Service,  
Cambridge, England.

Copyright (c) 1997-2020 University of Cambridge  
All rights reserved.

PCRE2 JUST-IN-TIME COMPILATION SUPPORT  
-----

Written by: Zoltan Herczeg  
Email local part: hzmester  
Email domain: freemail.hu

Copyright(c) 2010-2020 Zoltan Herczeg  
All rights reserved.

STACK-LESS JUST-IN-TIME COMPILER  
-----

Written by: Zoltan Herczeg  
Email local part: hzmester  
Email domain: freemail.hu

Copyright(c) 2009-2020 Zoltan Herczeg  
All rights reserved.

THE "BSD" LICENCE  
-----

Redistribution and use in source and binary forms, with or without  
modification, are permitted provided that the following conditions are met:

- \* Redistributions of source code must retain the above copyright notices,  
this list of conditions and the following disclaimer.
- \* Redistributions in binary form must reproduce the above copyright  
notices, this list of conditions and the following disclaimer in the  
documentation and/or other materials provided with the distribution.
- \* Neither the name of the University of Cambridge nor the names of any  
contributors may be used to endorse or promote products derived from this  
software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS "AS IS"  
AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE  
IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE  
ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT OWNER OR CONTRIBUTORS BE  
LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR  
CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF  
SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS  
INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN  
CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)  
ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE  
POSSIBILITY OF SUCH DAMAGE.

EXEMPTION FOR BINARY LIBRARY-LIKE PACKAGES  
-----

The second condition in the BSD licence (covering binary redistributions) does not apply all the way down a chain of software. If binary package A includes PCRE2, it must respect the condition, but if package B is software that includes package A, the condition is not imposed on package B unless it uses PCRE2 independently.

### Qt

The Qt Toolkit is Copyright (C) 2016 The Qt Company Ltd.  
Contact: <http://www.qt.io/licensing/>

License: LGPL 3.0

### SimpleXdmf

Copyright (c) 2017 hsimyu

License: MIT

### TCLAP

Copyright (c) 2003 Michael E. Smoot  
Copyright (c) 2004 Daniel Aarno  
Copyright (c) 2017 Google Inc.

License: MIT

### Vcpkg

Copyright (c) Microsoft Corporation

All rights reserved.

License: MIT

### Zlib

Copyright (C) 1995-2017 Jean-loup Gailly and Mark Adler

This software is provided 'as-is', without any express or implied warranty. In no event will the authors be held liable for any damages arising from the use of this software.

Permission is granted to anyone to use this software for any purpose, including commercial applications, and to alter it and redistribute it freely, subject to the following restrictions:

1. The origin of this software must not be misrepresented; you must not claim that you wrote the original software. If you use this software in a product, an acknowledgment in the product documentation would be appreciated but is not required.
2. Altered source versions must be plainly marked as such, and must not be misrepresented as being the original software.
3. This notice may not be removed or altered from any source distribution.

Jean-loup Gailly                      Mark Adler  
jloup@gzip.org                        madler@alumni.caltech.edu

### Zstd

Copyright (c) 2016-present, Facebook, Inc. All rights reserved.

License: BSD 2.0

## 1.2 Third party software licenses

### LGPL 3.0

GNU LESSER GENERAL PUBLIC LICENSE  
Version 3, 29 June 2007

Copyright (C) 2007 Free Software Foundation, Inc. <<https://fsf.org/>>  
Everyone is permitted to copy and distribute verbatim copies  
of this license document, but changing it is not allowed.

This version of the GNU Lesser General Public License incorporates  
the terms and conditions of version 3 of the GNU General Public  
License, supplemented by the additional permissions listed below.

#### 0. Additional Definitions.

As used herein, "this License" refers to version 3 of the GNU Lesser  
General Public License, and the "GNU GPL" refers to version 3 of the GNU  
General Public License.

"The Library" refers to a covered work governed by this License,  
other than an Application or a Combined Work as defined below.

An "Application" is any work that makes use of an interface provided  
by the Library, but which is not otherwise based on the Library.  
Defining a subclass of a class defined by the Library is deemed a mode  
of using an interface provided by the Library.

A "Combined Work" is a work produced by combining or linking an  
Application with the Library. The particular version of the Library  
with which the Combined Work was made is also called the "Linked  
Version".

The "Minimal Corresponding Source" for a Combined Work means the  
Corresponding Source for the Combined Work, excluding any source code  
for portions of the Combined Work that, considered in isolation, are  
based on the Application, and not on the Linked Version.

The "Corresponding Application Code" for a Combined Work means the  
object code and/or source code for the Application, including any data  
and utility programs needed for reproducing the Combined Work from the  
Application, but excluding the System Libraries of the Combined Work.

#### 1. Exception to Section 3 of the GNU GPL.

You may convey a covered work under sections 3 and 4 of this License  
without being bound by section 3 of the GNU GPL.

#### 2. Conveying Modified Versions.

If you modify a copy of the Library, and, in your modifications, a  
facility refers to a function or data to be supplied by an Application  
that uses the facility (other than as an argument passed when the  
facility is invoked), then you may convey a copy of the modified  
version:

- a) under this License, provided that you make a good faith effort to  
ensure that, in the event an Application does not supply the  
function or data, the facility still operates, and performs  
whatever part of its purpose remains meaningful, or
- b) under the GNU GPL, with none of the additional permissions of  
this License applicable to that copy.

#### 3. Object Code Incorporating Material from Library Header Files.

The object code form of an Application may incorporate material from

a header file that is part of the Library. You may convey such object code under terms of your choice, provided that, if the incorporated material is not limited to numerical parameters, data structure layouts and accessors, or small macros, inline functions and templates (ten or fewer lines in length), you do both of the following:

- a) Give prominent notice with each copy of the object code that the Library is used in it and that the Library and its use are covered by this License.
- b) Accompany the object code with a copy of the GNU GPL and this license document.

#### 4. Combined Works.

You may convey a Combined Work under terms of your choice that, taken together, effectively do not restrict modification of the portions of the Library contained in the Combined Work and reverse engineering for debugging such modifications, if you also do each of the following:

- a) Give prominent notice with each copy of the Combined Work that the Library is used in it and that the Library and its use are covered by this License.
- b) Accompany the Combined Work with a copy of the GNU GPL and this license document.
- c) For a Combined Work that displays copyright notices during execution, include the copyright notice for the Library among these notices, as well as a reference directing the user to the copies of the GNU GPL and this license document.

d) Do one of the following:

0) Convey the Minimal Corresponding Source under the terms of this License, and the Corresponding Application Code in a form suitable for, and under terms that permit, the user to recombine or relink the Application with a modified version of the Linked Version to produce a modified Combined Work, in the manner specified by section 6 of the GNU GPL for conveying Corresponding Source.

1) Use a suitable shared library mechanism for linking with the Library. A suitable mechanism is one that (a) uses at run time a copy of the Library already present on the user's computer system, and (b) will operate properly with a modified version of the Library that is interface-compatible with the Linked Version.

e) Provide Installation Information, but only if you would otherwise be required to provide such information under section 6 of the GNU GPL, and only to the extent that such information is necessary to install and execute a modified version of the Combined Work produced by recombining or relinking the Application with a modified version of the Linked Version. (If you use option 4d0, the Installation Information must accompany the Minimal Corresponding Source and Corresponding Application Code. If you use option 4d1, you must provide the Installation Information in the manner specified by section 6 of the GNU GPL for conveying Corresponding Source.)

#### 5. Combined Libraries.

You may place library facilities that are a work based on the Library side by side in a single library together with other library facilities that are not Applications and are not covered by this License, and convey such a combined library under terms of your choice, if you do both of the following:

a) Accompany the combined library with a copy of the same work based on the Library, uncombined with any other library facilities, conveyed under the terms of this License.

b) Give prominent notice with the combined library that part of it is a work based on the Library, and explaining where to find the accompanying uncombined form of the same work.

#### 6. Revised Versions of the GNU Lesser General Public License.

The Free Software Foundation may publish revised and/or new versions of the GNU Lesser General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Library as you received it specifies that a certain numbered version of the GNU Lesser General Public License "or any later version" applies to it, you have the option of following the terms and conditions either of that published version or of any later version published by the Free Software Foundation. If the Library as you received it does not specify a version number of the GNU Lesser General Public License, you may choose any version of the GNU Lesser General Public License ever published by the Free Software Foundation.

If the Library as you received it specifies that a proxy can decide whether future versions of the GNU Lesser General Public License shall apply, that proxy's public statement of acceptance of any version is permanent authorization for you to choose that version for the Library.

### GPL 3.0

GNU GENERAL PUBLIC LICENSE  
Version 3, 29 June 2007

Copyright (C) 2007 Free Software Foundation, Inc. <<https://fsf.org/>>  
Everyone is permitted to copy and distribute verbatim copies of this license document, but changing it is not allowed.

#### Preamble

The GNU General Public License is a free, copyleft license for software and other kinds of works.

The licenses for most software and other practical works are designed to take away your freedom to share and change the works. By contrast, the GNU General Public License is intended to guarantee your freedom to share and change all versions of a program--to make sure it remains free software for all its users. We, the Free Software Foundation, use the GNU General Public License for most of our software; it applies also to any other work released this way by its authors. You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for them if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs, and that you know you can do these things.

To protect your rights, we need to prevent others from denying you these rights or asking you to surrender the rights. Therefore, you have certain responsibilities if you distribute copies of the software, or if you modify it: responsibilities to respect the freedom of others.

For example, if you distribute copies of such a program, whether gratis or for a fee, you must pass on to the recipients the same freedoms that you received. You must make sure that they, too, receive

or can get the source code. And you must show them these terms so they know their rights.

Developers that use the GNU GPL protect your rights with two steps: (1) assert copyright on the software, and (2) offer you this License giving you legal permission to copy, distribute and/or modify it.

For the developers' and authors' protection, the GPL clearly explains that there is no warranty for this free software. For both users' and authors' sake, the GPL requires that modified versions be marked as changed, so that their problems will not be attributed erroneously to authors of previous versions.

Some devices are designed to deny users access to install or run modified versions of the software inside them, although the manufacturer can do so. This is fundamentally incompatible with the aim of protecting users' freedom to change the software. The systematic pattern of such abuse occurs in the area of products for individuals to use, which is precisely where it is most unacceptable. Therefore, we have designed this version of the GPL to prohibit the practice for those products. If such problems arise substantially in other domains, we stand ready to extend this provision to those domains in future versions of the GPL, as needed to protect the freedom of users.

Finally, every program is threatened constantly by software patents. States should not allow patents to restrict development and use of software on general-purpose computers, but in those that do, we wish to avoid the special danger that patents applied to a free program could make it effectively proprietary. To prevent this, the GPL assures that patents cannot be used to render the program non-free.

The precise terms and conditions for copying, distribution and modification follow.

#### TERMS AND CONDITIONS

##### 0. Definitions.

"This License" refers to version 3 of the GNU General Public License.

"Copyright" also means copyright-like laws that apply to other kinds of works, such as semiconductor masks.

"The Program" refers to any copyrightable work licensed under this License. Each licensee is addressed as "you". "Licensees" and "recipients" may be individuals or organizations.

To "modify" a work means to copy from or adapt all or part of the work in a fashion requiring copyright permission, other than the making of an exact copy. The resulting work is called a "modified version" of the earlier work or a work "based on" the earlier work.

A "covered work" means either the unmodified Program or a work based on the Program.

To "propagate" a work means to do anything with it that, without permission, would make you directly or secondarily liable for infringement under applicable copyright law, except executing it on a computer or modifying a private copy. Propagation includes copying, distribution (with or without modification), making available to the public, and in some countries other activities as well.

To "convey" a work means any kind of propagation that enables other parties to make or receive copies. Mere interaction with a user through a computer network, with no transfer of a copy, is not conveying.

An interactive user interface displays "Appropriate Legal Notices" to the extent that it includes a convenient and prominently visible feature that (1) displays an appropriate copyright notice, and (2) tells the user that there is no warranty for the work (except to the

extent that warranties are provided), that licensees may convey the work under this License, and how to view a copy of this License. If the interface presents a list of user commands or options, such as a menu, a prominent item in the list meets this criterion.

#### 1. Source Code.

The "source code" for a work means the preferred form of the work for making modifications to it. "Object code" means any non-source form of a work.

A "Standard Interface" means an interface that either is an official standard defined by a recognized standards body, or, in the case of interfaces specified for a particular programming language, one that is widely used among developers working in that language.

The "System Libraries" of an executable work include anything, other than the work as a whole, that (a) is included in the normal form of packaging a Major Component, but which is not part of that Major Component, and (b) serves only to enable use of the work with that Major Component, or to implement a Standard Interface for which an implementation is available to the public in source code form. A "Major Component", in this context, means a major essential component (kernel, window system, and so on) of the specific operating system (if any) on which the executable work runs, or a compiler used to produce the work, or an object code interpreter used to run it.

The "Corresponding Source" for a work in object code form means all the source code needed to generate, install, and (for an executable work) run the object code and to modify the work, including scripts to control those activities. However, it does not include the work's System Libraries, or general-purpose tools or generally available free programs which are used unmodified in performing those activities but which are not part of the work. For example, Corresponding Source includes interface definition files associated with source files for the work, and the source code for shared libraries and dynamically linked subprograms that the work is specifically designed to require, such as by intimate data communication or control flow between those subprograms and other parts of the work.

The Corresponding Source need not include anything that users can regenerate automatically from other parts of the Corresponding Source.

The Corresponding Source for a work in source code form is that same work.

#### 2. Basic Permissions.

All rights granted under this License are granted for the term of copyright on the Program, and are irrevocable provided the stated conditions are met. This License explicitly affirms your unlimited permission to run the unmodified Program. The output from running a covered work is covered by this License only if the output, given its content, constitutes a covered work. This License acknowledges your rights of fair use or other equivalent, as provided by copyright law.

You may make, run and propagate covered works that you do not convey, without conditions so long as your license otherwise remains in force. You may convey covered works to others for the sole purpose of having them make modifications exclusively for you, or provide you with facilities for running those works, provided that you comply with the terms of this License in conveying all material for which you do not control copyright. Those thus making or running the covered works for you must do so exclusively on your behalf, under your direction and control, on terms that prohibit them from making any copies of your copyrighted material outside their relationship with you.

Conveying under any other circumstances is permitted solely under the conditions stated below. Sublicensing is not allowed; section 10



makes it unnecessary.

### 3. Protecting Users' Legal Rights From Anti-Circumvention Law.

No covered work shall be deemed part of an effective technological measure under any applicable law fulfilling obligations under article 11 of the WIPO copyright treaty adopted on 20 December 1996, or similar laws prohibiting or restricting circumvention of such measures.

When you convey a covered work, you waive any legal power to forbid circumvention of technological measures to the extent such circumvention is effected by exercising rights under this License with respect to the covered work, and you disclaim any intention to limit operation or modification of the work as a means of enforcing, against the work's users, your or third parties' legal rights to forbid circumvention of technological measures.

### 4. Conveying Verbatim Copies.

You may convey verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice; keep intact all notices stating that this License and any non-permissive terms added in accord with section 7 apply to the code; keep intact all notices of the absence of any warranty; and give all recipients a copy of this License along with the Program.

You may charge any price or no price for each copy that you convey, and you may offer support or warranty protection for a fee.

### 5. Conveying Modified Source Versions.

You may convey a work based on the Program, or the modifications to produce it from the Program, in the form of source code under the terms of section 4, provided that you also meet all of these conditions:

- a) The work must carry prominent notices stating that you modified it, and giving a relevant date.
- b) The work must carry prominent notices stating that it is released under this License and any conditions added under section 7. This requirement modifies the requirement in section 4 to "keep intact all notices".
- c) You must license the entire work, as a whole, under this License to anyone who comes into possession of a copy. This License will therefore apply, along with any applicable section 7 additional terms, to the whole of the work, and all its parts, regardless of how they are packaged. This License gives no permission to license the work in any other way, but it does not invalidate such permission if you have separately received it.
- d) If the work has interactive user interfaces, each must display Appropriate Legal Notices; however, if the Program has interactive interfaces that do not display Appropriate Legal Notices, your work need not make them do so.

A compilation of a covered work with other separate and independent works, which are not by their nature extensions of the covered work, and which are not combined with it such as to form a larger program, in or on a volume of a storage or distribution medium, is called an "aggregate" if the compilation and its resulting copyright are not used to limit the access or legal rights of the compilation's users beyond what the individual works permit. Inclusion of a covered work in an aggregate does not cause this License to apply to the other parts of the aggregate.

### 6. Conveying Non-Source Forms.

You may convey a covered work in object code form under the terms of sections 4 and 5, provided that you also convey the machine-readable Corresponding Source under the terms of this License, in one of these ways:

- a) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by the Corresponding Source fixed on a durable physical medium customarily used for software interchange.
- b) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by a written offer, valid for at least three years and valid for as long as you offer spare parts or customer support for that product model, to give anyone who possesses the object code either (1) a copy of the Corresponding Source for all the software in the product that is covered by this License, on a durable physical medium customarily used for software interchange, for a price no more than your reasonable cost of physically performing this conveying of source, or (2) access to copy the Corresponding Source from a network server at no charge.
- c) Convey individual copies of the object code with a copy of the written offer to provide the Corresponding Source. This alternative is allowed only occasionally and noncommercially, and only if you received the object code with such an offer, in accord with subsection 6b.
- d) Convey the object code by offering access from a designated place (gratis or for a charge), and offer equivalent access to the Corresponding Source in the same way through the same place at no further charge. You need not require recipients to copy the Corresponding Source along with the object code. If the place to copy the object code is a network server, the Corresponding Source may be on a different server (operated by you or a third party) that supports equivalent copying facilities, provided you maintain clear directions next to the object code saying where to find the Corresponding Source. Regardless of what server hosts the Corresponding Source, you remain obligated to ensure that it is available for as long as needed to satisfy these requirements.
- e) Convey the object code using peer-to-peer transmission, provided you inform other peers where the object code and Corresponding Source of the work are being offered to the general public at no charge under subsection 6d.

A separable portion of the object code, whose source code is excluded from the Corresponding Source as a System Library, need not be included in conveying the object code work.

A "User Product" is either (1) a "consumer product", which means any tangible personal property which is normally used for personal, family, or household purposes, or (2) anything designed or sold for incorporation into a dwelling. In determining whether a product is a consumer product, doubtful cases shall be resolved in favor of coverage. For a particular product received by a particular user, "normally used" refers to a typical or common use of that class of product, regardless of the status of the particular user or of the way in which the particular user actually uses, or expects or is expected to use, the product. A product is a consumer product regardless of whether the product has substantial commercial, industrial or non-consumer uses, unless such uses represent the only significant mode of use of the product.

"Installation Information" for a User Product means any methods, procedures, authorization keys, or other information required to install and execute modified versions of a covered work in that User Product from a modified version of its Corresponding Source. The information must suffice to ensure that the continued functioning of the modified object code is in no case prevented or interfered with solely because modification has been made.

If you convey an object code work under this section in, or with, or specifically for use in, a User Product, and the conveying occurs as part of a transaction in which the right of possession and use of the User Product is transferred to the recipient in perpetuity or for a fixed term (regardless of how the transaction is characterized), the Corresponding Source conveyed under this section must be accompanied by the Installation Information. But this requirement does not apply if neither you nor any third party retains the ability to install modified object code on the User Product (for example, the work has been installed in ROM).

The requirement to provide Installation Information does not include a requirement to continue to provide support service, warranty, or updates for a work that has been modified or installed by the recipient, or for the User Product in which it has been modified or installed. Access to a network may be denied when the modification itself materially and adversely affects the operation of the network or violates the rules and protocols for communication across the network.

Corresponding Source conveyed, and Installation Information provided, in accord with this section must be in a format that is publicly documented (and with an implementation available to the public in source code form), and must require no special password or key for unpacking, reading or copying.

#### 7. Additional Terms.

"Additional permissions" are terms that supplement the terms of this License by making exceptions from one or more of its conditions. Additional permissions that are applicable to the entire Program shall be treated as though they were included in this License, to the extent that they are valid under applicable law. If additional permissions apply only to part of the Program, that part may be used separately under those permissions, but the entire Program remains governed by this License without regard to the additional permissions.

When you convey a copy of a covered work, you may at your option remove any additional permissions from that copy, or from any part of it. (Additional permissions may be written to require their own removal in certain cases when you modify the work.) You may place additional permissions on material, added by you to a covered work, for which you have or can give appropriate copyright permission.

Notwithstanding any other provision of this License, for material you add to a covered work, you may (if authorized by the copyright holders of that material) supplement the terms of this License with terms:

- a) Disclaiming warranty or limiting liability differently from the terms of sections 15 and 16 of this License; or
- b) Requiring preservation of specified reasonable legal notices or author attributions in that material or in the Appropriate Legal Notices displayed by works containing it; or
- c) Prohibiting misrepresentation of the origin of that material, or requiring that modified versions of such material be marked in reasonable ways as different from the original version; or
- d) Limiting the use for publicity purposes of names of licensors or authors of the material; or
- e) Declining to grant rights under trademark law for use of some trade names, trademarks, or service marks; or
- f) Requiring indemnification of licensors and authors of that material by anyone who conveys the material (or modified versions of it) with contractual assumptions of liability to the recipient, for any liability that these contractual assumptions directly impose on those licensors and authors.

All other non-permissive additional terms are considered "further restrictions" within the meaning of section 10. If the Program as you received it, or any part of it, contains a notice stating that it is governed by this License along with a term that is a further restriction, you may remove that term. If a license document contains a further restriction but permits relicensing or conveying under this License, you may add to a covered work material governed by the terms of that license document, provided that the further restriction does not survive such relicensing or conveying.

If you add terms to a covered work in accord with this section, you must place, in the relevant source files, a statement of the additional terms that apply to those files, or a notice indicating where to find the applicable terms.

Additional terms, permissive or non-permissive, may be stated in the form of a separately written license, or stated as exceptions; the above requirements apply either way.

#### 8. Termination.

You may not propagate or modify a covered work except as expressly provided under this License. Any attempt otherwise to propagate or modify it is void, and will automatically terminate your rights under this License (including any patent licenses granted under the third paragraph of section 11).

However, if you cease all violation of this License, then your license from a particular copyright holder is reinstated (a) provisionally, unless and until the copyright holder explicitly and finally terminates your license, and (b) permanently, if the copyright holder fails to notify you of the violation by some reasonable means prior to 60 days after the cessation.

Moreover, your license from a particular copyright holder is reinstated permanently if the copyright holder notifies you of the violation by some reasonable means, this is the first time you have received notice of violation of this License (for any work) from that copyright holder, and you cure the violation prior to 30 days after your receipt of the notice.

Termination of your rights under this section does not terminate the licenses of parties who have received copies or rights from you under this License. If your rights have been terminated and not permanently reinstated, you do not qualify to receive new licenses for the same material under section 10.

#### 9. Acceptance Not Required for Having Copies.

You are not required to accept this License in order to receive or run a copy of the Program. Ancillary propagation of a covered work occurring solely as a consequence of using peer-to-peer transmission to receive a copy likewise does not require acceptance. However, nothing other than this License grants you permission to propagate or modify any covered work. These actions infringe copyright if you do not accept this License. Therefore, by modifying or propagating a covered work, you indicate your acceptance of this License to do so.

#### 10. Automatic Licensing of Downstream Recipients.

Each time you convey a covered work, the recipient automatically receives a license from the original licensors, to run, modify and propagate that work, subject to this License. You are not responsible for enforcing compliance by third parties with this License.

An "entity transaction" is a transaction transferring control of an organization, or substantially all assets of one, or subdividing an organization, or merging organizations. If propagation of a covered work results from an entity transaction, each party to that

transaction who receives a copy of the work also receives whatever licenses to the work the party's predecessor in interest had or could give under the previous paragraph, plus a right to possession of the Corresponding Source of the work from the predecessor in interest, if the predecessor has it or can get it with reasonable efforts.

You may not impose any further restrictions on the exercise of the rights granted or affirmed under this License. For example, you may not impose a license fee, royalty, or other charge for exercise of rights granted under this License, and you may not initiate litigation (including a cross-claim or counterclaim in a lawsuit) alleging that any patent claim is infringed by making, using, selling, offering for sale, or importing the Program or any portion of it.

#### 11. Patents.

A "contributor" is a copyright holder who authorizes use under this License of the Program or a work on which the Program is based. The work thus licensed is called the contributor's "contributor version".

A contributor's "essential patent claims" are all patent claims owned or controlled by the contributor, whether already acquired or hereafter acquired, that would be infringed by some manner, permitted by this License, of making, using, or selling its contributor version, but do not include claims that would be infringed only as a consequence of further modification of the contributor version. For purposes of this definition, "control" includes the right to grant patent sublicenses in a manner consistent with the requirements of this License.

Each contributor grants you a non-exclusive, worldwide, royalty-free patent license under the contributor's essential patent claims, to make, use, sell, offer for sale, import and otherwise run, modify and propagate the contents of its contributor version.

In the following three paragraphs, a "patent license" is any express agreement or commitment, however denominated, not to enforce a patent (such as an express permission to practice a patent or covenant not to sue for patent infringement). To "grant" such a patent license to a party means to make such an agreement or commitment not to enforce a patent against the party.

If you convey a covered work, knowingly relying on a patent license, and the Corresponding Source of the work is not available for anyone to copy, free of charge and under the terms of this License, through a publicly available network server or other readily accessible means, then you must either (1) cause the Corresponding Source to be so available, or (2) arrange to deprive yourself of the benefit of the patent license for this particular work, or (3) arrange, in a manner consistent with the requirements of this License, to extend the patent license to downstream recipients. "Knowingly relying" means you have actual knowledge that, but for the patent license, your conveying the covered work in a country, or your recipient's use of the covered work in a country, would infringe one or more identifiable patents in that country that you have reason to believe are valid.

If, pursuant to or in connection with a single transaction or arrangement, you convey, or propagate by procuring conveyance of, a covered work, and grant a patent license to some of the parties receiving the covered work authorizing them to use, propagate, modify or convey a specific copy of the covered work, then the patent license you grant is automatically extended to all recipients of the covered work and works based on it.

A patent license is "discriminatory" if it does not include within the scope of its coverage, prohibits the exercise of, or is conditioned on the non-exercise of one or more of the rights that are specifically granted under this License. You may not convey a covered work if you are a party to an arrangement with a third party that is in the business of distributing software, under which you make payment

to the third party based on the extent of your activity of conveying the work, and under which the third party grants, to any of the parties who would receive the covered work from you, a discriminatory patent license (a) in connection with copies of the covered work conveyed by you (or copies made from those copies), or (b) primarily for and in connection with specific products or compilations that contain the covered work, unless you entered into that arrangement, or that patent license was granted, prior to 28 March 2007.

Nothing in this License shall be construed as excluding or limiting any implied license or other defenses to infringement that may otherwise be available to you under applicable patent law.

#### 12. No Surrender of Others' Freedom.

If conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot convey a covered work so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not convey it at all. For example, if you agree to terms that obligate you to collect a royalty for further conveying from those to whom you convey the Program, the only way you could satisfy both those terms and this License would be to refrain entirely from conveying the Program.

#### 13. Use with the GNU Affero General Public License.

Notwithstanding any other provision of this License, you have permission to link or combine any covered work with a work licensed under version 3 of the GNU Affero General Public License into a single combined work, and to convey the resulting work. The terms of this License will continue to apply to the part which is the covered work, but the special requirements of the GNU Affero General Public License, section 13, concerning interaction through a network will apply to the combination as such.

#### 14. Revised Versions of this License.

The Free Software Foundation may publish revised and/or new versions of the GNU General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies that a certain numbered version of the GNU General Public License "or any later version" applies to it, you have the option of following the terms and conditions either of that numbered version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of the GNU General Public License, you may choose any version ever published by the Free Software Foundation.

If the Program specifies that a proxy can decide which future versions of the GNU General Public License can be used, that proxy's public statement of acceptance of a version permanently authorizes you to choose that version for the Program.

Later license versions may give you additional or different permissions. However, no additional obligations are imposed on any author or copyright holder as a result of your choosing to follow a later version.

#### 15. Disclaimer of Warranty.

THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM "AS IS" WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE PROGRAM

IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.

#### 16. Limitation of Liability.

IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MODIFIES AND/OR CONVEYS THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

#### 17. Interpretation of Sections 15 and 16.

If the disclaimer of warranty and limitation of liability provided above cannot be given local legal effect according to their terms, reviewing courts shall apply local law that most closely approximates an absolute waiver of all civil liability in connection with the Program, unless a warranty or assumption of liability accompanies a copy of the Program in return for a fee.

END OF TERMS AND CONDITIONS

#### How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively state the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

```
<one line to give the program's name and a brief idea of what it does.>
Copyright (C) <year> <name of author>
```

```
This program is free software: you can redistribute it and/or modify
it under the terms of the GNU General Public License as published by
the Free Software Foundation, either version 3 of the License, or
(at your option) any later version.
```

```
This program is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.
```

```
You should have received a copy of the GNU General Public License
along with this program. If not, see <https://www.gnu.org/licenses/>.
```

Also add information on how to contact you by electronic and paper mail.

If the program does terminal interaction, make it output a short notice like this when it starts in an interactive mode:

```
<program> Copyright (C) <year> <name of author>
This program comes with ABSOLUTELY NO WARRANTY; for details type `show w'.
This is free software, and you are welcome to redistribute it
under certain conditions; type `show c' for details.
```

The hypothetical commands `show w' and `show c' should show the appropriate parts of the General Public License. Of course, your program's commands might be different; for a GUI interface, you would use an "about box".

You should also get your employer (if you work as a programmer) or school, if any, to sign a "copyright disclaimer" for the program, if necessary. For more information on this, and how to apply and follow the GNU GPL, see

<<https://www.gnu.org/licenses/>>.

The GNU General Public License does not permit incorporating your program into proprietary programs. If your program is a subroutine library, you may consider it more useful to permit linking proprietary applications with the library. If this is what you want to do, use the GNU Lesser General Public License instead of this License. But first, please read <<https://www.gnu.org/licenses/why-not-lgpl.html>>.

## GPL 2.0

### GNU GENERAL PUBLIC LICENSE Version 2, June 1991

Copyright (C) 1989, 1991 Free Software Foundation, Inc.,  
51 Franklin Street, Fifth Floor, Boston, MA 02110-1301 USA  
Everyone is permitted to copy and distribute verbatim copies  
of this license document, but changing it is not allowed.

#### Preamble

The licenses for most software are designed to take away your freedom to share and change it. By contrast, the GNU General Public License is intended to guarantee your freedom to share and change free software--to make sure the software is free for all its users. This General Public License applies to most of the Free Software Foundation's software and to any other program whose authors commit to using it. (Some other Free Software Foundation software is covered by the GNU Lesser General Public License instead.) You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.

To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the software, or if you modify it.

For example, if you distribute copies of such a program, whether gratis or for a fee, you must give the recipients all the rights that you have. You must make sure that they, too, receive or can get the source code. And you must show them these terms so they know their rights.

We protect your rights with two steps: (1) copyright the software, and (2) offer you this license which gives you legal permission to copy, distribute and/or modify the software.

Also, for each author's protection and ours, we want to make certain that everyone understands that there is no warranty for this free software. If the software is modified by someone else and passed on, we want its recipients to know that what they have is not the original, so that any problems introduced by others will not reflect on the original authors' reputations.

Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that redistributors of a free program will individually obtain patent licenses, in effect making the program proprietary. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

The precise terms and conditions for copying, distribution and modification follow.



GNU GENERAL PUBLIC LICENSE  
TERMS AND CONDITIONS FOR COPYING, DISTRIBUTION AND MODIFICATION

0. This License applies to any program or other work which contains a notice placed by the copyright holder saying it may be distributed under the terms of this General Public License. The "Program", below, refers to any such program or work, and a "work based on the Program" means either the Program or any derivative work under copyright law: that is to say, a work containing the Program or a portion of it, either verbatim or with modifications and/or translated into another language. (Hereinafter, translation is included without limitation in the term "modification".) Each licensee is addressed as "you".

Activities other than copying, distribution and modification are not covered by this License; they are outside its scope. The act of running the Program is not restricted, and the output from the Program is covered only if its contents constitute a work based on the Program (independent of having been made by running the Program). Whether that is true depends on what the Program does.

1. You may copy and distribute verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice and disclaimer of warranty; keep intact all the notices that refer to this License and to the absence of any warranty; and give any other recipients of the Program a copy of this License along with the Program.

You may charge a fee for the physical act of transferring a copy, and you may at your option offer warranty protection in exchange for a fee.

2. You may modify your copy or copies of the Program or any portion of it, thus forming a work based on the Program, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:

- a) You must cause the modified files to carry prominent notices stating that you changed the files and the date of any change.
- b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License.
- c) If the modified program normally reads commands interactively when run, you must cause it, when started running for such interactive use in the most ordinary way, to print or display an announcement including an appropriate copyright notice and a notice that there is no warranty (or else, saying that you provide a warranty) and that users may redistribute the program under these conditions, and telling the user how to view a copy of this License. (Exception: if the Program itself is interactive but does not normally print such an announcement, your work based on the Program is not required to print an announcement.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Program, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Program, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Program.

In addition, mere aggregation of another work not based on the Program with the Program (or with a work based on the Program) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may copy and distribute the Program (or a work based on it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you also do one of the following:

- a) Accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
- b) Accompany it with a written offer, valid for at least three years, to give any third party, for a charge no more than your cost of physically performing source distribution, a complete machine-readable copy of the corresponding source code, to be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
- c) Accompany it with the information you received as to the offer to distribute corresponding source code. (This alternative is allowed only for noncommercial distribution and only if you received the program in object code or executable form with such an offer, in accord with Subsection b above.)

The source code for a work means the preferred form of the work for making modifications to it. For an executable work, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the executable. However, as a special exception, the source code distributed need not include anything that is normally distributed (in either source or binary form) with the major components (compiler, kernel, and so on) of the operating system on which the executable runs, unless that component itself accompanies the executable.

If distribution of executable or object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place counts as distribution of the source code, even though third parties are not compelled to copy the source along with the object code.

4. You may not copy, modify, sublicense, or distribute the Program except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense or distribute the Program is void, and will automatically terminate your rights under this License. However, parties who have received copies, or rights, from you under this License will not have their licenses terminated so long as such parties remain in full compliance.

5. You are not required to accept this License, since you have not signed it. However, nothing else grants you permission to modify or distribute the Program or its derivative works. These actions are prohibited by law if you do not accept this License. Therefore, by modifying or distributing the Program (or any work based on the Program), you indicate your acceptance of this License to do so, and all its terms and conditions for copying, distributing or modifying the Program or works based on it.

6. Each time you redistribute the Program (or any work based on the Program), the recipient automatically receives a license from the original licensor to copy, distribute or modify the Program subject to these terms and conditions. You may not impose any further restrictions on the recipients' exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.

7. If, as a consequence of a court judgment or allegation of patent infringement or for any other reason (not limited to patent issues),

conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot distribute so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not distribute the Program at all. For example, if a patent license would not permit royalty-free redistribution of the Program by all those who receive copies directly or indirectly through you, then the only way you could satisfy both it and this License would be to refrain entirely from distribution of the Program.

If any portion of this section is held invalid or unenforceable under any particular circumstance, the balance of the section is intended to apply and the section as a whole is intended to apply in other circumstances.

It is not the purpose of this section to induce you to infringe any patents or other property right claims or to contest validity of any such claims; this section has the sole purpose of protecting the integrity of the free software distribution system, which is implemented by public license practices. Many people have made generous contributions to the wide range of software distributed through that system in reliance on consistent application of that system; it is up to the author/donor to decide if he or she is willing to distribute software through any other system and a licensee cannot impose that choice.

This section is intended to make thoroughly clear what is believed to be a consequence of the rest of this License.

8. If the distribution and/or use of the Program is restricted in certain countries either by patents or by copyrighted interfaces, the original copyright holder who places the Program under this License may add an explicit geographical distribution limitation excluding those countries, so that distribution is permitted only in or among countries not thus excluded. In such case, this License incorporates the limitation as if written in the body of this License.

9. The Free Software Foundation may publish revised and/or new versions of the General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies a version number of this License which applies to it and "any later version", you have the option of following the terms and conditions either of that version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of this License, you may choose any version ever published by the Free Software Foundation.

10. If you wish to incorporate parts of the Program into other free programs whose distribution conditions are different, write to the author to ask for permission. For software which is copyrighted by the Free Software Foundation, write to the Free Software Foundation; we sometimes make exceptions for this. Our decision will be guided by the two goals of preserving the free status of all derivatives of our free software and of promoting the sharing and reuse of software generally.

#### NO WARRANTY

11. BECAUSE THE PROGRAM IS LICENSED FREE OF CHARGE, THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM "AS IS" WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.

12. IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MAY MODIFY AND/OR REDISTRIBUTE THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

#### END OF TERMS AND CONDITIONS

#### How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

```
<one line to give the program's name and a brief idea of what it does.>
Copyright (C) <year> <name of author>
```

```
This program is free software; you can redistribute it and/or modify
it under the terms of the GNU General Public License as published by
the Free Software Foundation; either version 2 of the License, or
(at your option) any later version.
```

```
This program is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.
```

```
You should have received a copy of the GNU General Public License along
with this program; if not, write to the Free Software Foundation, Inc.,
51 Franklin Street, Fifth Floor, Boston, MA 02110-1301 USA.
```

Also add information on how to contact you by electronic and paper mail.

If the program is interactive, make it output a short notice like this when it starts in an interactive mode:

```
Gnomovision version 69, Copyright (C) year name of author
Gnomovision comes with ABSOLUTELY NO WARRANTY; for details type `show w'.
This is free software, and you are welcome to redistribute it
under certain conditions; type `show c' for details.
```

The hypothetical commands `show w' and `show c' should show the appropriate parts of the General Public License. Of course, the commands you use may be called something other than `show w' and `show c'; they could even be mouse-clicks or menu items--whatever suits your program.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a "copyright disclaimer" for the program, if necessary. Here is a sample; alter the names:

```
Yoyodyne, Inc., hereby disclaims all copyright interest in the program
`Gnomovision' (which makes passes at compilers) written by James Hacker.
```

```
<signature of Ty Coon>, 1 April 1989
Ty Coon, President of Vice
```

This General Public License does not permit incorporating your program into proprietary programs. If your program is a subroutine library, you may consider it more useful to permit linking proprietary applications with the library. If this is what you want to do, use the GNU Lesser General

Public License instead of this License.

## Apache 2.0

Apache License  
Version 2.0, January 2004  
<http://www.apache.org/licenses/>

### TERMS AND CONDITIONS FOR USE, REPRODUCTION, AND DISTRIBUTION

#### 1. Definitions.

"License" shall mean the terms and conditions for use, reproduction, and distribution as defined by Sections 1 through 9 of this document.

"Licensor" shall mean the copyright owner or entity authorized by the copyright owner that is granting the License.

"Legal Entity" shall mean the union of the acting entity and all other entities that control, are controlled by, or are under common control with that entity. For the purposes of this definition, "control" means (i) the power, direct or indirect, to cause the direction or management of such entity, whether by contract or otherwise, or (ii) ownership of fifty percent (50%) or more of the outstanding shares, or (iii) beneficial ownership of such entity.

"You" (or "Your") shall mean an individual or Legal Entity exercising permissions granted by this License.

"Source" form shall mean the preferred form for making modifications, including but not limited to software source code, documentation source, and configuration files.

"Object" form shall mean any form resulting from mechanical transformation or translation of a Source form, including but not limited to compiled object code, generated documentation, and conversions to other media types.

"Work" shall mean the work of authorship, whether in Source or Object form, made available under the License, as indicated by a copyright notice that is included in or attached to the work (an example is provided in the Appendix below).

"Derivative Works" shall mean any work, whether in Source or Object form, that is based on (or derived from) the Work and for which the editorial revisions, annotations, elaborations, or other modifications represent, as a whole, an original work of authorship. For the purposes of this License, Derivative Works shall not include works that remain separable from, or merely link (or bind by name) to the interfaces of, the Work and Derivative Works thereof.

"Contribution" shall mean any work of authorship, including the original version of the Work and any modifications or additions to that Work or Derivative Works thereof, that is intentionally submitted to Licensor for inclusion in the Work by the copyright owner or by an individual or Legal Entity authorized to submit on behalf of the copyright owner. For the purposes of this definition, "submitted" means any form of electronic, verbal, or written communication sent to the Licensor or its representatives, including but not limited to communication on electronic mailing lists, source code control systems, and issue tracking systems that are managed by, or on behalf of, the Licensor for the purpose of discussing and improving the Work, but excluding communication that is conspicuously marked or otherwise designated in writing by the copyright owner as "Not a Contribution."

"Contributor" shall mean Licensor and any individual or Legal Entity on behalf of whom a Contribution has been received by Licensor and subsequently incorporated within the Work.

2. Grant of Copyright License. Subject to the terms and conditions of this License, each Contributor hereby grants to You a perpetual, worldwide, non-exclusive, no-charge, royalty-free, irrevocable copyright license to reproduce, prepare Derivative Works of, publicly display, publicly perform, sublicense, and distribute the Work and such Derivative Works in Source or Object form.
3. Grant of Patent License. Subject to the terms and conditions of this License, each Contributor hereby grants to You a perpetual, worldwide, non-exclusive, no-charge, royalty-free, irrevocable (except as stated in this section) patent license to make, have made, use, offer to sell, sell, import, and otherwise transfer the Work, where such license applies only to those patent claims licensable by such Contributor that are necessarily infringed by their Contribution(s) alone or by combination of their Contribution(s) with the Work to which such Contribution(s) was submitted. If You institute patent litigation against any entity (including a cross-claim or counterclaim in a lawsuit) alleging that the Work or a Contribution incorporated within the Work constitutes direct or contributory patent infringement, then any patent licenses granted to You under this License for that Work shall terminate as of the date such litigation is filed.
4. Redistribution. You may reproduce and distribute copies of the Work or Derivative Works thereof in any medium, with or without modifications, and in Source or Object form, provided that You meet the following conditions:
  - (a) You must give any other recipients of the Work or Derivative Works a copy of this License; and
  - (b) You must cause any modified files to carry prominent notices stating that You changed the files; and
  - (c) You must retain, in the Source form of any Derivative Works that You distribute, all copyright, patent, trademark, and attribution notices from the Source form of the Work, excluding those notices that do not pertain to any part of the Derivative Works; and
  - (d) If the Work includes a "NOTICE" text file as part of its distribution, then any Derivative Works that You distribute must include a readable copy of the attribution notices contained within such NOTICE file, excluding those notices that do not pertain to any part of the Derivative Works, in at least one of the following places: within a NOTICE text file distributed as part of the Derivative Works; within the Source form or documentation, if provided along with the Derivative Works; or, within a display generated by the Derivative Works, if and wherever such third-party notices normally appear. The contents of the NOTICE file are for informational purposes only and do not modify the License. You may add Your own attribution notices within Derivative Works that You distribute, alongside or as an addendum to the NOTICE text from the Work, provided that such additional attribution notices cannot be construed as modifying the License.

You may add Your own copyright statement to Your modifications and may provide additional or different license terms and conditions for use, reproduction, or distribution of Your modifications, or for any such Derivative Works as a whole, provided Your use, reproduction, and distribution of the Work otherwise complies with the conditions stated in this License.
5. Submission of Contributions. Unless You explicitly state otherwise, any Contribution intentionally submitted for inclusion in the Work by You to the Licensor shall be under the terms and conditions of this License, without any additional terms or conditions. Notwithstanding the above, nothing herein shall supersede or modify the terms of any separate license agreement you may have executed

with Licensor regarding such Contributions.

6. Trademarks. This License does not grant permission to use the trade names, trademarks, service marks, or product names of the Licensor, except as required for reasonable and customary use in describing the origin of the Work and reproducing the content of the NOTICE file.
7. Disclaimer of Warranty. Unless required by applicable law or agreed to in writing, Licensor provides the Work (and each Contributor provides its Contributions) on an "AS IS" BASIS, WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied, including, without limitation, any warranties or conditions of TITLE, NON-INFRINGEMENT, MERCHANTABILITY, or FITNESS FOR A PARTICULAR PURPOSE. You are solely responsible for determining the appropriateness of using or redistributing the Work and assume any risks associated with Your exercise of permissions under this License.
8. Limitation of Liability. In no event and under no legal theory, whether in tort (including negligence), contract, or otherwise, unless required by applicable law (such as deliberate and grossly negligent acts) or agreed to in writing, shall any Contributor be liable to You for damages, including any direct, indirect, special, incidental, or consequential damages of any character arising as a result of this License or out of the use or inability to use the Work (including but not limited to damages for loss of goodwill, work stoppage, computer failure or malfunction, or any and all other commercial damages or losses), even if such Contributor has been advised of the possibility of such damages.
9. Accepting Warranty or Additional Liability. While redistributing the Work or Derivative Works thereof, You may choose to offer, and charge a fee for, acceptance of support, warranty, indemnity, or other liability obligations and/or rights consistent with this License. However, in accepting such obligations, You may act only on Your own behalf and on Your sole responsibility, not on behalf of any other Contributor, and only if You agree to indemnify, defend, and hold each Contributor harmless for any liability incurred by, or claims asserted against, such Contributor by reason of your accepting any such warranty or additional liability.

END OF TERMS AND CONDITIONS

APPENDIX: How to apply the Apache License to your work.

To apply the Apache License to your work, attach the following boilerplate notice, with the fields enclosed by brackets "[]" replaced with your own identifying information. (Don't include the brackets!) The text should be enclosed in the appropriate comment syntax for the file format. We also recommend that a file or class name and description of purpose be included on the same "printed page" as the copyright notice for easier identification within third-party archives.

Copyright [yyyy] [name of copyright owner]

Licensed under the Apache License, Version 2.0 (the "License");  
you may not use this file except in compliance with the License.  
You may obtain a copy of the License at

<http://www.apache.org/licenses/LICENSE-2.0>

Unless required by applicable law or agreed to in writing, software distributed under the License is distributed on an "AS IS" BASIS, WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied. See the License for the specific language governing permissions and limitations under the License.

**BSL 1.0**

Boost Software License - Version 1.0 - August 17th, 2003

Permission is hereby granted, free of charge, to any person or organization obtaining a copy of the software and accompanying documentation covered by this license (the "Software") to use, reproduce, display, distribute, execute, and transmit the Software, and to prepare derivative works of the Software, and to permit third-parties to whom the Software is furnished to do so, all subject to the following:

The copyright notices in the Software and this entire statement, including the above license grant, this restriction and the following disclaimer, must be included in all copies of the Software, in whole or in part, and all derivative works of the Software, unless such copies or derivative works are solely in the form of machine-executable object code generated by a source language processor.

THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, TITLE AND NON-INFRINGEMENT. IN NO EVENT SHALL THE COPYRIGHT HOLDERS OR ANYONE DISTRIBUTING THE SOFTWARE BE LIABLE FOR ANY DAMAGES OR OTHER LIABILITY, WHETHER IN CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

#### BSD 2.0

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

- \* Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
- \* Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.
- \* Neither the name of the <organization> nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS "AS IS" AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL <COPYRIGHT HOLDER> BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

#### MIT

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the "Software"), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.

THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NON-INFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

#### FTL



## The FreeType Project LICENSE

2006-Jan-27

Copyright 1996-2002, 2006 by  
David Turner, Robert Wilhelm, and Werner Lemberg

## Introduction

=====

The FreeType Project is distributed in several archive packages; some of them may contain, in addition to the FreeType font engine, various tools and contributions which rely on, or relate to, the FreeType Project.

This license applies to all files found in such packages, and which do not fall under their own explicit license. The license affects thus the FreeType font engine, the test programs, documentation and makefiles, at the very least.

This license was inspired by the BSD, Artistic, and IJG (Independent JPEG Group) licenses, which all encourage inclusion and use of free software in commercial and freeware products alike. As a consequence, its main points are that:

- o We don't promise that this software works. However, we will be interested in any kind of bug reports. ('as is' distribution)
- o You can use this software for whatever you want, in parts or full form, without having to pay us. ('royalty-free' usage)
- o You may not pretend that you wrote this software. If you use it, or only parts of it, in a program, you must acknowledge somewhere in your documentation that you have used the FreeType code. ('credits')

We specifically permit and encourage the inclusion of this software, with or without modifications, in commercial products. We disclaim all warranties covering The FreeType Project and assume no liability related to The FreeType Project.

Finally, many people asked us for a preferred form for a credit/disclaimer to use in compliance with this license. We thus encourage you to use the following text:

"""

Portions of this software are copyright © <year> The FreeType Project (www.freetype.org). All rights reserved.

"""

Please replace <year> with the value from the FreeType version you actually use.

## Legal Terms

=====

## 0. Definitions

-----

Throughout this license, the terms 'package', 'FreeType Project', and 'FreeType archive' refer to the set of files originally distributed by the authors (David Turner, Robert Wilhelm, and Werner Lemberg) as the 'FreeType Project', be they named as alpha, beta or final release.

'You' refers to the licensee, or person using the project, where 'using' is a generic term including compiling the project's source code as well as linking it to form a 'program' or 'executable'. This program is referred to as 'a program using the FreeType engine'.

This license applies to all files distributed in the original FreeType Project, including all source code, binaries and documentation, unless otherwise stated in the file in its original, unmodified form as distributed in the original archive. If you are unsure whether or not a particular file is covered by this license, you must contact us to verify this.

The FreeType Project is copyright (C) 1996-2000 by David Turner, Robert Wilhelm, and Werner Lemberg. All rights reserved except as specified below.

### 1. No Warranty

-----

THE FREETYPE PROJECT IS PROVIDED 'AS IS' WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. IN NO EVENT WILL ANY OF THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY DAMAGES CAUSED BY THE USE OR THE INABILITY TO USE, OF THE FREETYPE PROJECT.

### 2. Redistribution

-----

This license grants a worldwide, royalty-free, perpetual and irrevocable right and license to use, execute, perform, compile, display, copy, create derivative works of, distribute and sublicense the FreeType Project (in both source and object code forms) and derivative works thereof for any purpose; and to authorize others to exercise some or all of the rights granted herein, subject to the following conditions:

- o Redistribution of source code must retain this license file ('FTL.TXT') unaltered; any additions, deletions or changes to the original files must be clearly indicated in accompanying documentation. The copyright notices of the unaltered, original files must be preserved in all copies of source files.
- o Redistribution in binary form must provide a disclaimer that states that the software is based in part of the work of the FreeType Team, in the distribution documentation. We also encourage you to put an URL to the FreeType web page in your documentation, though this isn't mandatory.

These conditions apply to any software derived from or based on the FreeType Project, not just the unmodified files. If you use our work, you must acknowledge us. However, no fee need be paid to us.

### 3. Advertising

-----

Neither the FreeType authors and contributors nor you shall use the name of the other for commercial, advertising, or promotional purposes without specific prior written permission.

We suggest, but do not require, that you use one or more of the following phrases to refer to this software in your documentation or advertising materials: 'FreeType Project', 'FreeType Engine', 'FreeType library', or 'FreeType Distribution'.

As you have not signed this license, you are not required to accept it. However, as the FreeType Project is copyrighted

material, only this license, or another one contracted with the authors, grants you the right to use, distribute, and modify it. Therefore, by using, distributing, or modifying the FreeType Project, you indicate that you understand and accept all the terms of this license.

#### 4. Contacts

-----

There are two mailing lists related to FreeType:

- o `freetype@nongnu.org`

Discusses general use and applications of FreeType, as well as future and wanted additions to the library and distribution. If you are looking for support, start in this list if you haven't found anything to help you in the documentation.

- o `freetype-devel@nongnu.org`

Discusses bugs, as well as engine internals, design issues, specific licenses, porting, etc.

Our home page can be found at

`https://www.freetype.org`