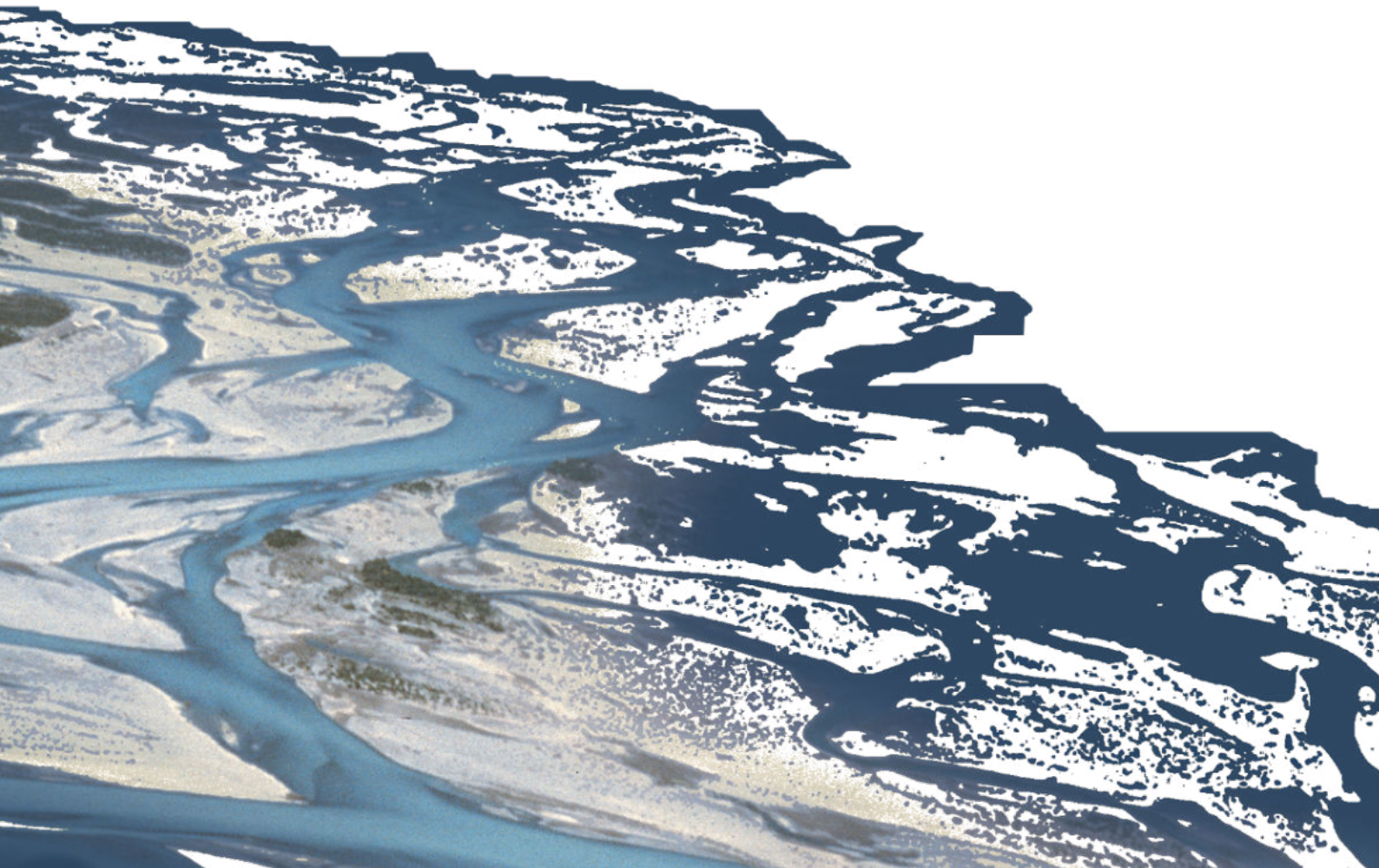
BASEMENT

BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

SYSTEM MANUALS

VERSION 4.1.0
JUNE 2024



Preamble

VERSION 4.1.0

June 2024

Credits

Contributors

Over the years, many enthusiastic engineers and developers have contributed to the development, testing and documentation of BASEMENT. An up-to-date overview of the current development team, along with current and former contributors, can be found on our website:

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For Software:

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BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

USER MANUAL

VERSION 4.1.0
JUNE 2024

Contents

1

Basic Simulation Environment

1.1 Introduction

The software system BASEMENT (BAsic-Simulation-EnvironMENT) provides a functional environment for numerical simulation of river flows with sediment transport in alpine and sub-alpine regions. The main focus of conception and development is the robustness of the numerical models, the flexibility of the computational grid and the combination and efficiency of the method of calculation (problem dependent equations, coupling of models, parallelization).

BASEMENT version 4 consists of two main modules (Figure 1.1), namely BASEMD (MD stands for Multi Domain) and BASEHPC (HPC stands for High Performance Computing, based on the possibility to use GPGPUs). The BASEMD module contains the three simulation submodules BASEchain (1D open-channel flow), BASEplane (2D open-channel flow), BASEsub (3D subsurface flow) and allows for submodule coupling. Further, there is the BASEextern submodule for simulation data exchange during runtime. The BASEHPC module contains only the BASEplane submodule which has a simpler spatial discretization but improved performance compared to BASEMD::BASEplane. The software provides a unified simulation workflow and graphic user interface (GUI) for setting up numerical models with the two modules. # Main Features

The three submodules of the BASEMD module offer a wide range of different modelling features originating from more than 20 years of model development. Both modules BASEMD and BASEHPC have a submdule BASEPLANE but the BASEHPC::BASEPLANE submodule is tuned for performance using GPGPUs. The two main modules contain all the features of the two previous versions 2.8.2 (BASEMD) and 3.2 (BASEHPC). Table 1.1 gives an overview of the various features of both modules.

Table 1.1 *List of BASEMENT main features*

Feature	**BASEMD**	**BASEHPC**
1-D model	✓	
2-D model	✓	✓

Feature	**BASEMD**	**BASEHPC**
Hydrodynamics	✓	✓
Morphodynamics:		
- Bed load	✓	✓
- Suspended load	✓	✓
Tracer advection		✓
External sub-domain	✓	
Model coupling (multi domain)	✓	
Controller	✓	
Subsurface flow	✓	
Vegetation	✓	✓
Water temperature		✓
SMP hardware	✓	✓
GPU/HPC support		✓

1.2 General Use

1.2.1 Problem Description

In connection with watercourses and river scapes, increasingly complex problems have to be addressed. The assessment of flood risk, the more frequent planning of river 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 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 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.

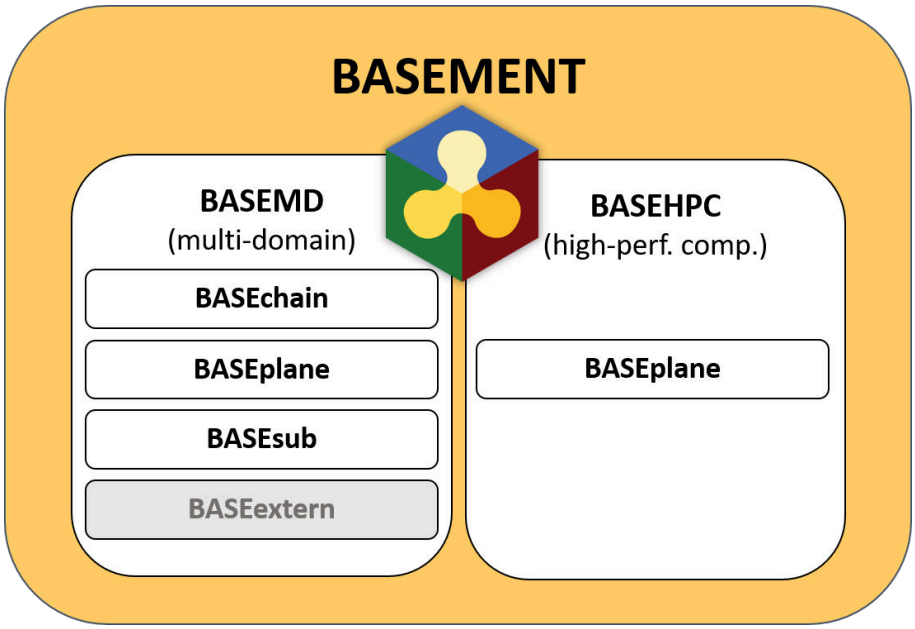

Figure 1.1 *Overview of BASEMENT modules*

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 related 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 risk 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.
- Ecohydraulic application, such as habitat modelling

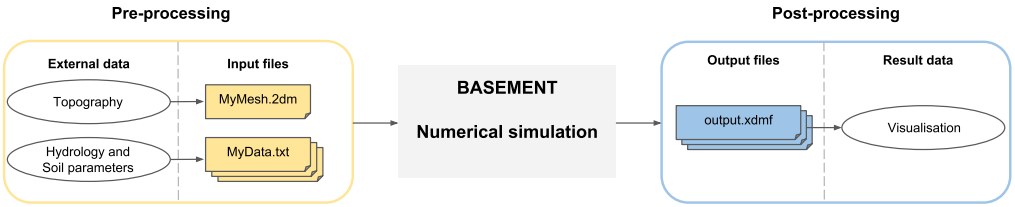

Figure 1.2 *Overview of the modelling procedure with BASEMENT*

1.3 Modelling Procedure

The modelling procedure involves three stages: the pre-processing, the simulation and the post-processing (Figure 1.2). A project is usually 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. It is recommended to organize your files in different directories, considering static and varying input data of the scenarios.

1.3.1 Pre-processing

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 characterized 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.

1.3.1.1 Topographical data

The numerical methods used in BASEMENT are based on a discretization of the domain topography into river cross sections (for 1D model) or using an unstructured mesh consisting of triangular elements (for 2D models). 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. The procedure to setup computational meshes for BASEMENT is introduced in Section 2.0.1.

1.3.1.2 Hydrological data

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 1.2). 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.

1.3.1.3 Sediment data

The river bed is characterized by a porosity and a mean grain size diameter (m) determined from sediment or line samples. In BASEHPC, 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.

1.3.1.4 Dissolved species data

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.

1.3.2 Simulation

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 3.

1.3.3 Postprocessing

1.3.3.1 Output Files

The BASEMD::BASEchain and BASEMD:BASEplane models provide different output variables and formats. BASEchain results are in ASCII format in tabular form ready to drag and drop to spread sheet software. BASEplane results are stored in a binary HDF file format (.h5) to be converted to xdmf format using the result binary of the simulation workflow. Available output variables and formats are summarized in the "Introduction and Installation" part of the manual.

1.3.3.2 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 1.2) 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".

2

Grid Generation

2.0.1 General

Computational meshes must be generated to perform numerical simulations with the 1D (BASEMD::BASEchain) or 2D (BASEMD::BASEplane or BASEHPC::BASEplane) models. For BASEchain, the computational mesh consist of river cross sections. River cross section geometry data can be imported from survey data, generated by tools or defined by hand (see Section 2.1). For BASEplane, an unstructured mesh consisting of triangular elements must be generated. For that purpose, BASEMENT provides the tool BASEmesh (Section 2.2) but other grid generation software may work as well.

2.1 1D grid generation

2.1.1 The "BASEMENT 1D Grid File Editor"

The 1D grid file editor of BASEMENT is integrated into the GUI of version 4 (Tools-menu) and can be used to create or adjust computational grids for BASEchain. If you have an existing 1D grid from HEC-RAS or in GEWISS format, please refer to the conversion tools provided on the BASEMENT website (basement.ethz.ch/download/tools). If you would like to create a 1D grid from scratch, we suggest to use the tool BASEchange from the BASEmesh package.

2.1.2 Edit Existing Geometry File

After opening a 1D grid file with the 1D Grid File Editor (see Figure 2.1), in the left part of the window a list of all cross sections is shown where the cross sections can be seen and selected. In the right part of the window a visualization of the whole subdomain with all cross sections is drawn and new cross sections can be created with the *Add Block* option. The subdomain view allows zooming and shifting of the display and the selection of a

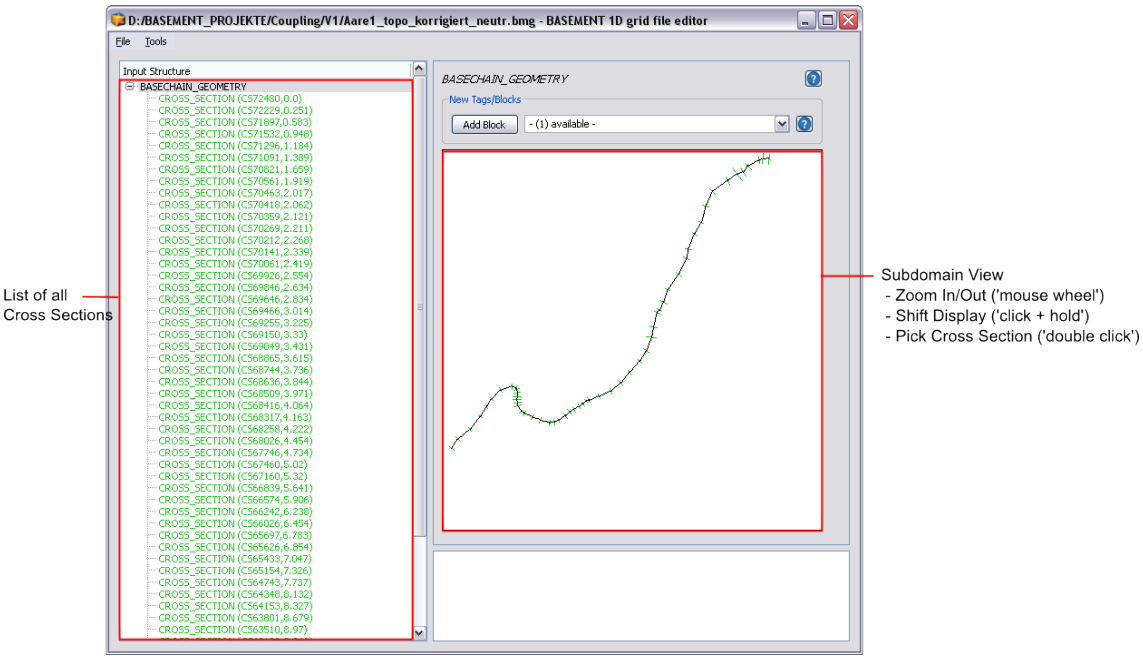

Figure 2.1 *Grid File Editor – Subdomain View*

specific cross section by double clicking. If a cross section is selected then the view changes to the cross section view.

The real (usually curved) shape of the stream can only be illustrated if all cross sections are geo-referenced and if all corresponding data is set (the *orientation_angle* and the *left_point_global_coordinates* must be set for each cross section). If these data are not given than the cross sections are drawn along a straight line.

2.1.3 Create New of Edit Cross Section Data

If a specific cross section is selected or a new cross section is created, than a profile view of the selected cross section is shown (see Figure 2.2). With this visualization of the profile one can easily check for input errors in the geometrical definition of the cross section profile. Furthermore, the most important cross section parameters are indicated visually with different colours, like e.g. the definition of the main channel, the range of the soils, the friction parameters, the cross section fixpoints, etc. Again, one can visually check if these parameters are set up correctly and thus easily detect type errors. New input tags can be added and the validation message box shows warnings or errors if some problematic inputs have been made.

For details on how to set up a new cross section and for information about the various cross section parameters see the 1D tutorial, hydrodynamics and sediment transport at the river Thur.

2.1.4 Tools

BASEMENT supports several tools which support the user in creating and modifying the 1D grid file. In the following sections some information about the usage and the methods

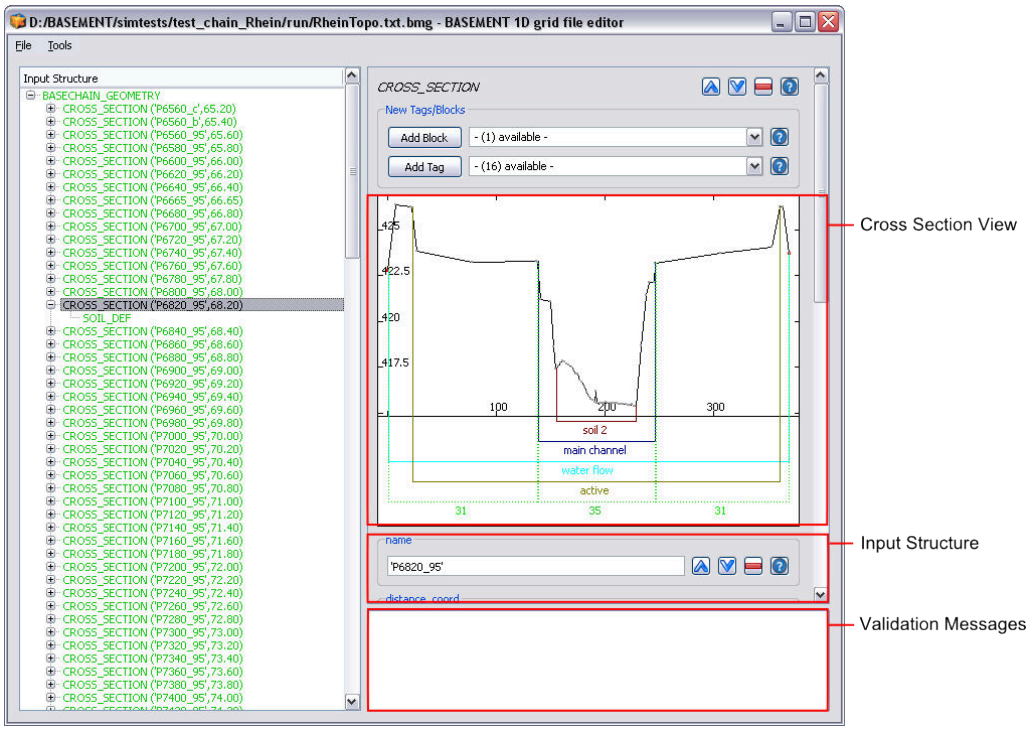

Figure 2.2 *Grid File Editor – Cross Section View*

of these tools are given. Please be aware that some of the offered tools are still in a beta-status.

2.1.4.1 Edit Raw

Another way to edit a grid file is to edit the grid file in raw text mode. For this purpose choose *Tools* on the menu bar and select *Edit Raw*. The Editor window will pop up as shown in Figure 2.3. In the lower part of the window the Input is validated and possible parse errors are indicated. For the sake of completeness it is mentioned here that the grid file can still be built up and edited with a simple text editor.

2.1.4.2 Friction

With this tool (see Figure 2.4) the friction value of the main channel, the forelands and the bottom can be assigned to a range of consecutive cross sections. The names of the first and the last cross section of the range have to be given.

2.1.4.3 Remove Nodes

Cross sections often consist of a large number of nodes and slices which consumes significant computational performance. If multiple nodes lie on a straight line within the cross section there is redundant information present which can be removed without reducing the accuracy of the computations. Therefore identifying and removing these redundant nodes is a frequent and recommended task before running the simulations. BASEMENT offers a tool which performs this task automatically without need for costly manual operations.

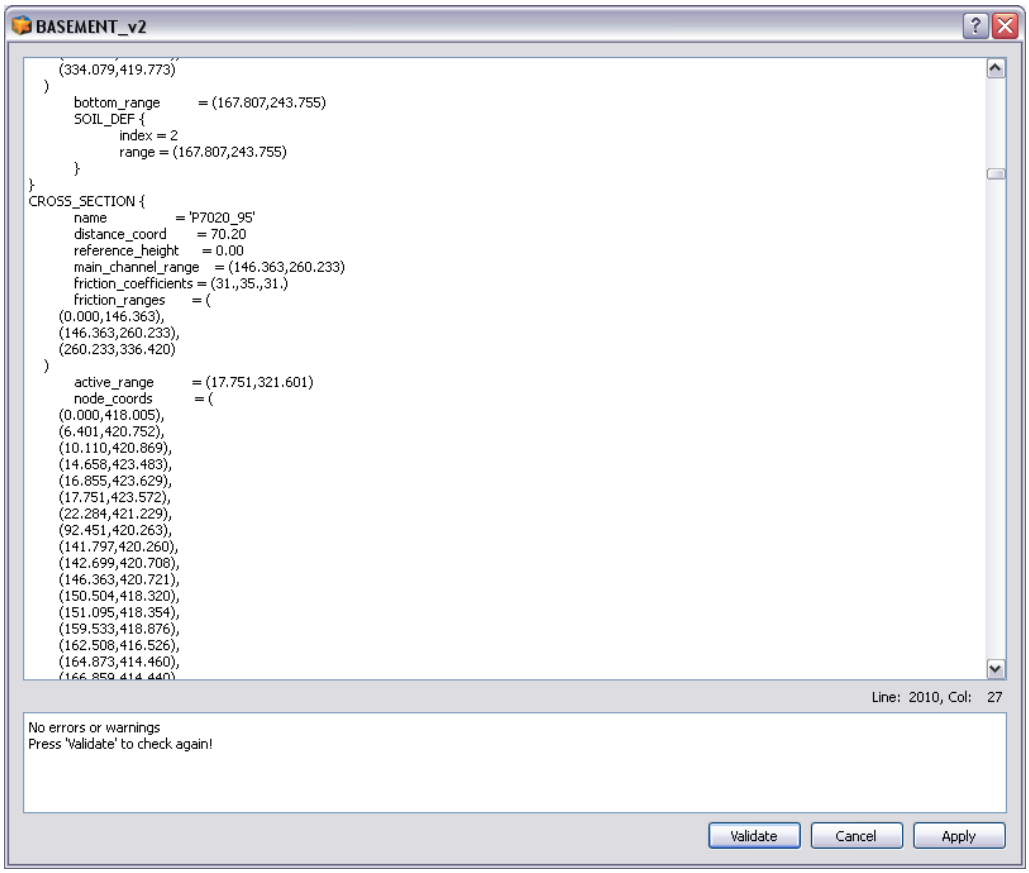

Figure 2.3 *Grid File Editor: Raw Edit Window*

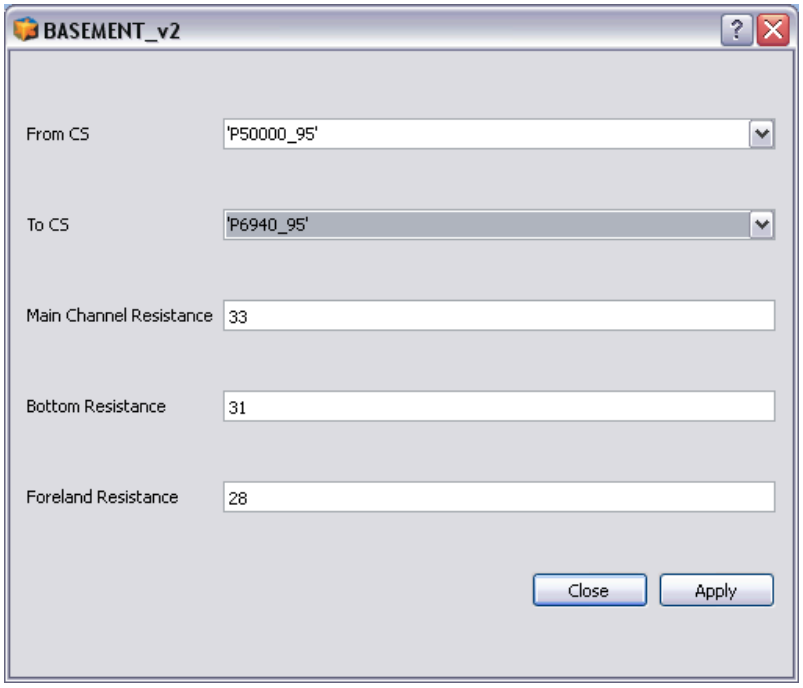

Figure 2.4 *Friction assignment*

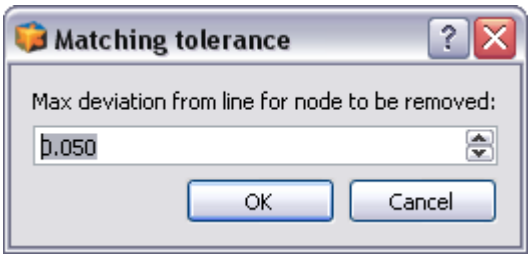

Figure 2.5 *Node removal dialog for setting up the tolerance*

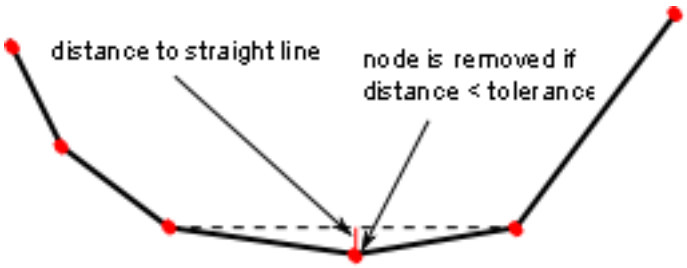

Figure 2.6 *Schematic sketch of node removal*

To access this tool open the *Tools* menu and click on the *Remove nodes option*. The dialog opens as shown in Figure 2.5:

In this dialog you can define the maximum tolerance by which a node may deviate from the straight line of its two neighbours. If the node lies within this tolerance the node removal is applied. If you set the tolerance to small values only nodes are removed which are almost exactly situated on the line. If you increase the tolerance more nodes will be removed but some more information about the cross section profile may get lost. Usually one should try different tolerances until the best compromise between computational performance and accuracy is found. Also, the algorithm can be applied multiple times.

The applied algorithm loops all nodes of the cross sections and checks if a node is situated on a straight line between its two neighboured nodes (considering the given tolerance). If this is the case the node is removed from the profile (see Figure 2.6). Nodes which are used as fixpoint or which are explicitly referenced by a slice_index range are excluded from the algorithm and cannot be removed automatically.

Guess Active Range

This tool provides a definition of the active range where it is not yet defined. For this purpose the lowest point of the cross section is searched and then the highest points to the left and the right of it (usually the dam crests) are set as limits of the active range. The definition of the active range can always be changed manually by the user in the interface. As an example on how the active range is set see Figure 2.7.

2.1.4.4 Guess Fixpoints

This tool provides the definition of some fix points, which are needed for a correct interpolation of new cross sections between existing cross sections. So this should be done before an interpolation is executed. The fix points are displayed in red. The points which are automatically set as fix points are:

- The limits of soils

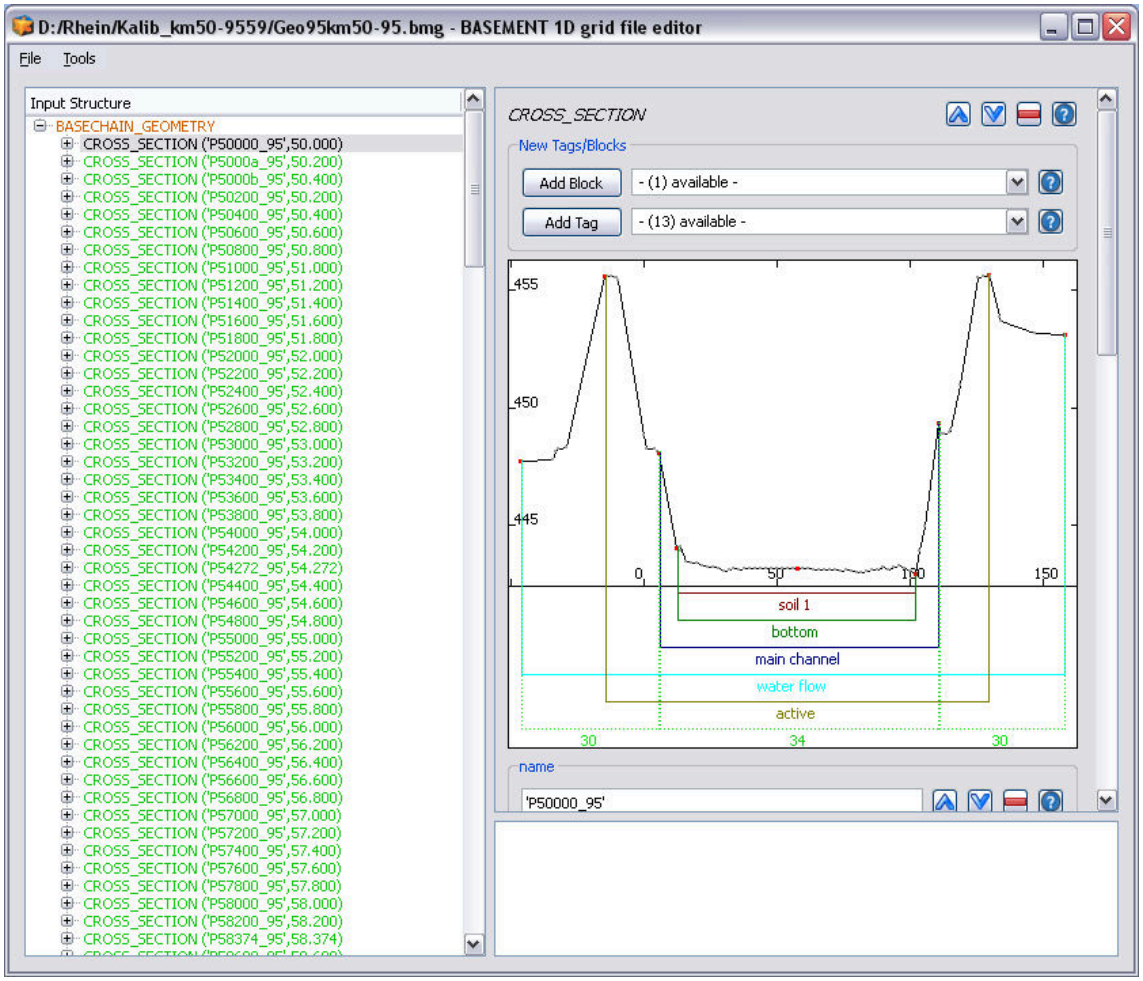

Figure 2.7 *In red the guessed fix points for cross section interpolation*

- The limits of the main channel
- The limits of the active range
- The midpoint of the main channel.

It is recommended to check the points visually and add other important points, especially on the break lines. For the interpolation all involved cross sections must have the same number of fix points.

2.1.4.5 Interpolation

First of all, before an interpolation of 1-D cross sections can be performed some information is needed about the spatial alignment of all cross sections in the x-y plane.

There are two main tags which determine the spatial orientation of the cross section which are crucial for the interpolation algorithm. The *orientation_angle* provides the information which is needed for the orientation of the cross sections. This is the angle between the normal vector of the cross section and the vector in x-direction (1,0). Consequently, in a fully straight channel in x-direction all cross sections would have the angle 0°. If the orientation angle is not given it is set to this value. The other essential tag is the

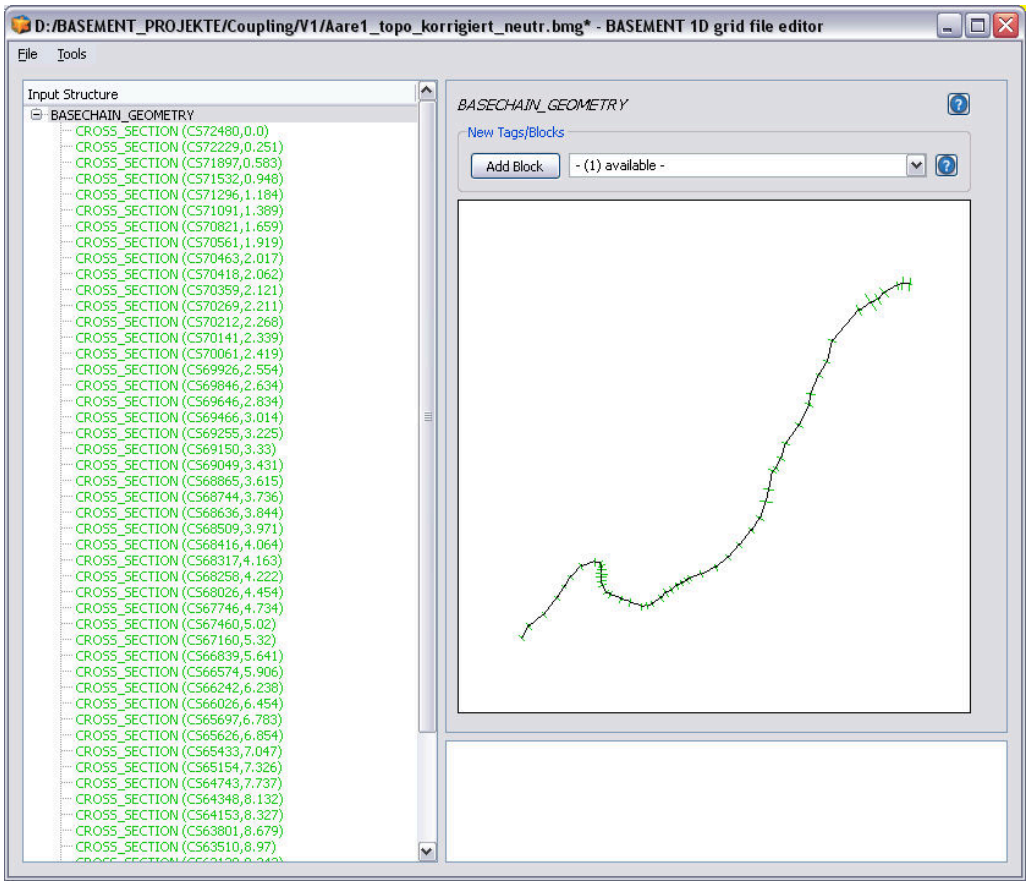

Figure 2.8 *Curved alignment of the cross sections.*

left_point_global_coordinates. This parameter sets the global (real world) x,y,z-coordinates of the outer left point of the cross section. This parameter in combination with the orientation angle delivers all needed information about the spatial configuration of the cross section. If this coordinates are not given the value of *distance_coord* is used for x and the elevation of the first point on the left for z. y is set to negative distance of the first point on the left from the middle of the cross section. If both parameters are set for all cross sections, one can see the curved alignment of the stream in the right-hand visualization (see Figure 2.8).

The algorithm of the cross section interpolation is briefly sketched in the following. To grasp the meaning of the different parameters it is helpful to understand the basics of this interpolation algorithm.

This interpolation algorithm bases on the creation of spline curves (a spline is a special polynomial function which is often used for smooth interpolations between given points). For each fixpoint of the cross sections such a spline curve is determined which connects all the corresponding fixpoints with each other in a smooth way. Therefore every cross section must have the same number of fix points. Furthermore, the spline curves have the special property that they are aligned orthogonal to each cross section profile.

After the spline curves have been calculated, the positions of the new interpolated cross sections are determined in given intervals along the spline curves. As soon as these positions are known, the cross sections are created orthogonal to the tangent direction of the master spline. To determine the fixpoints of the new cross sections the intersections

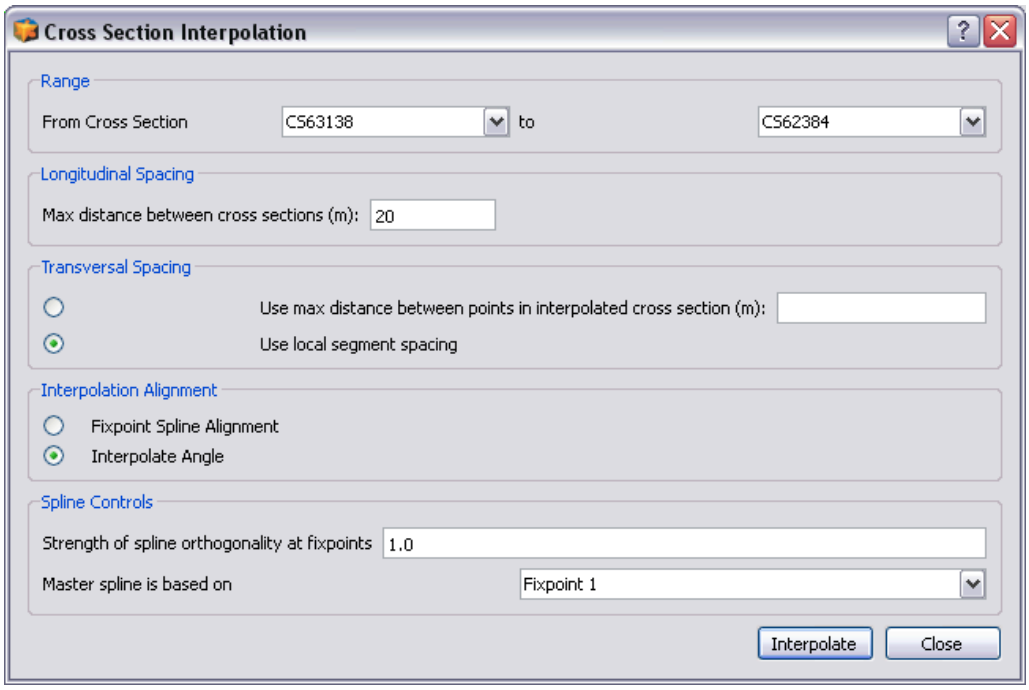

Figure 2.9 *Setup dialog for the cross section interpolation*

of this orthogonal cross section line with all spline curves (of the other fixpoints) are calculated. Finally the new cross section points are determined in between the fixpoints in a given transversal distance interval. The elevations of the cross section points are finally determined using a weighting procedure between the elevations of the left and the right cross section.

In Figure 2.9 the setup dialog for the interpolation is shown. The different parameters are explained briefly in the following. By clicking on *Interpolate* the interpolation of the cross sections finally starts if all data is available.

First of all the *Range* of the interpolation must be defined. This is done by specifying two subsequent cross sections which are chosen from a list of all existing cross sections in the drop down menus.

Another important parameter is the *Longitudinal spacing* which determines the resolution of the interpolated grid. Enter the maximum distance between two interpolated cross sections in [m]. If you choose a small value than many cross sections in small distances will be generated, if you choose a large value only few cross sections in large distances will be generated. The optimal choice depends on the type of simulation.

Furthermore, also the *Transversal spacing* can be specified. It determines the spacing of the points in the newly generated cross section profile. There are two possible choices here two determine the transversal spacing. You can either explicitly specify the maximum distance in [m] using the first option. Alternatively, by using the second option, the distance is chosen automatically from the left and right cross sections by the interpolation algorithm *(local segment spacing)*.

The alignment of the new cross sections in the x-y plane can be determined with two different methods in the *Interpolation Alignment section*. The *Fixpoint Spline Alignment* means that the cross sections are always oriented orthogonal to the master spline's tangent direction. Alternatively, by using the option *Interpolate Angle* the orientation of the new

cross section is determined by interpolation of the orientation angles of the left and the right cross sections. This latter option is recommended in strongly curved streams in order to prevent overlapping cross sections.

Finally in the *Spline controls* section some parameters of the spline calculations can be adapted to special needs. The *Strength of spline orthogonality* parameter determines if the spline always must be completely orthogonal to the cross sections or not. In strongly curved streams some relaxation from strict orthogonality (different from 1.0) may lead to nicer shaped spline curves. Some variations and iterative testing with this parameter may improve the interpolation result in such situations. Finally, also the fixpoint that determines the master spline can be chosen. The master spline thereby is the spline which determines the orientation of the interpolated cross sections.

Please note: In order to generate a 2D mesh from a given 1D mesh, this interpolation option can be very helpful in combination with the *Export DTM* option.

2.1.4.6 Export DTM for BASEplane

This tool enables the user to convert a 1-D BASECHAIN_GEOMETRY (Figure 2.10) into a digital terrain model (DTM) for further processing in SMS and BASEplane. The main application for this tool is to be found in combination with the Interpolation tool (see Section 2.1.4.5): In a first step the cross sections are interpolated with the Interpolation tool in order to get a smooth river topography. In a next step the DTM is exported with the *Export DTM for BASEplane* tool (on the menu bar choose *Tools*). The generated DTM can be imported in SMS. Although the file is of .2dm type it can be easily converted into scatter points (DTM) in SMS. Then it can be used for the interpolation of the elevation information on any computational mesh.

Basically a computational mesh can be obtained directly from the *Export DTM for BASEplane* tool, if the interpolated cross sections are chosen in a close and optimal distance to each other. Nevertheless it is suggested to generate the mesh properly in SMS and to consider the generated DTM just as a terrain model from which to get the elevation information.

2.2 2D grid generation with BASEmesh QGIS plugin

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 BASEMD and BASEHPC, 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.

2.2.1 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.

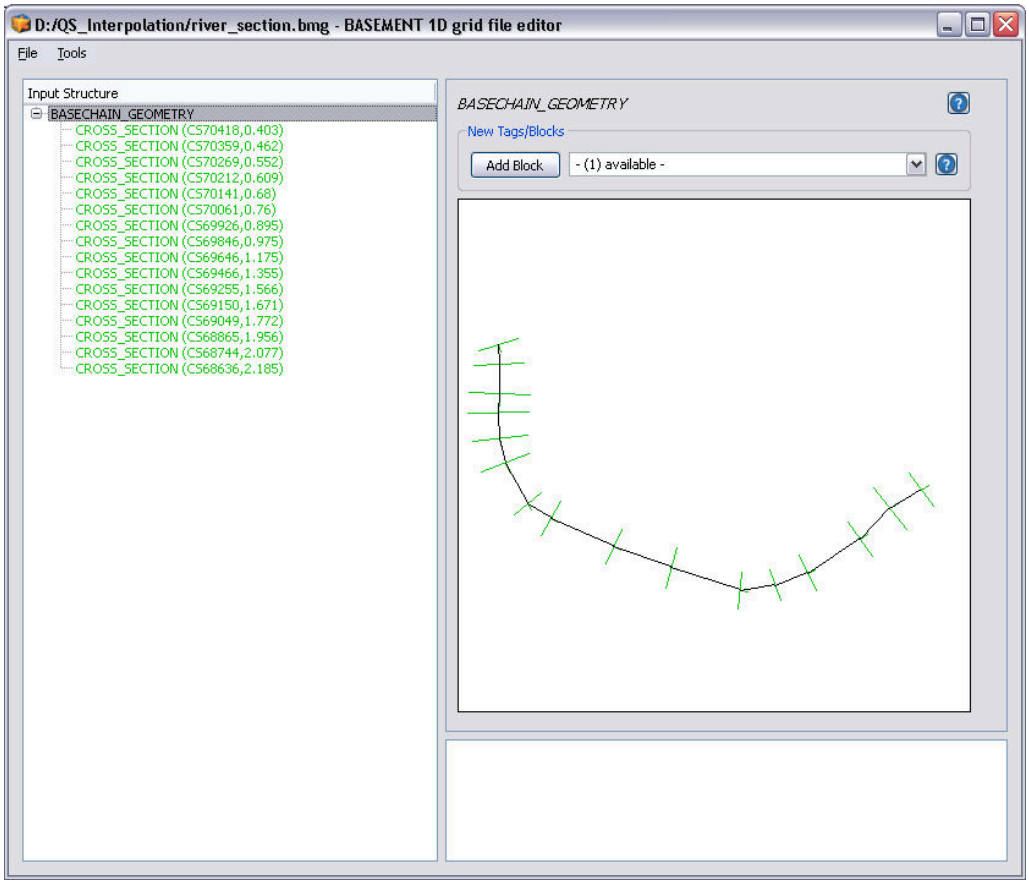

Figure 2.10 *GUI of the BASEMENT 1D grid file editor. The 1-D BASECHAIN_GEOMETRY can be exported with Export DTM for BASEplane under the menu bar Tools.*

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

2.2.2 Fundamentals

Computational meshes used with BASEplane (applies to BASEMD::BASEplane and BASEHPC::BASEplane) are of the format "2dm" (see Aquaveo XMS Wiki). 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.

2.2.2.1 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 with the consideration that the computational mesh attributes a single elevation to the cell center. There is a risk of lost 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, etc.). 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.

2.2.2.2 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 information 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 BASEHPC, the number of nodes per nodestring is limited to 40, i.e. larger nodestrings must be split up.

2.2.2.3 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 Mesh generation workflow

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 and the Tutorial *Introduction to BASEmesh*.

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, BASEMD), the mesh elements (BASEMENT v3.x, BASEHPC), or both, which allows use of the same computational grid for both environments.

2.2.3.1 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 useful 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, the quality meshing process can be used to define the StringDefs of break lines. They are defined through line strings in a separate map layer and will be preserved in the resulting mesh as break lines. The following outputs can be generated related to StringDefs:

- *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. Require for BASEMD.

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

2.2.3.2 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.

2.2.3.3 Mesh interpolation

The interpolation step converts the flat quality mesh generated by Triangle into a suitable computational mesh for BASEMENT. For BASEMD, this means adding elevation information to the mesh nodes, for BASEHPC, 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.

3

Simulation workflow

3.1 General

The simulation workflow of the software system BASEMENT (light grey rectangular background on Figure 3.1) 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 3.1).

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

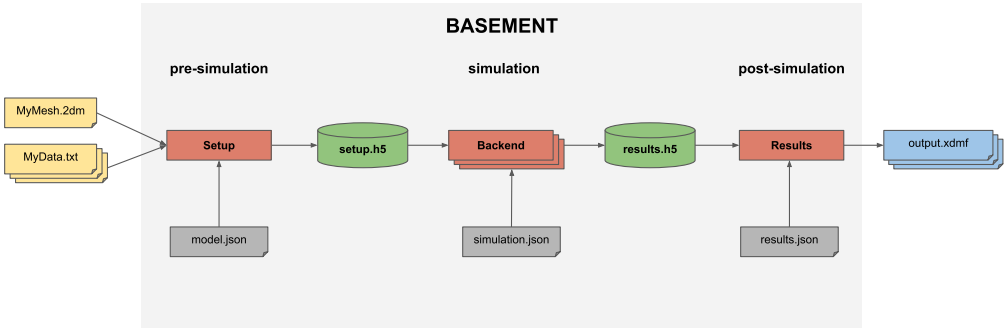

Figure 3.1 *BASEMENT simulation workflow*

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.

3.2 Pre-Simulation

3.2.1 Command Files

The first command file model.json defines the parameters required to run a numerical simulation on the generated computational mesh. In this command file, either the BASEMD or the BASEHPC module must be selected.

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 module BASEMD::BASEplane 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 2.2.2.2). 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 .2dm 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 futher 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.

3.2.2 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.

3.3 Simulation

3.3.1 Command File

The command file simulation.json contains information about the simulation time, the type of output (see Table 6.8) 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.

3.3.2 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.

3.4 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 3.1). 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 3.1.

Table 3.1 *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 [m3/s] as compact volume, no porosity (output)
Bedload transport	total bed load transport capacity [m3/s] as compact volume, no porosity

3.5 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.

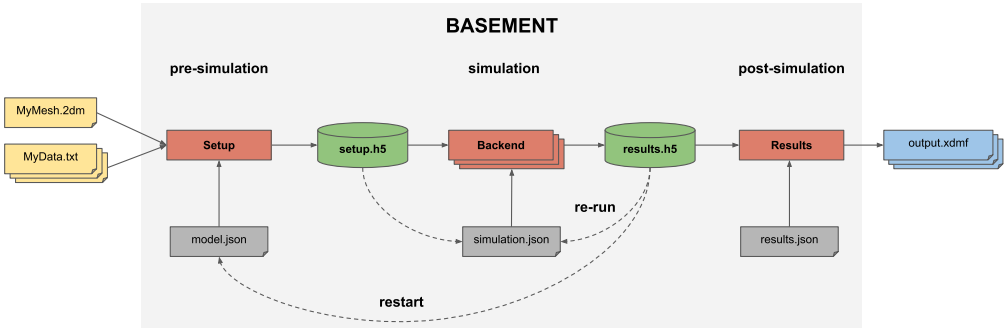

Figure 3.2 *BASEMENT simulation workflow with restart and re-run processes*

3.6 Restart Simulation

Restarting a simulation (Figure 3.2) 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.

4

Graphical User Interface (GUI)

4.1 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.

4.2 First Steps

Once started, the BASEMENT user interface application displays the welcome screen (see Figure 4.1). 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.

4.2.1 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.

4.2.2 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

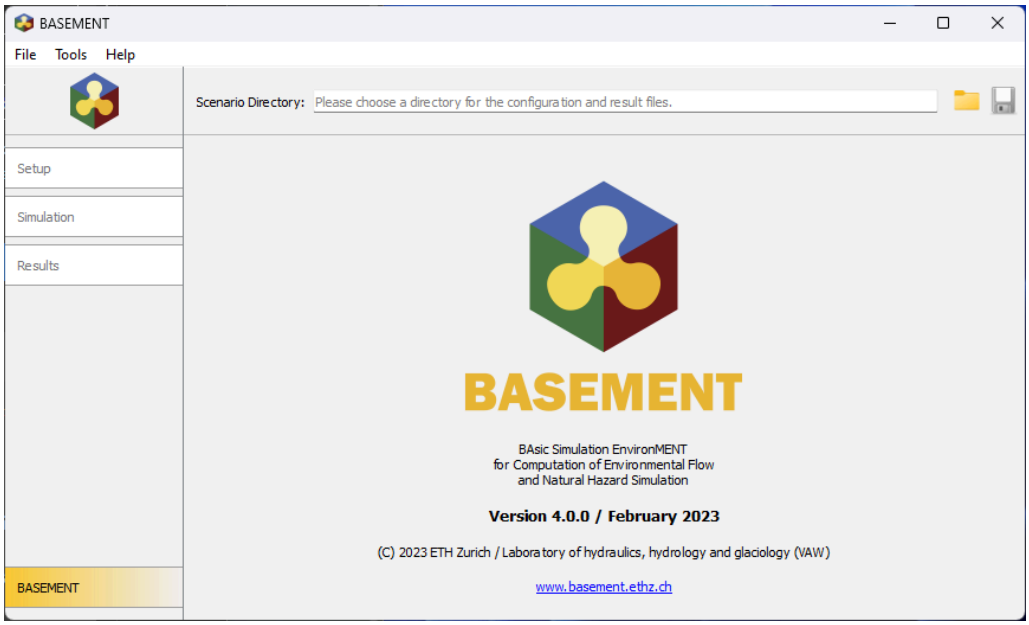

Figure 4.1 *Welcome Screen*

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.

4.3 Setup

The setup screen (Figure 4.2) 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.

4.3.1 Adding and Deleting Items

To add a subitem to a parameter group (i.e. a JSON array or a JSON array), right-click on the item to open a context menu as shown in Figure 4.3. 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).

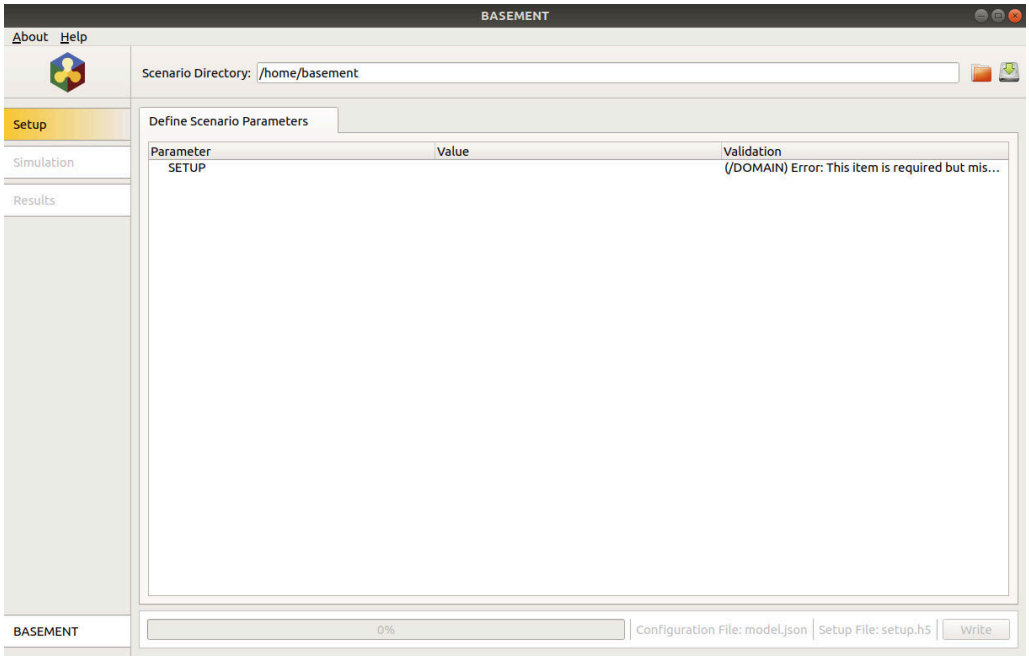

Figure 4.2 *Setup Screen*

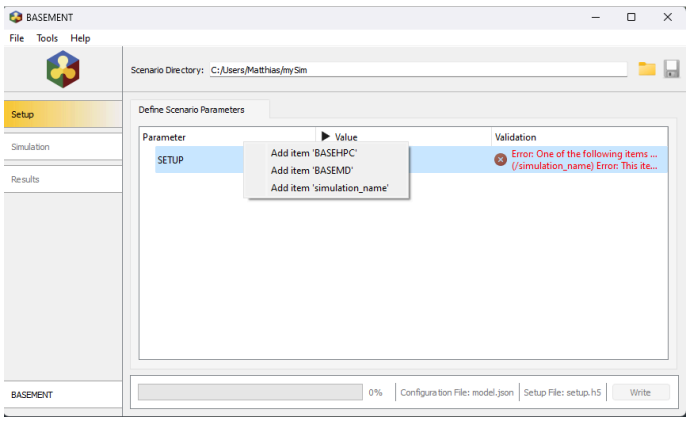

Figure 4.3 *Adding JSON Items*

Figure 4.4 *File Name Editor*

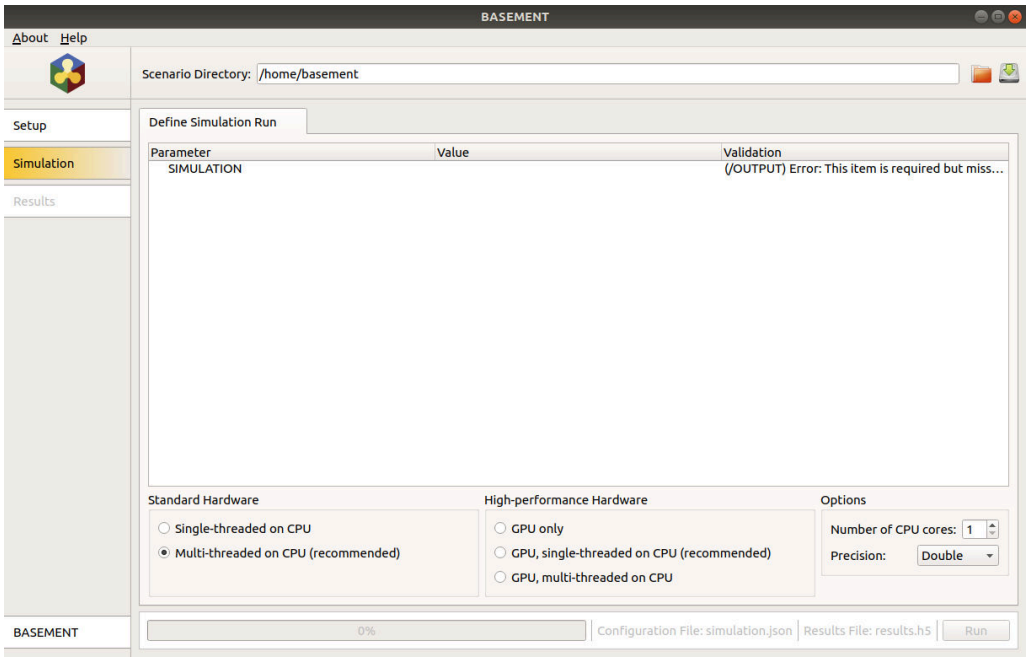

Figure 4.5 *Simulation Screen*

4.3.2 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 4.4).

4.3.3 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.

4.4 Simulation

The simulation screen (Figure 4.5) 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.

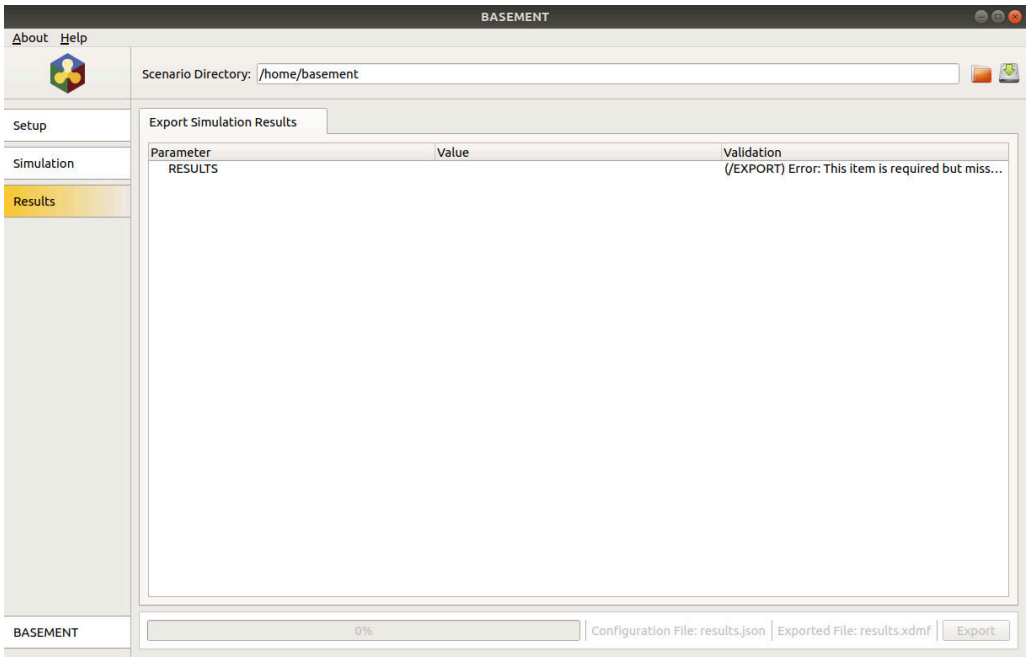

Figure 4.6 *Results Screen*

4.4.1 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.

4.4.2 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.

4.5 Results

The results tab (Figure 4.6) 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.

5

Run the program

5.1 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 4.1.

5.2 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.

5.2.1 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:

```
$ BMv4_setup model.json -o setup.h5
```

The arguments of the setup can be obtained in the command prompt (console) with the help flag '-h'. Table 5.1 shows the setup arguments.

```
$ BMv4_setup -h
```

Table 5.1 *Command line flags and arguments for the setup. Some flags are restricted to model definitions making use of the BASEHPC module.*

Setup flag	Definition and arguments
-h , –help	display help information
-v , –version	displays version information
-o , –output	path to HDF5 output file
-l , –log	level of debug messages [BASEHPC]
-n , –nthreads	number of threads [BASEHPC]

5.2.2 Simulation

The execution of the simulation is executed from the command prompt (console) using the following line:

```
$ BMv4_simulation simulation.json setup.h5 -o results.h5
```

Different option for running the simulation are available via command line flags, while some flags, such as the backend type, are only available for simulations with the module BASEHPC. The following backends are available for simulations with the module BASEHPC:

- seq
- omp
- cuda
- cudaC
- cudaO

The backend "omp" stands for parallel execution with OpenMP and the number of thread should be specified. The backend "cuda" stands for GPU simulation. The backend "cudaC" executes the simulation using a coupled GPU and sequential processor and finally "cudaO" uses a coupled GPU and parallel processor. Simulations with the BASEMD module are always executed with the "omp" backend and the selected number of threads.

The various backends available for the BASEHPC module can also be run with single precision.

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

The command line arguments of the simulation executable are shown in Table 5.2.

Table 5.2 *Command line flags and arguments for the simulation*

Setup flag	Definition and arguments
-h , –help	display help information
-v , –version	displays version information
-p , –progress	print simulation progress
-o , –output	path to HDF5 output file
-b , –backend name	the computational backend to use [BASEHPC]
-s , –single-precision	use single-precision arithmetic [BASEHPC]
-n , –nthreads number	number of threads (int)
-l , –log level	level of debug messages [BASEHPC]

5.2.3 Results

The last backend converts the simulation results into XDMF format. This executable must only be applied for simulations with the BASEHPC module, or for the BASEMD module involving a BASEplane domain. The result file ("results.json") is executed as follow:

```
$ BMv4_results results.json results.h5 -o results.xdmf
```

The command line arguments for the output generation are listed in Table 5.3

Table 5.3 *Command line flags and arguments for the results*

Setup flag	Definition and arguments
-h , –help	display help information
-v , –version	displays version information
-o , –output	path to HDF5 output file
-l , –log	level of debug messages [BASEHPC]
-n , –nthreads	number of threads (int)

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
```

```
BMv4_setup /home/MyUser/Project_1/model.json \
      --output /home/MyUser/Project_1/setup.h5

BMv4_simulation /home/MyUser/Project_1/simulation.json \
      /home/MyUser/Project_1/setup.h5 \
      --output /home/MyUser/Project_1/results.h5 \
      --backend omp --nthreads 4

BMv4_results /home/MyUser/Project_1/results.json \
      /home/MyUser/Project_1/results.h5 \
      -o /home/MyUser/Project_1/mySim_output

# Project 2
BMv4_setup /home/MyUser/Project_2/model.json \
      --output /home/MyUser/Project_2/setup.h5

BMv4_simulation /home/MyUser/Project_2/simulation.json \
      /home/MyUser/Project_2/setup.h5 \
      --output /home/MyUser/Project_2/results.h5 \
      --backend omp --nthreads 4

BMv4_results /home/MyUser/Project_2/results.json \
      /home/MyUser/Project_2/results.h5 \
      --output /home/MyUser/Project_2/results.xdmf
```

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
```

5.3 Batch mode under Windows

Running BASEMENT 4.x in with a graphical user interface under Microsoft Windows can be done with the same work flow as described in Section 5.2. 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 4.x in under the path “C:\Program Files\BASEMENT 4.1.0” and your simulation scenario is stored on drive “F:\” in the folder “Project_1”, then you should run the simulation with the following three commands:

```
C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_setup.exe `
```

```
      F:\Project_1\model.json `
      -o F:\Project_1\setup.h5

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_simulation.exe `
      F:\Project_1\simulation.json `
      F:\Project_1\setup.h5 `
      --output F:\Project_1\results.h5 --backend omp --nthreads 4

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_results.exe `
      F:\Project_1\results.json `
      F:\Project_1\results.h5 `
      --output F:\Project_1\results.xdmf
```

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

```
C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_setup.exe `
      F:\Project_1\model.json `
      -o F:\Project_1\setup.h5

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_simulation.exe `
      F:\Project_1\simulation.json `
      F:\Project_1\setup.h5 `
      --output F:\Project_1\results.h5 --backend omp --nthreads 4

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_results.exe `
      F:\Project_1\results.json `
      F:\Project_1\results.h5 `
      --output F:\Project_1\results.xdmf


C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_setup.exe `
      F:\Project_2\model.json `
      -o F:\Project_2\setup.h5

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_simulation.exe `
      F:\Project_2\simulation.json `
      F:\Project_2\setup.h5 `
      --output F:\Project_2\results.h5 --backend omp --nthreads 4

C:\"Program Files\BASEMENT 4.1.0"\bin\BMv4_results.exe `
      F:\Project_2\results.json `
      F:\Project_2\results.h5 `
      --output F:\Project_2\results.xdmf
```

Then run the batch file by double clicking on it.

6

Differences between modules BASEMD and BASEHPC

The specific differences between the BASEMD and BASEHPC modules regarding the grid generation, the workflow, the model setup, the simulation and result configuration, are listed in this chapter by tables. Further, the differences are illustrated by a case study.

6.1 General

The specific differences between the BASEMD and BASEHPC modules regarding the grid generation, the workflow, the model setup, the simulation and result configuration, are listed in this chapter by tables. Further, the differences are illustrated by a case study. It it worth to remark that, given the differences summarized later, the numerical solutions of BASEMD and BASEHPC are not identical, even when conducted on the same domain. Nevertheless, both version are tested for robusteness, accuracy and convergence.

6.2 Grid topology and generation

Table 6.1 *Main differences regarding the computational mesh*

BASEMD	**BASEHPC**
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

BASEMD	BASEHPC
Computational mesh in 2dm format (SMS), including material indices (stringdefs defined separately in *.bmc file)	Computational mesh in 2dm format (SMS), including material indices and stringdefs
Domain differentiation with element_ids	Domain differentiation with regiondef

Table 6.2 *Main differences regarding the grid generation with BASEmesh*

BASEMD	BASEHPC
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

6.3 Workflow

Table 6.3 *Major changes in workflow*

	BASEMD	BASEHPC
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)

	BASEMD	BASEHPC
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

6.4 Setup

Table 6.4 *Main changes regarding model setup*

	BASEMD	BASEHPC
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 6.5 *Main changes in the* ***hydraulics*** *block of the domain BASEplane*

	BASEMD	BASEHPC
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
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

	BASEMD	**BASEHPC**
Safe mode	no	yes
Friction		
Type	Manning	Manning
	Strickler	Strickler
	Chezy	Chezy
	Yalin	-
	Darcy-Weissbach	-
	Bezzola	Bezzola
Wall friction	yes	no
Grain size friction	yes	no
Boundary		
Type	-	**Standard**
	hydrograph	uniform_in
		uniform_out
	-	**Standard**
	zhydrograph	zhydrograph
		Linked
		zhydrograph_linked,
		zhydrograph_linked_kinE
	zero_gradient	zero_gradient_out
	weir	weir_out_constant,
		weir_out_dynamic
		Linked
		weir_linked_constant,
		weir_linked_dynamic
	gate	-
	-	**Standard**
	HQ_relation	hqrelation_out
		Linked
		2way_hqrelation_linked,
		hqrelation_linked
	coupling	-
	-	**Internal**:
	wall	wall_internal

	BASEMD	BASEHPC
		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 6.6 *Main changes in the* ***morphology*** *block of the domain BASEplane*

	BASEMD	BASEHPC
Parameter		
Active layer	yes (control_volume)	yes
Porosity	porosity	sediment_porosity
Density	density	sediment_density

	BASEMD	**BASEHPC**
Starting time	- (bedload)	morphodynamic_start
morph_cycle	yes	no
morphological factor	no	yes
time scaling	no	with morphological factor
Create new layers	yes	Up to 2 layers
Grid perturbation (random)	distortion	-
Bedmaterial		
Grain class	Single or multi grain classes	Single or multi grain classes
Layer	Multiple layers	Up to 2 layers
Fix bed elevation	.2dm mesh or node list	via SOILDEF, .2dm mesh or over region (index)
Bedload		
Bedload transport	Simple upwind scheme	HLL-type Approximate Riemann Solver (Soares-Frazão and Zech, 2011) Simple upwind scheme Simple upwind scheme
Closure formula	mpm - engelundhansen mpmh power_law mpm_multi wilcockcrowe ashidamichiue	MPM MPM_like (adaptable) engelundhansen - GRASS_like (adaptable) MPM_multi (adaptable) wilcockcrowe -

	BASEMD	**BASEHPC**
	parker	-
	rickenmann	-
	smartjaeggi	smartjaeggi
	smartjaeggi_multi	-
	wu	-
	vanrijn	-
Boundary		
- Inflow	-	**Standard**
	sediment_discharge	sedimentograph
	-	sedimentograph_warea
	-	sedimentograph_conveyance
	IOUp	equilibrium_in
	transport_capacity	transport_capacity
	-	transport_capacity_warea
	-	transport_capacity_conveyance
- Outflow	IODown	equilibrium_out
Parameters	upwind factor	-
	cell average bedload flux	cell average bedload flux (default)
Direction	lateral_bed_slope	LATERAL_SLOPE
	curvature_effect_static	-
	curvature_effect_dynamic	CURVATURE
Inner boundary	weir, open	**Internal**:
	-	equilibrium_linked
Incipient motion	angle_of_repose	repose_angle
	local_slope_vanrijn	van_rijn
	local_slope_chen	chen_et_al
Gravitational transport	yes	yes
Source		
Type	sediment_discharge	sediment_discharge
	dredge	-

Table 6.7 *Introduction of the* ***tracers*** *block in the domain BASEplane*

	BASEMD	**BASEHPC**
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

6.5 Simulation

Table 6.8 *Main changes regarding simulation parameters*

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

	BASEMD	BASEHPC
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
	-	active_layer_thickness
	-	active_layer_fractions
	-	sublayer_fractions0
	-	sublayer_fractions1
	-	sublayer_elevations
	-	sublayer_id
	-	dm_arithmetic
	-	dm_geometric
	-	d_16
	-	d_50
	-	d_84
	-	d_90
	-	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

BASEMD	BASEHPC

6.6 Results

Table 6.9 *Main changes regarding the results parameters*

	BASEMD	BASEHPC
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	-

6.7 Case example

6.7.1 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 differences between BASEMD::BASEplane and BASEHPC::BASEplane. 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 6.10.

Table 6.10 *Geometry of trapezoidal channel*

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

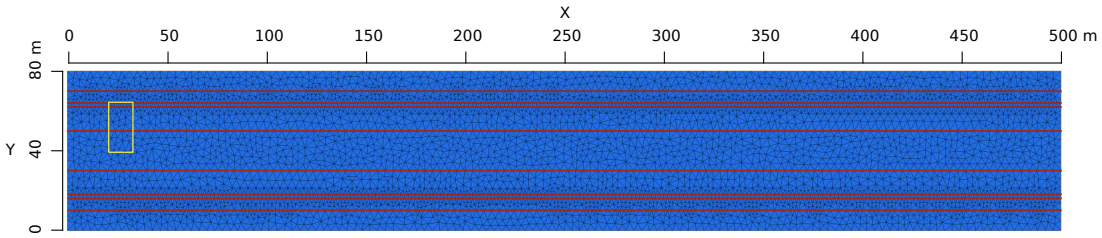

Figure 6.1 *Quality mesh used for the case example with breaklines (red)*

6.7.2 Computational mesh

The topology of the computational mesh used for BASEHPC::BASEplane is different than for BASEMD::BASEplane, see Tables 6.1 and 6.2. This section describes the differences between the two mesh types and provides a guideline on how to import a v2.x (or BASEMD::BASEplane) mesh into BASEMENT version 4.

6.7.2.1 Quality mesh

Table 6.11 *Quality mesh attributes*

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

The quality mesh contains all the mesh attributes defined by the user, i.e. cell size, breaklines, regiondefs, minimum triangle angle and maximum cell area, but has no elevation information. The quality mesh of the simple straight trapezoidal channel (Figure 6.1) is identical for both versions, BASEMD and BASEHPC and its attributes are listed in Table 6.11. The procedure to generate a quality mesh with QGIS using the BASEmesh plugin is explain in the Tutorial of BASEMENT v2.8 documentation.

6.7.2.2 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 BASEHPC and BASEMD lies in the process of attributing the elevation information to the mesh cells. A small surface area (yellow rectangle, Figure 6.1) is schematically reproduced on Figure 6.2 in order to illustrate the two approaches used to create the computational mesh.

In BASEMD, the topographic elevation is attributed to the cell vertices (Figure 6.2 a). The quality mesh defines the location on the elevation model at which the elevation information

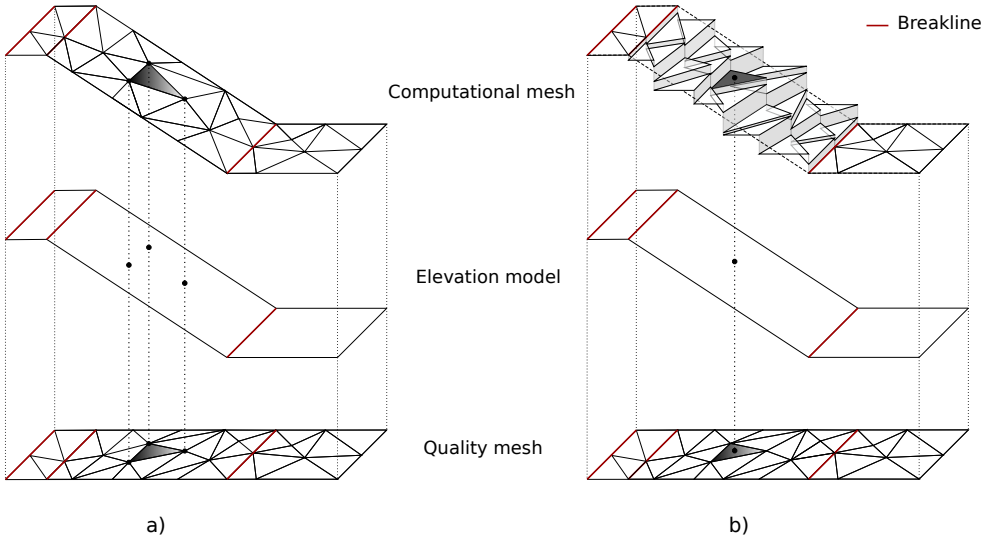

Figure 6.2 *Schematic sketch of the elevation interpolation methods with breaklines (red): a) BASEMD b) BASEHPC*

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 BASEHPC, the elevation information is assigned to the coordinate of the cell center, resulting in a constant elevation over the cell surface (Figure 6.2 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 BASEMD, 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 BASEHPC, where two or more breaklines need to be defined in order to obtain cells at desired elevation (e.g. the elevation at the bank crest has to be garanteed by two breaklines).

The computational mesh of the trapezoidal channel for the simulation with BASEMD is represented on Figure 6.3 and the computational mesh for the simulation with BASEHPC on Figure 6.4. The flow direction is from top to bottom.

6.7.2.3 Import of a 2.x to a compatible 4.x computational mesh

The computational mesh of BASEHPC::BASEplane (version 4) 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 4.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

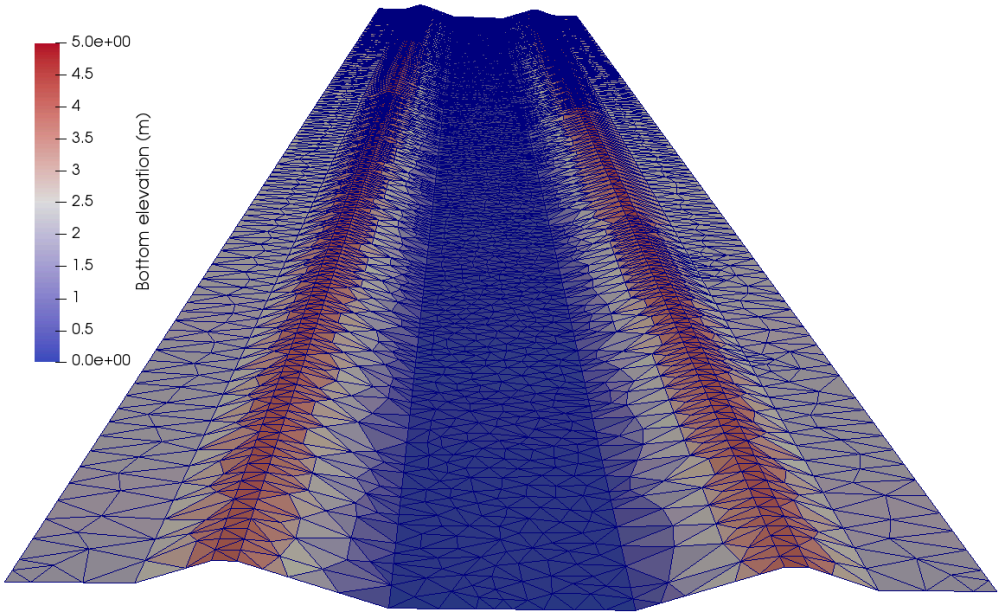

Figure 6.3 *Computational grid BASEMD with breaklines (view from downstream)*

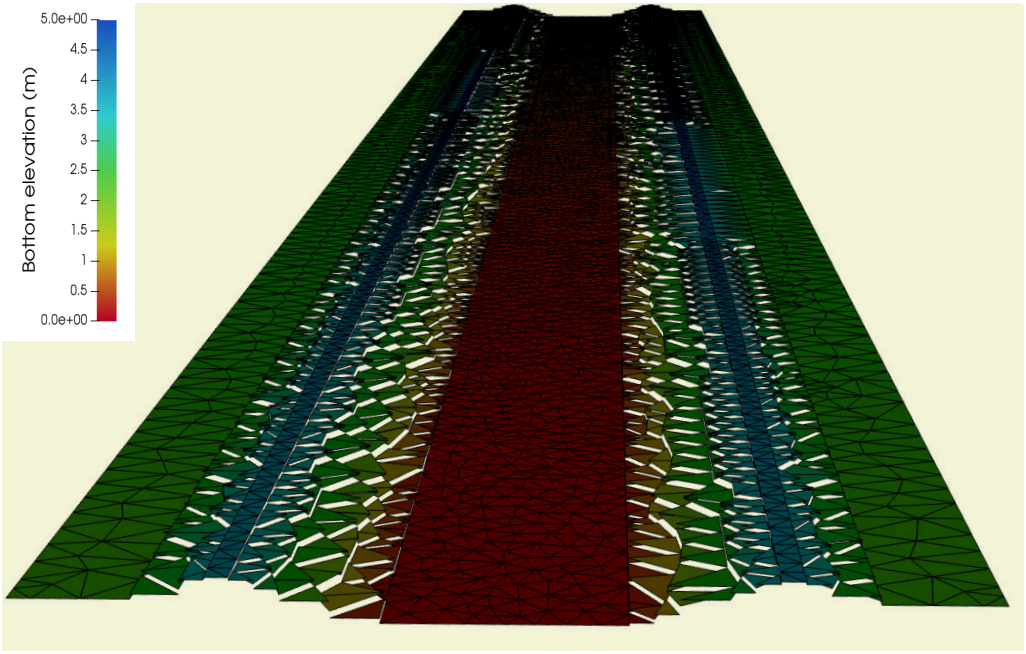

Figure 6.4 *Computational grid BASEHPC with breaklines (view from downstream)*

```
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 6.5 *Lines to add manually to the 2dm mesh file (orange)*

separate .txt file. In order to use the computational mesh version 2.x for simulations with BASEHPC::BASEplane (version 4), 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 6.5). 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 6.7.3), give the name of the modified .2dm mesh file in the GEOMETRY block and choose between the interpolation methods:

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

The interpolation method defines how the elevation information stored on the nodes of the computational mesh version 2.x is interpolated in order to generate a computational mesh compatible with BASEHPC::BASEplane (version 4). 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 6.6, where a cross section of the trapezoidal mesh illustrates the local differences between the mesh of BASEMD::BASEplane and the different interpolated meshes used in simulations with BASEHPC::BASEplane.

Moreover, Figure 6.7 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 6.6 and most of the interpolation methods can't preserve the bank elevation. In the case

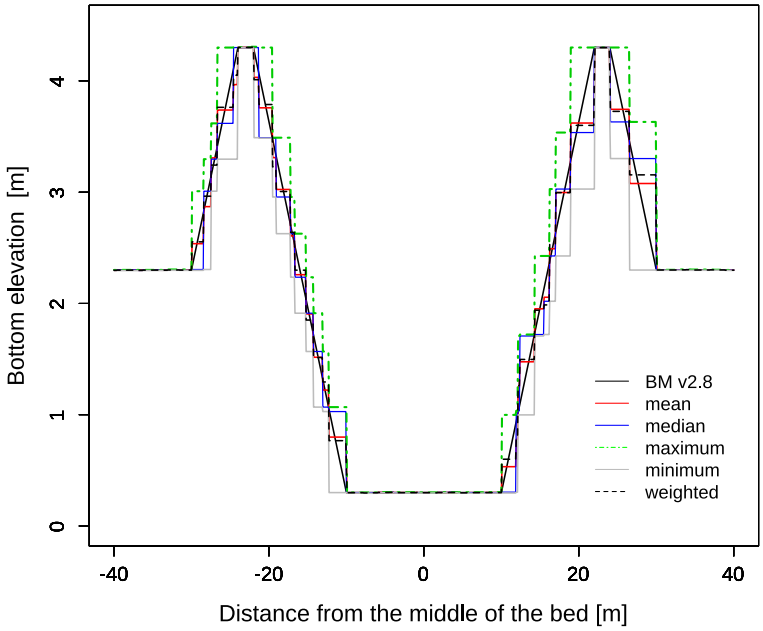

Figure 6.6 *Comparison of interpolation methods with the mesh of BASEMD::BASEplane on a cross section at x= 150 m of the trapezoidal channel with breaklines*

of a numerical simulation where the exact elevation of the bank is required (e.g. to calculate the bordfull discharge), the definition of breaklines ensures the conservation of the bank elevation, independently from the chosen interpolation methods. Otherwise, the 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 6.8 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".

6.7.3 Setup and simulation

The simulations were performed for all the interpolation methods using BASEMENT version 4. 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

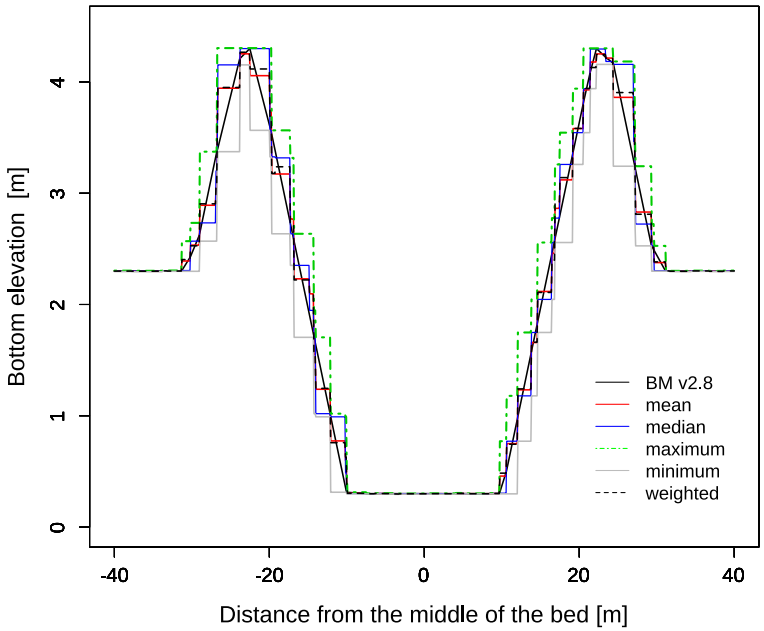

Figure 6.7 *Comparison of interpolation methods with the mesh of BASEMD::BASEplane on a cross section at x= 150 m of the trapezoidal channel with only one breakline defined at the bank crest*

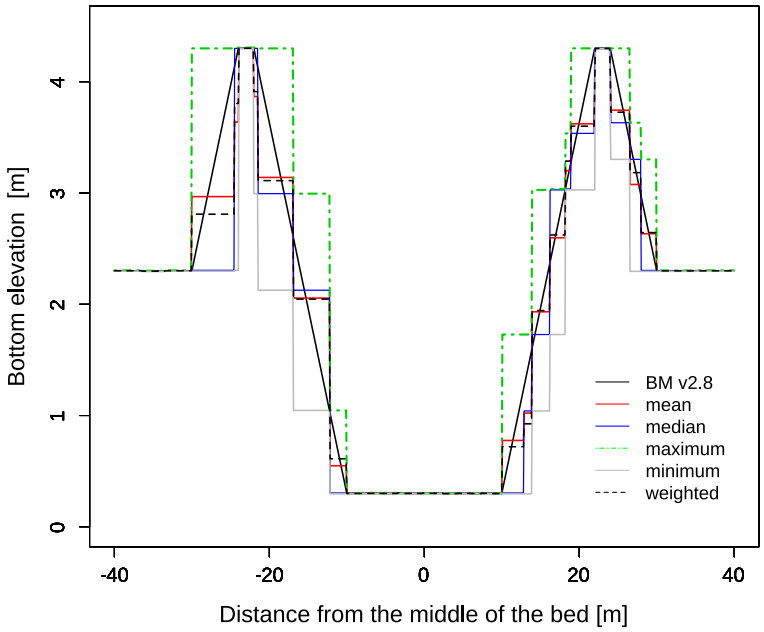

Figure 6.8 *Comparison of interpolation methods with the mesh of BASEMD::BASEplane on a cross section at x= 150 m of the trapezoidal channel with breaklines and for a coarser mesh resolution*

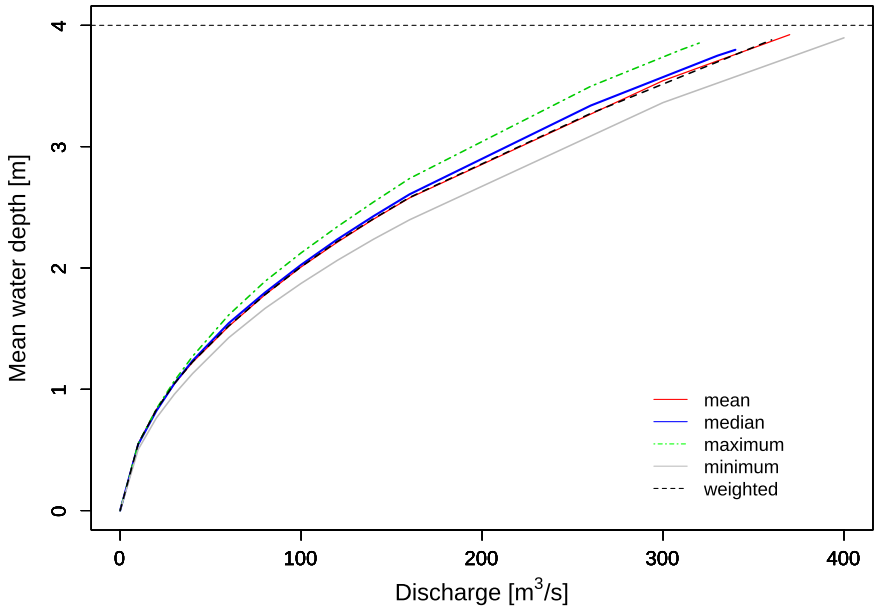

Figure 6.9 *Comparison of H-Q relations between the simulations of BASEMENT v3 for different interpolation types on the trapezoidal channel at x = 150 m.*

- Configuration files (model.json, simulation.json and results.json)
- 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 decribed in Section 6.7.2.3, the specification of stringsdefs, i.e. the list of nodes is included in the computational mesh (.2dm) in BASEHPC::BASEplane (version 4).

6.7.4 Results and discussion

In BASEMENT version 4.x, the output data are generated either on cells (cell centered) or at the boundaries (stringdefs). Various results are available (see Table 6.9 and Table 6.8).

6.7.4.1 Hydraulic results

The result of the simulations with BASEMENT version 4 for different interpolation methods are compared in a stage discharge rating curve (Figure 6.9). The mesh features are summarized in Tables 6.10 and 6.11.

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

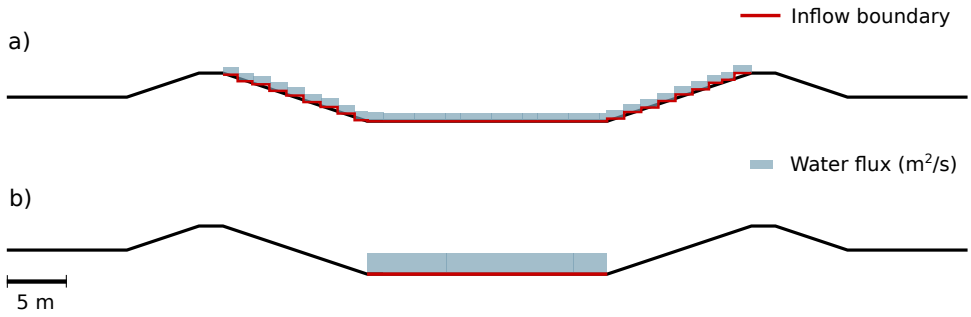

Figure 6.10 *Channel cross section and inflow boundary limit in BASEHPC::BASEplane a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit*

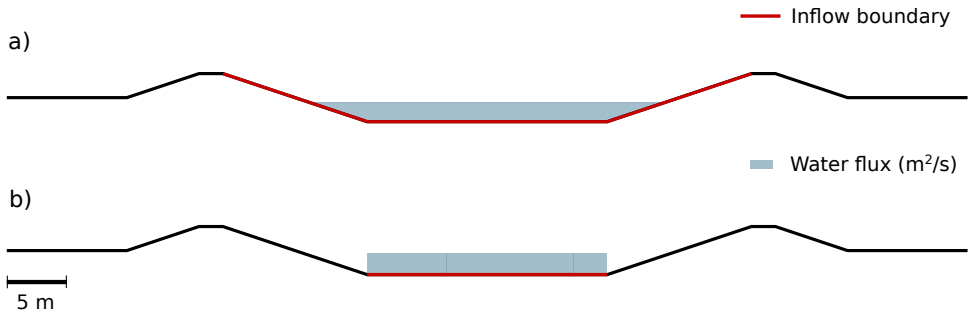

Figure 6.11 *Channel cross section and inflow boundary limit in BASEMD::BASEplane a) Inflow boundary limit set at levee's highest point b) Reduced inflow boundary limit*

6.7.4.2 Boundary conditions

In BASEHPC::BASEplane, 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 BASEMD::BASEplane. Figure 6.10 and Figure 6.11 show two simplified representation of the averaged discharge value distribution on the element edges of the inflow boundary cross section for BASEMD::BASEplane and BASEMD::BASEplane respectively.

An inflow boundary defined between the top elevation of the two levees in BASEHPC (red line in Figure 6.10, a) generates an undesired converging flow from the bank towards the channel center (Q= 60 m^3/s) and small flux towards the floodplains as represented on Figure 6.12 for a discharge value Q= 200m^3/s. An inflow boundary restricted to the channel bed width (Figure 6.10, 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 6.13 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 v4 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

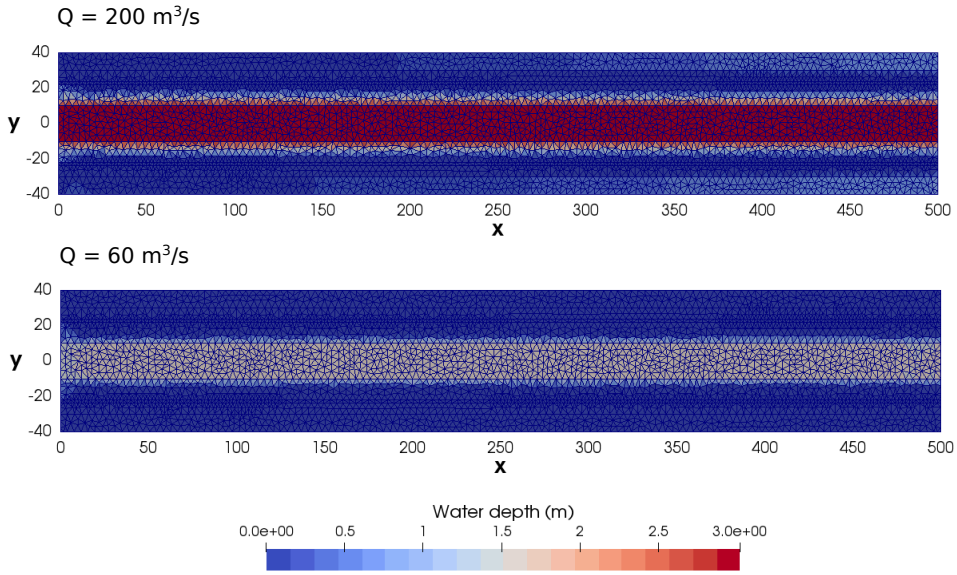

Figure 6.12 *Planar view of the simulation results using BASEMENT version 4 of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary (x= 0.0 m) defined between the top elevation of the levees (Figure 6.10, a), inducing a converging flow from the levee towards the channel center and small fluxes towards the floodplains for higher discharge Q= 200 m^3/s*

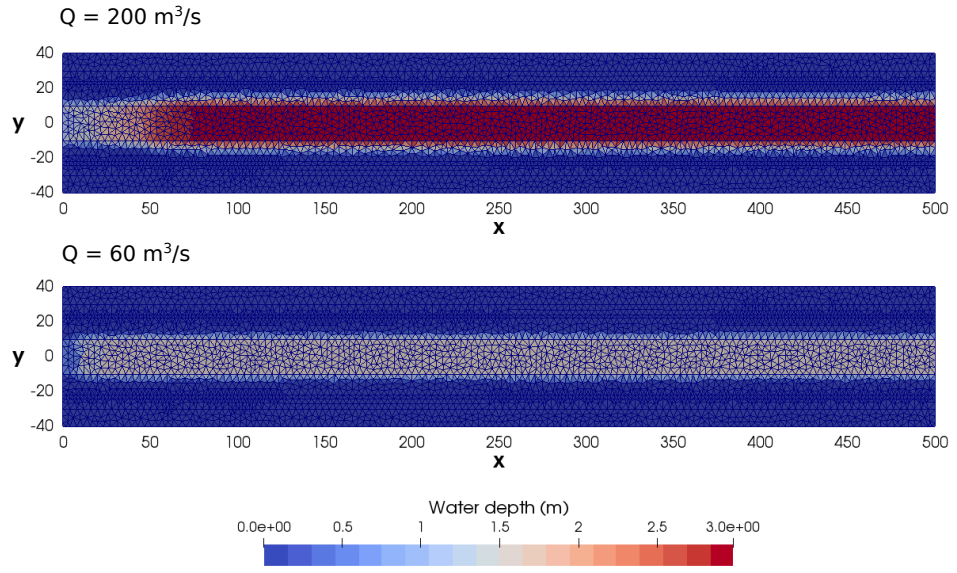

Figure 6.13 *Planar view of the simulation results using BASEHPC of the trapezoidal channel with breaklines and for two discharge stages. Inflow boundary (x= 0.0m) restricted to the channel bed (Figure 6.10, b), inducing an increase of the flow velocity.*

boundaries shall be split into several smaller stringdef of equal length and consequently, the discharge applied to the boundaries has to be adapted.

6.7.4.3 Discussion

This case example of the hydraulic simulation of a trapezoidal channel pointed out the differences between BASEMD::BASEplane and BASEHPC::BASEplane for the topology and the boundary setup. The use of a BASEMENT v2.x mesh into BASEMENT v4.x is possible by interpolation but the simulation results may differ between the two versions due to the new topology. The simulation with BASEMENT v4.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.

7

Performance on Multi-Core Processors and GPU

7.1 General

The performance of BASEMD and BASEHPC 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 BASEMD on multi-core processors (there is no GPU option for BASEMD), i.e. using the CPU backend on 1, 2, 4, 8 and 12 cores. For BASEHPC the CPU backends with up to 32 cores and the GPU backend using different GPU cards was used. 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).

7.2 Scalability

The speedup of the simulations performed on CPU hardware is shown in Figure 7.1. 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 modules only scale linearly up to approximately 4 threads before reaching a plateau (due to overhead).

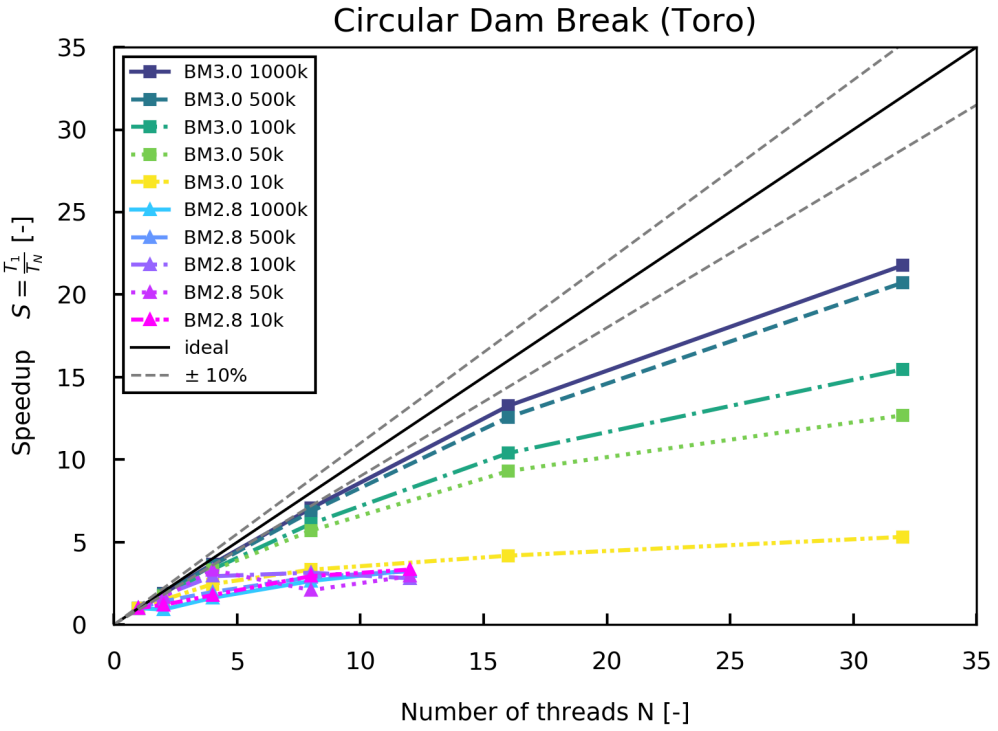

Figure 7.1 *Speedup of the circular dam break test case performed on CPU for an increasing number of threads and different mesh sizes*

For BASEMD, 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 BASEHPC scales almost linearly up to 16 threads for the four larger meshes and up to 32 cores for the two largest meshes. Overall, BASEHPC exhibits significantly improved scalability compared to BASEMD.

7.3 Computational Time

The execution time of all the simulations is shown in Figure 7.2. 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 BASEHPC compared BASEMD. This increase in performance by a factor of up to 13 is the results of completely restructuring the software. The performance of BASEHPC 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 has about the same performance as the Intel Xeon Gold 6154 processors when using 32 cores, but with a 6 times lower purchasing price.

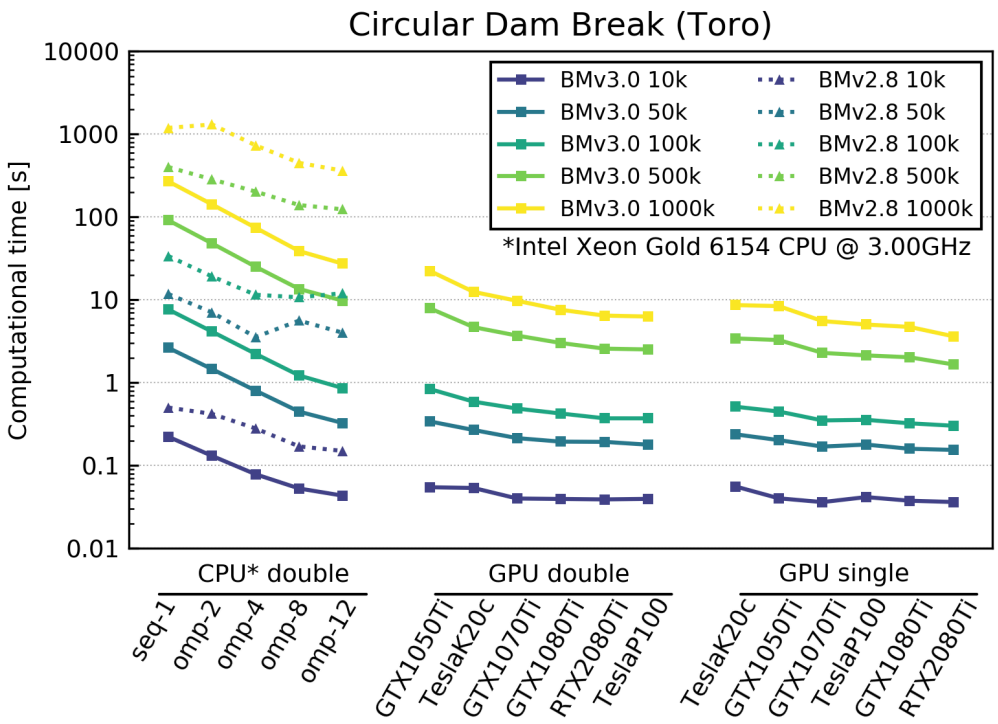

Figure 7.2 *Execution time of the circular dam break test case for different backends and mesh sizes*

8

Specific Features of BASEMD

8.1 General

This chapter details some specific features of the BASEMD module which are not available for the BASEHPC module. The specific features of BASEMD include the coupling of the various submodules and with external programs during runtime via BASEextern, the automatic flow control using controllers, and the built-in runtime GUI tools BASEviz and HID.

8.2 Model Coupling

8.2.1 Introduction

In addition to the simulation of single sub-domains using BASEchain (1-D) or BASEplane (2-D), the software BASEMENT also provides the possibility to connect sub-domains for combined numerical simulations. Such coupled simulations can range from simple configurations up to simulations of river networks with integrated river junctions / bifurcations or integrated 1-D/2-D modelling. In Figure 8.1 a river network of multiple sub-domains with several coupling interfaces is illustrated. The coupling mechanisms thereby allow to couple hydrodynamic simulations as well as morphological simulations with sediment transport and suspended load.

Some typical applications of coupled simulations are:

- A step wise modeling approach to the overall problem using smaller parts of the whole domain. This approach has the advantages of reduced complexity and reduced execution and calibration times. Also extensions of existing and calibrated models can be easily made with coupled simulations without the need to redesign the existing models.

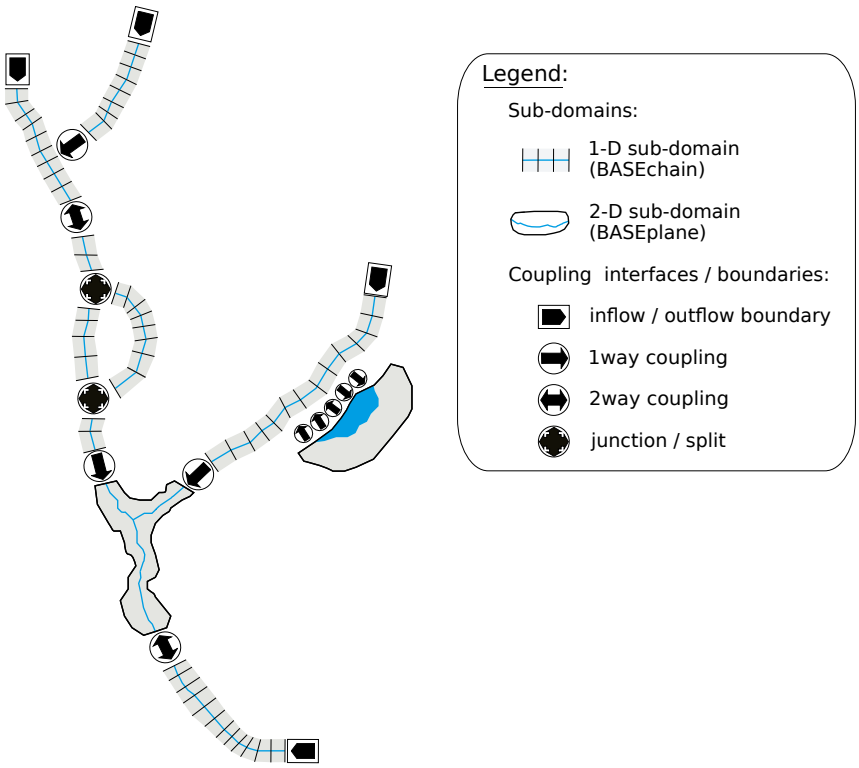

Figure 8.1 *River network with multiple BASEchain (1-D) and BASEplane (2-D) sub-domains and several coupling interfaces.*

- Simulations with hydraulic structures (like weirs or gates) within the domain of interest can be realized by using multiple sub-domains, which are coupled via these hydraulic structures.
- Coupled simulations can be helpful for mixed-dimensional modeling approaches, e.g. for cases where large scale 1-D simulations shall be combined with detailed modeling of local areas in 2-D. Thereby, the advantage of efficient and robust modeling in 1-D is combined with the capability to simulate 2-D flow characteristics. Also, the required efforts for data acquisition and data preparation can be minimized using mixed-dimensional modeling approaches.

8.2.2 Coupling Types

The implemented coupling types are briefly sketched below.

- **Sequential, Riemann (1D)**

  Single sub-domains can be combined sequentially via coupling interfaces at the upstream or downstream boundaries (Figure 8.2). This can also be done for sub-domains with mixed dimensionalities (1-D / 2-D, 2-D / 1-D), see Figure 8.3.

  These **sequential** coupling types can be used to combine sub-domains over their boundary conditions or external sources. For example, a weir outflow boundary can be combined with an input hydrograph of a downstream boundary.

  Beside sequential couplings, also so called **Riemann** couplings can be used (at the moment only 1D) which set a Riemann solver between the sub-domains and allow

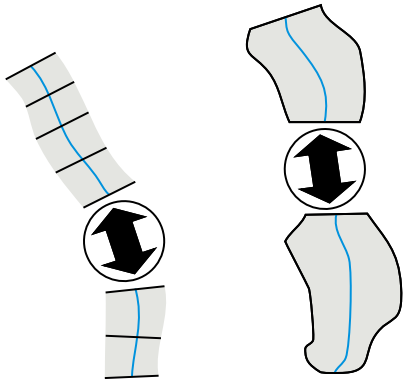

Figure 8.2 *1-D / 1-D coupling (left), 2-D / 2-D coupling (right)*

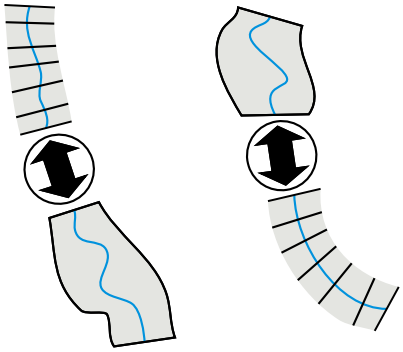

Figure 8.3 *1-D / 2-D coupling (left), 2-D / 1-D coupling (right)*

flow in any direction. This coupling type requires special 'connection' boundaries at the coupling interfaces.

- **Junctions / Bifurcations / ConfluenceWSE (1D)**

  Coupling interfaces for river **junctions** or river **bifurcations** allow a simplified modelling of conjunctions of river branches within a 1-D river network (Figure 8.4).

  Beside these both coupling types also a **confluenceWSE** coupling can be used which tries to establish a common water surface elevation (WSE) at the confluence point (at the moment only 1D). This coupling allows flow in any direction and requires special 'connection' boundaries at the coupling interfaces.

- **Lateral coupling.**

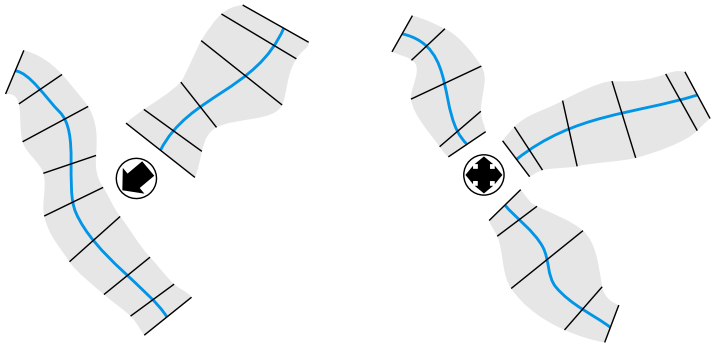

Figure 8.4 *junction /bifurcation / confluence WSE (1-D)*

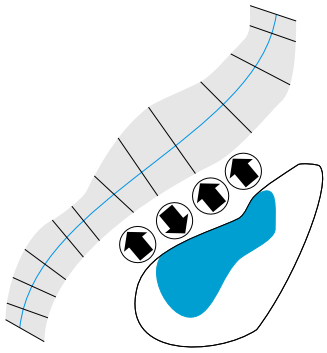

Figure 8.5 *lateral coupling*

For integrated 1-D and 2-D modelling, a 1-D sub-domain can be coupled laterally with a 2-D sub-domain. The coupling takes place along the river channel via multiple coupling interfaces which connect cross sections (1-D) with corresponding mesh elements (2-D), see Figure 8.5.

8.2.3 Coupling Mechanisms

8.2.3.1 Explicit coupling of sub-domains

Coupling of sub-domains is implemented as an explicit coupling approach, which means that data is exchanged explicitly between the sub-domains at certain time intervals. This approach is simpler to implement than an implicit approach, especially regarding the coupling of sub-domains with mixed dimensionalities. However, in comparison to an implicit coupling approach, special care must be taken to achieve robust and stable combined simulations.

8.2.3.2 One-way coupling and two-way coupling

A simple way to couple two sub-domains is to exchange data only in one direction from upstream to downstream. Such a situation is termed as 1-way coupling from here on. It has the advantage that the upstream sub-domain can run independently from the downstream sub-domain and the flow variables are passed over at some time intervals to the downstream sub-domain. But being a one-directional coupling, no information from downstream can travel upstream. Therefore, this type of coupling is restricted to cases where no backwater effects from downstream take place or such influences can be neglected.

In contrast, a two-way coupling enables mutual interactions between the sub-domains by providing mutual data exchange. In two-way coupled sub-domains, backwater effects from downstream can influence the upstream sub-domain. Instead of executing the sub-domains sequentially from upstream to downstream direction, here the sub-domains are executed simultaneously. The two-way coupling approach has the difficulty that no unique flow variables are present at the coupling cross sections, as water levels from upstream and downstream direction may differ for a given time. In principle, iterations between the sub-domains are required and must be performed until the differences of the variables at the coupling cross section do no longer change within subsequent iteration steps. Although a rather small number of iterations has to be expected (as reported by Miglio et al. (2005)),

these iterations lead to large additional computational efforts. Therefore these iterations are not performed here. As the time steps in the explicit approach are usually very small, the differences between the upstream and downstream variables are rather small and iterations may be neglected without substantial loss of accuracy. But in cases of crucial and abrupt changes in the flow variables, oscillations may result.

A combination of both concepts can be used in the coupled river simulation. One-way coupled sub-domains are executed sequentially from upstream to downstream direction, whereas two-way coupled sub-domains are treated as being a single sub-domain within the execution sequence.

8.2.4 Definitions of Exchange Conditions

8.2.4.1 General remarks

Data can be exchanged between the sub-domains by coupling interfaces using boundary conditions and source terms. The following table shows the exchange variables grouped by the direction of the exchange.

Table 8.1 *Possible exchange conditions between sub-domains.*

direction of exchange	type of coupling	exchange variables
in downstream direction	boundary conditions & sources	Q : discharge $q_{b,g}$: bed load C_g : concentration
in upstream direction	boundary conditions & sources	z_s : water surface elevation

In order to enable simple, flexible and efficient coupled simulations, some assumptions are made here:

- It is assumed that flow directions at the coupling interfaces of the river network are known a priori and do not change during the simulation (with the exception of special coupling types, like the lateral coupling).
- The cross sections (1-D) or mesh elements (2-D) of the coupling interfaces should ideally be located at the same or nearby locations and have the same geometries. This is necessary to reduce possible errors around the coupling interfaces due to the disregard flow taking place in between and to avoid discontinuities due to abrupt changes in the geometries.
- It is assumed that the flow is orthogonal over the boundaries, i.e. the directional x- and y flow components in 2-D are not exchanged separately.
- In 2-D coupling only summarized or averaged data are exchanged, instead of exchanging data separately for each edge or element. This approach simplifies the coupling setup since no restrictions are set regarding the geometries and number of cells at the boundaries or sources.

8.2.4.2 Exchange conditions for mixed-dimensional sub-domains

Exchange via boundary/sources:

Table 8.2 *Exchange conditions for mixed-dimensional coupling (i=index of 2-D edge or 2-D element)*

Echange variable	Exchange equations	Nr of exchange terms
Discharge	$1D \rightarrow 2D$: $q_i^{2D} = \omega_i Q^{1D}$ (ω_i=area/length weighting or conveyance weighting) $2D \rightarrow 1D$: $Q^{1D} = \sum_i^n q_i^{2D}$	1
Water surface	$1D \rightarrow 2D$: $z_{S,i}^{2D} = z_S^{1D}$ $2D \rightarrow 1D$: $z_S^{1D} = \frac{1}{n} \sum_i^n z_{S,i}^{2D}$	1
Bed load	$1D \rightarrow 2D$: $q_{b,g,i}^{2D} = \omega_i q_{b,g}^{1D}$ (ω_i=area/length weighting) $2D \rightarrow 1D$: $q_{b,g}^{1D} = \sum_i^n q_{b,g,i}^{2D}$	g=1..ng
Suspended load	not available yet in 2D	g=1..ng

8.2.4.3 Exchange conditions for river junctions in 1-D river networks

Within a river network locations are encountered where river branches flow together or where a river bifurcates into several branches. The flow characteristics at such conjunctions generally are multidimensional. Therefore the preferable modelling approach to achieve a good accuracy is to simulate a 2-D sub-domain. But if such a situation shall be modelled with 1-D sub-domains than special coupling concepts are required.

Two different approaches are implemented in BASEMENT (see Figure 8.6). These approaches allow no more than three sub-domains being part of a junction. If a larger numbers of river branches are to be modelled, they must be approximated by multiple junctions, placed in small distances.

Following the first approach a junction can be regarded as region where three different river branches meet and mutually exchange data (a). A control volume is defined to which mass and momentum conservation principles can be applied. A simple approach is here balancing discharges and assuming equal water surface elevations along the junction.

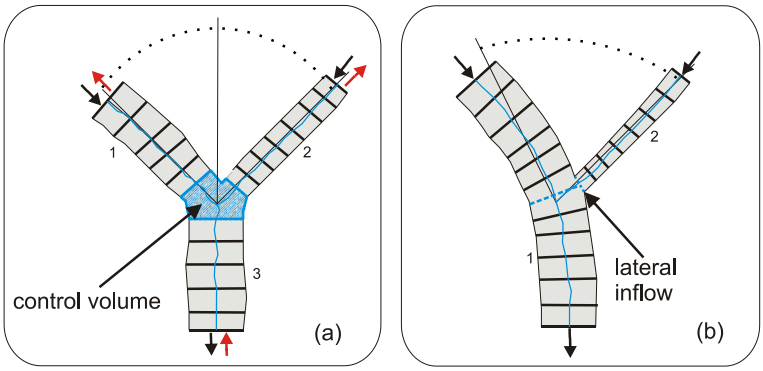

Figure 8.6 *Modeling of a river junction with two different approaches (black arrows indicate a confluence of river branches, red arrows a bifurcation): (a) = river junction with 3 different river branches, (b) = junction as a lateral inflow of a tributary.*

Table 8.3 *Exchange conditions for river junctions*

	Exchange conditions	Nr. of equations
Discharge	$Q_{up1} + Q_{up2} = Q_{down}$	1
Bed load	$Q_{up1,bed,g} + Q_{up2,bed,g} = Q_{down,bed,g}$	g=1..ng
Suspension	$Q_{up1}C_{up1,g} + Q_{up2}C_{up2,g} = Q_{down}C_{down,g}$	g=1..ng

The second approach is to regard the junction as a lateral inflow of a tributary into a river at a specified location (b). The discharge (and sediment) is passed from the tributary to the river as lateral inflow via source term. Additionally, the water level at the inflow cross section can be passed in return to the tributary. Despite its simplicity this approach can be suited well to simulate simple river junctions in 1-D.

8.2.4.4 Exchange conditions for river bifurcations in 1-D river networks

In case of modeling a river branch which bifurcates into two branches, the upstream discharge (and sediment) must be distributed among the two downstream sub-domains. The distribution factor ϕ among the downstream sub-domains has to be chosen according the local conditions. The downstream water elevations of the two downstream sub-domains are averaged and then passed in upstream direction.

Table 8.4 *Exchange conditions for river bifurcations*

	Exchange conditions	Nr. of equations
Discharge	$Q_{up} = \phi Q_{down1} + (1-\phi) Q_{down2}$	1
Bed load	$Q_{up,b,g} = \phi Q_{down1,b,g} + (1-\phi) Q_{down2,b,g}$	g=1..ng
Suspension	$Q_{up} C_g = \phi Q_{down1} C_{down1,g} + (1-\phi) Q_{down2,g} C_{down2,g}$	g=1..ng

8.2.4.5 Exchange conditions for combined 1-D and 2-D modelling

The combined 1-D river flow and 2-D floodplain modelling bases mainly on the approach presented by Beffa (2002). A conceptual overview is given in Figure 8.7 which illustrates river cross sections of the BASEchain sub-domain and the 2-D mesh of a floodplain modelled with a BASEplane sub-domain.

The coupling interfaces between the sub-domains are implemented as one-way couplings via source terms. As a consequence, only discharges are exchanged between the sub-domains. The exchange between the sub-domains is calculated as weir flow over the dykes of the 1-D cross section or as weir flow over the edges of 2-D sub-domain. The weir level is chosen as the higher elevation of the dyke or the corresponding edge. As weir width in the weir formula the length of the 2-D boundary edge is taken. Exchange of discharge is possible in both directions, either from the river into the floodplains or backwards depending on the water elevations in the 1-D cross section and the corresponding 2-D element.

To enable a flexible coupling approach it is possible to connect a 1-D cross section with multiple 2-D elements (1:n-relation). For each 2-Element, in contrast, only one connection to a 1-D cross section is possible (1:1-relation). The coupling interfaces are defined using a list, from which the connections are automatically extracted and generated during a pre-processing step.

Table 8.5 *Exchange conditions for lateral coupling*

	Exchange conditions	Nr. of equations
Discharge	$1D \rightarrow 2D$: $Q = \delta\ \mu \frac{2}{3} b_{weir} \sqrt{2g} h^{3/2}$ if $(z_{S,1D} \geq z_{S,2D})$ (side weir, δ= side weir reduction factor)	1
	$2D \rightarrow 1D$: $Q = \mu \frac{2}{3} b_{weir} \sqrt{2g} h^{3/2}$ if $(z_{S,1D} < z_{S,2D})$ (weir overfall over edge)	

The 1-D dyke crest elevation, where the water overtops, as well as the 1-D water surface elevation are interpolated between the cross section at the location of the 2-D edge. This procedure shall increase the accuracy of the lateral exchange modeling. It is assumed hereby, that the dyke-crest elevation and the water surface elevation vary linearly between

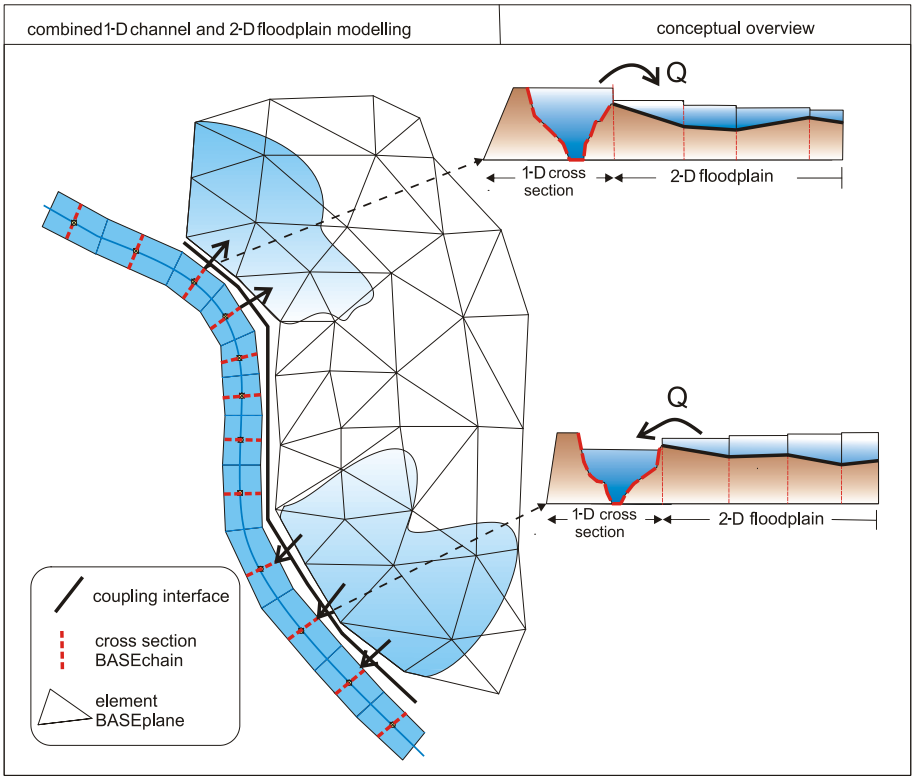

Figure 8.7 *Conceptual overview of combined 1-D river flow and 2-D floodplain modeling*

two adjacent 1-D cross-sections.

8.2.4.6 Data exchange for morphological simulations with multiple grain classes

In morphological, coupled simulations the possibility exists that sub-domains can have differing grain compositions. The handling of data exchange for such cases is not trivial and unclear. But such situations may arise in coupled large-scale simulations where grain classes get finer along course of the river. A flexible approach is adopted here which allows the usage of differing compositions as well as different numbers of grain classes of the sub-domains.

For data exchange the bed loads of each grain class are mapped on the grain classes of the receiving sub-domain. The mapping is achieved by three successive steps as illustrated in Figure 8.8. The sediment mass balance is thereby fulfilled.

8.2.5 Synchronization Concept

8.2.5.1 General remarks on synchronization

For the coupling of sub-domains a synchronization mechanism must be implemented which directs the execution of the sub-domains and controls the data exchanges at the appropriate times. The type and complexity of the synchronization effort thereby generally depends on the degree of spatial and temporal compatibility of the sub-domains. Especially in case

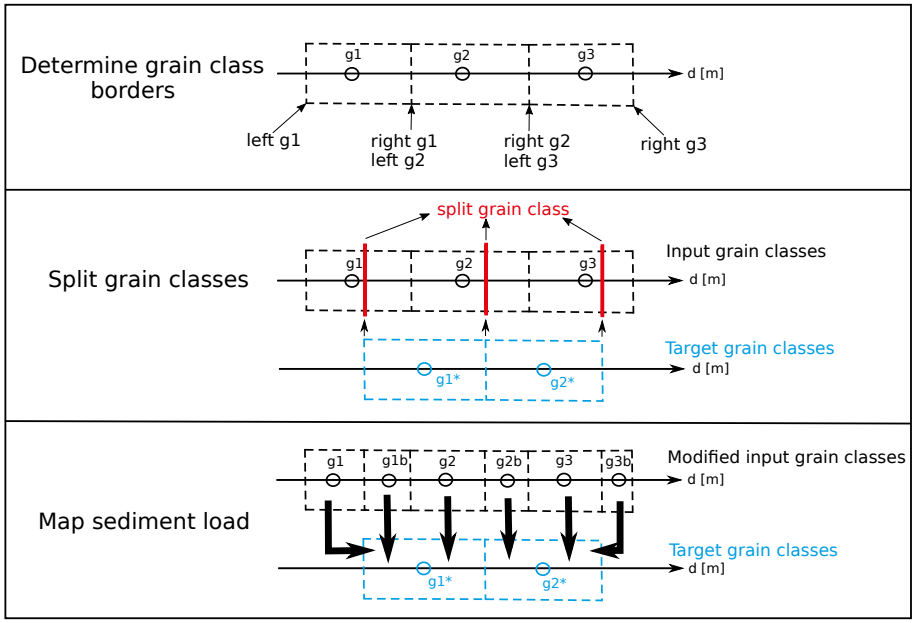

Figure 8.8 *Mapping of grain compositions from one sub-domain to another*

of combined 1-D and 2-D simulations the spatial extends and time step sizes can vary considerable.

Mainly two different coupling concepts are often encountered for the selection of the time step sizes of the sub-domains.

- All sub-domains are executed in a synchronous manner with an equal time step size. To guarantee stable execution the chosen time step size ("global time step") is set to the minimum time step size of all sub-domains, which is determined by stability conditions (CFL criterion). But due to the fact that the sub-domain time step sizes can vary considerable, such a restriction on the minimum time step size can lead to inefficient small time step sizes resulting in large computational efforts.
- In contrast, all sub-domains can be executed asynchronous with different time step sizes ("local time steps"), which are chosen according the sub-domain's optimal time step size. This approach does not suffer the computational inefficiency due to small time step sizes. But generally more synchronization efforts are required and data exchange between the sub-domains requires interpolations and can become cumbersome especially for complex interfaces like junctions or bifurcations.

Here, another approach is selected, a local-time stepping approach, lying in between these concepts and combining efficiency and simplicity.

8.2.5.2 "Local time stepping" approach

This approach bases on the method of local time stepping (LTS) as presented by Osher and Sanders (1983) and Sanders (2008). But in contrast to these methods, LTS is applied here to whole sub-domains instead of single grid elements. Different local time step sizes are allowed for the sub-domains instead of using one global time step for all sub-domains. This enables efficient computations by preventing very small time steps of single sub-domains to

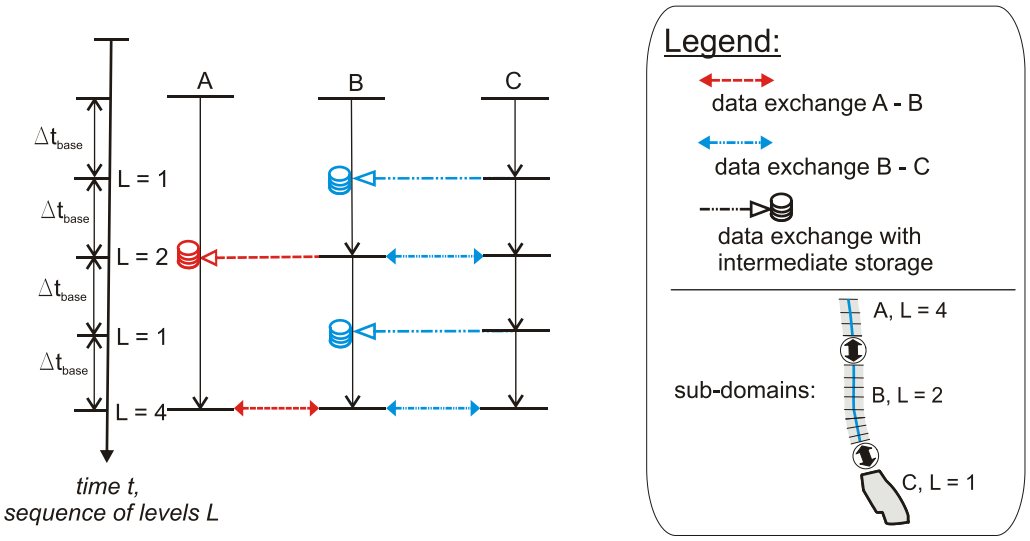

Figure 8.9 *LTS-synchronization for 3 sub-domains with different time step sizes. The sub-domain C with the smallest time step size determines the base time step. Sub-domains A and B run for multiples of 4 and 2 of the base time step size.*

dominate the time step sizes of the other sub-domains. But restrictions are set for the time step sizes in a way to ensure that the sub-domains always reach common time levels. At these common time levels data can be exchanged easily without the need for interpolations.

Hierarchical levels L are introduced and attributed to each sub-domain. These levels categorize the sub-domains into groups of common time step sizes. These levels are thereby chosen as power-of-two multiples of the base time step size Δt_{base} . This base time step is selected as the minimum time step size of all coupled sub-domains. The attribution of levels L to a sub-domain i depends on the relation of its present time step size to the base time step size and is determined as:

$$2^k \leq \frac{\Delta t_i}{\Delta t_{base}} < 2^{k+1} \rightarrow L_i = 2^k, k = 0..n$$

where L_i is the level attributed to the sub-domain i , k indicates the level and n is the number of levels. Each sub-domain determines its own local time step size as its level L_i multiplied with the base time step size $\Delta t_i = L_i \Delta t_{base}$.

The execution of the sub-domains takes place in loops over level sequences. One loop sequence of the LTS synchronization is sketched in Figure 8.9 for three sub-domains with different time step sizes ($\Delta t_A > \Delta t_B > \Delta t_C$) and levels L_i.

For example, in case that the maximum level of a sub-domain is 8, a level sequence of $m =$ [1,2,1,4,1,2,8] is executed, where m equals the present level of the loop. Each sub-domain is executed only if its level L_i is smaller or equal to the present level m. These sub-domains are then advanced for a time step size of $\Delta t_i = L_i \Delta t_{base}$. Data exchange between adjacent sub-domains takes place only when the sub-domains have reached a common level. If adjacent sub-domains have different time levels then the exchanged data must be stored intermediately to guarantee conservation principles. The data is finally passed over when the sub-domains reach a common time level. After the end of the loop of the level sequence, all sub-domains have been executed at least once and have finally have reached a common final time $t_{new} = t_{old} + n\Delta t_{base}$. From this starting point the levels L_i are assigned again

to the sub-domains and the procedure is repeated.

The selection of the base time level is done at the beginning of each level loop. To account for the possibility that the minimum time step could change during the loop iterations, due to changed flow conditions, the base time level can be reduced by a factor $F \leq 1$ for stability reasons.

8.3 BASEextern - data exchange during runtime

8.3.1 Introduction

The term "external coupling" means the coupling between the program BASEMENT and an external program. This may be e.g. a rainfall-run off model which delivers input data for a river reach or it may be a standalone groundwater model which makes use of the stream water elevations computed by BASEMENT. As described in the model coupling section, one can also distinguish here between one-way coupling and two-way coupling.

One-way coupling

Two different scenarios can be distinguished here:

- An external Program may receive data which is sent by BASEMENT. Therefore the external program must be defined as an external sub-domain in the command file. In the OUTPUT block an output must be defined and connected with this external sub-domain. While executing, BASEMENT sends data as soon as it is computed using the output routines to the specified external sub-domain. The external program must fetch the data using TCP/IP routines and must take care of the synchronization, i.e. it must always wait until new data is available.
- Another scenario is to send input data to BASEMENT. Thereby the external program again has to be defined as an external sub-domain in the coupling process and it must be connected with other sub-domains using boundary conditions. Then, the external program can send its data in XML format to BASEMENT using TCP/IP routines. BASEMENT takes care of the synchronization within the coupling process and always waits until new data is available before executing.

Two-way coupling

It is possible to couple an external program with BASEMENT with mutual data exchange. Again, the external program must be defined as an external sub-domain in the coupling process. Furthermore, the external program must implement a synchronization mechanism in order to check if the needed data is available. Differing from previous versions, BAEMENT now does NOT apply the local-time-stepping algorithm (LTS) to the external coupling. Data exchange takes place, when either BASEMENT or the external program is ahead in time.

For example:

- The external program is executed until it is ahead in time compared to BASEMENT. Then it has to send its current time and input data to BASEMENT. Afterwards, it waits and checks for incoming data over TCP/IP.

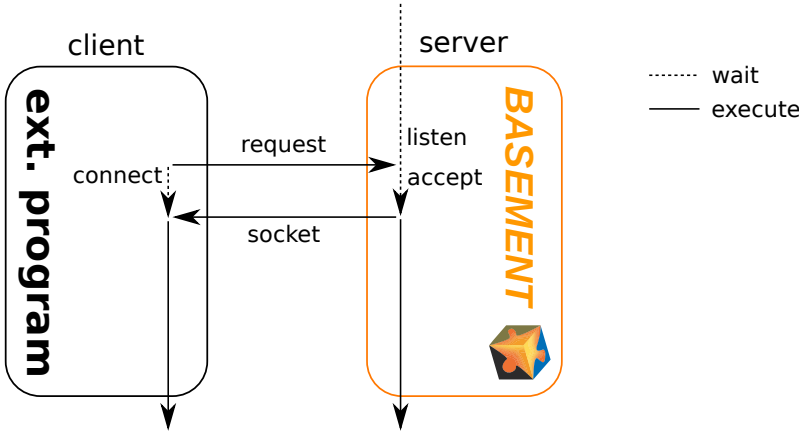

Figure 8.10 *Connection request from external program (client) to BASEMENT (server)*

- BASEMENT waits until the external program is ahead in time. While waiting, it checks for incoming data over TC/IP. If the incoming data shows that the external program is ahead in time, then BASEMENT runs as long as its current time is behind the time of the external program. Afterwards, if BASEMENT run-time exceeds the current time of the external program, it sends its current time and data to the external program.

Note

Please be aware that the external coupling approach is still in an experimental stage. In addition, the usage of this coupling requires programming efforts and knowledge in TCP/IP programing and XML parsing. External coupling may require the implementation of special boundary conditions in the BASEMENT model. For example, coupling with a groundwater model requires leakage boundaries for water exchange to be set. If you want to make use of such a coupling type, you may contact the developer team regarding the implementation of appropriate boundary conditions in the model.

8.3.1.1 Data exchange over TCP/IP

The data exchange between BASEMENT and the external program takes place using TCP/IP communication. This has the advantages that it is generally faster than communications via files and enables the coupling between different computers via intra- or internet, even using different operating systems.

Create connection

The communication requires an IP-address and a port-number as identifier and takes place using TCP-sockets. Usually BASEMENT runs as the server application and must be started first. Then, it waits for an incoming connection request. After the incoming request, a connection is established with the external program and the connection information is sent to the external program (socket descriptor). In case of multiple external programs, BASEMENT waits until all connections are established before it starts the computations.

Data packet

The data is wrapped in “data packets” using the common XML-format, whereby the data values and several additional attributes must be specified. All communications between

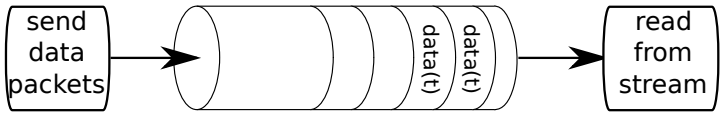

Figure 8.11 *Sending and receiving data from socket stream (FIFO pipe)*

the programs take place by sending data packets. Therefore, also additional information, like e.g. the time, or the time step size, must be included in the data packet. It is also possible to send or receive multiple data packets for different data types or boundaries. The XML-tag has the following structure

```
<Data attribute1="..." attribute2="...">...<\Data>
```

The data values within the XML tag can either be written as ascii or binary data. If ascii format is used, a semicolon separates multiple data values from each other, e.g.

```
<Data>10.0;10.0;10.0</Data>
```

The following attributes can be set:

Attribute	Values	Obligatory
size	number of data values	Yes
time	time of data values in sec	Yes
type	[Q,h,v,...] type of data	Yes
encoding	[ascii, binary]	No (default=ascii)
byte_order	[little_endian]	No
boundary	name of boundary condition of data values	Only if data is sent to BASEMENT
timestep	current time step of model in sec	Only for local time stepping

Data communication

The data communication via sockets can be compared to data exchange via file-streams. The data packets are inserted into a pipe and the other side of the connection reads the contents after the FIFO concept (First In First Out). The receiving part of the connection must parse the contents of the pipe and extract the data packets. The time attribute of the data packets indicate the time level of the other program required for the synchronization. If the time levels of the data packets are behind the program's time or if no data is in the pipe, than the program must wait and continuously check for incoming data.

8.4 Flow Control in River Systems

8.4.1 Introduction

The flow characteristics of a river system are not only governed by the character of a channel, the morphology and topography, but also by regulations for hydropower stations and lakes. Such regulations commonly demand that a certain water level is maintained or impose certain limits on the maximum discharge. The exertion of control structures has commonly a significant direct impact on certain river sections or even on the whole river system. The setting of the control structures over time cannot be defined in advance, but depends on the reaction to a change of the whole river system.

The numerical simulation of regulations is very helpful to properly judge such river systems, as it allows assessing and optimizing the effect of individual regulations of control structures on the whole system. This is of great importance as efficient flood control demands an optimal use of existing retention structures.

Therefore, the automatic steering of control structures has been added to BASEMENT, covering 1-D and 2-D simulations as well. The chosen approach allows the simultaneous combination of different controlled and manipulated variables. Controlled variables can be either water surface elevations or discharges. Here not only fixed values can be defined, but also series in time or values depending on the current flow in the river system. As manipulated variable, settings of weir or gates and an abstract outflow hydrograph has been implemented.

Within the present implementation, the determination of the control structure settings have been strongly abstracted, which allow a very flexible integration of further controlling algorithms in the future. As reference, a classical Proportional-Integral-Derivative (PID) controller has been implemented. By combining various control and manipulated variables within a single controller, BASEMENT now offers the possibility to simulate complex series of weirs over coupled regions.

8.4.2 Concept of Flow Control

There are many cases where the behaviour of boundary conditions such as weirs or gates depends on the actual state of the river system and cannot be described by a simple time-dependent boundary setting. An example would be adjusting the weir height in order to maintain a specific water level in front of the weir. This process is commonly denoted as controlling. The basic controller has a controlled variable, such as water surface elevation, which is desired to be kept at a certain level, i.e. its target value. The deviation from the current value of the controlled variable and its target value, also denoted as error, is then fed into the controller. The controller reads the deviation and calculates the new value for its manipulated variable. An example for a manipulated variable would be a weir height. The new value for the manipulated variable is then fed into the system, i.e. the hydraulic simulation, which finally affects the controlled variable.

In Basement, the system is represented by the simulation, the controller is a mathematical function $\boldsymbol{f}(.)$, determining the values of the manipulated variables $\boldsymbol{u}(t)$ from the values of the monitored variables $\boldsymbol{m}(t)$. This can be expressed using the following mathematical expression:

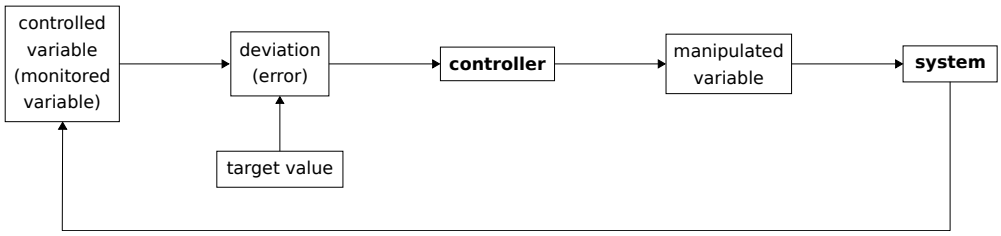

Figure 8.12 *Basic Control Cycle*

$$\boldsymbol{u}(t) = \boldsymbol{f}(\boldsymbol{m}(t))$$

Logically, there can be multiple monitored and manipulated variables.

8.4.2.1 Monitored Variable

A monitored variable is defined by

$$m_i(t) = \nu_i(t - \tau_i) - \nu_{target,i}$$

Here, ν_i can be either a water surface elevation, measured on a specific cross-section (1-D) or element (2-D), or a water flow over a cross section (1-D) or a STRINGDEF (2-D). $\nu_{target,i}$ describes the target value, or in case of a *feed forward* controller, the equilibrium state. τ_i is a delay time controlling when the information of the measured variable is fed into the controller.

8.4.2.2 Manipulated Variable

A *manipulated variable* refers to a boundary condition and can be a weir height, a gate level or an outflow (in case of 1-D hydrographs as downstream boundary).

8.4.3 Controller Types

8.4.3.1 PID-Controller

One possible approach to describe the mathematical function $\boldsymbol{f}(.)$ is a PID (proportional-integral-derivative) controller. This type of controller relates a monitored variable to a manipulated variable by three additive controller elements:

$$u_i(t) = \underbrace{K_{p,ij} m_j(t)}_{P-Element} + \underbrace{\int_0^t K_{I,ij} m_j(t')dt'}_{I-Element} + \underbrace{K_{D,ij} \frac{d}{dt} m_j(t)}_{D-Element}$$

Internally, the PID-controller is implemented in its differential form (i.e. the change of is calculated in each time step). The three required variables are K_P, K_I and K_D. The correct definition of these variables is very crucial to the proper operation of the controller. Which values should be used is highly dependent on the system and therefore requires some care and experience.

The P-element represents an adjustment proportional to the deviation and therefore only limits the deviation, but does not bring the system back into the state where no deviation exists. For this reason, the I-Element integrates the deviation and consequently, the system can be forced into its equilibrium state. If the response of the I-Element is too strong compared to the P-Element, the system oscillates. If the values of both P and I elements are too small, the reaction of the system is very slow or even too weak to re-establish the given targets. The D-Element depends on the change of the monitored variable and is used to quickly adapt the manipulated variables in case of a fast change.

More on the determination of correct PID coefficients can be found in the article by Fäh and Kühne (1987). Recommendations on how to choose the coefficients are given in the integrated help of the software.

8.5 Built-In GUI Tools

In this section some built-in BUI tools are explained and information about the usage is provided. Built-in GUI Tools will pop up if a certain tag is activated by the user.

8.5.1 Interactive Visualization during run time using BASEviz

BASEviz is a small and lightweight visualization tool which can be used to visualize simulation results during run time. To activate the visualization tool, a *SPECIAL_OUTPUT* block of 'BASEviz' type must be created within the parent OUTPUT block. Then the BASEviz window will appear automatically by starting the simulation. The output can be visualized interactively using the mouse and keyboard keys according to the legend shown in the BASEviz window (see Figure 8.13 and Figure 8.14). The view can be changed and the displayed variables can be selected. This visualization tool allows to easily check for a correct simulation setup and to stop a simulation run if some evident problems arise. Furthermore, it is possible to dump the rendered images from the visualization window in a JPEG image for a given time interval.

- BASEviz for 1-D simulations with BASEchain:

  All 1-D cross sections with its multiple slices are plotted one after the other along the x-axis. The water elevation is plotted within each cross section slice according to its present value.

- BASEviz for 2-D simulations with BASEplane:

  The unstructured 2-D mesh is plotted in combination with a contour plot of a chosen output flow variable. Optionally, velocity vectors can be added to the data visualization.

BASEviz is based on the visualization libraries of the Visualization ToolKit (VTK,http://www.vtk.org) which makes use of OpenGL for rendering.

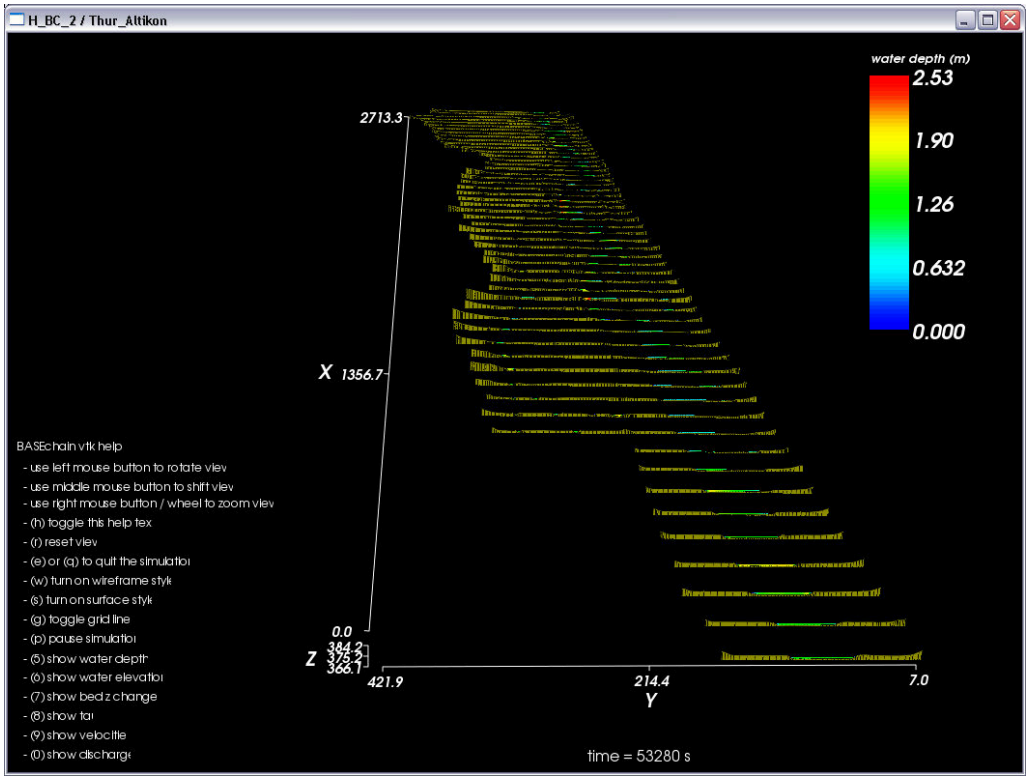

Figure 8.13 *Visualization of BASEchain with BASEviz*

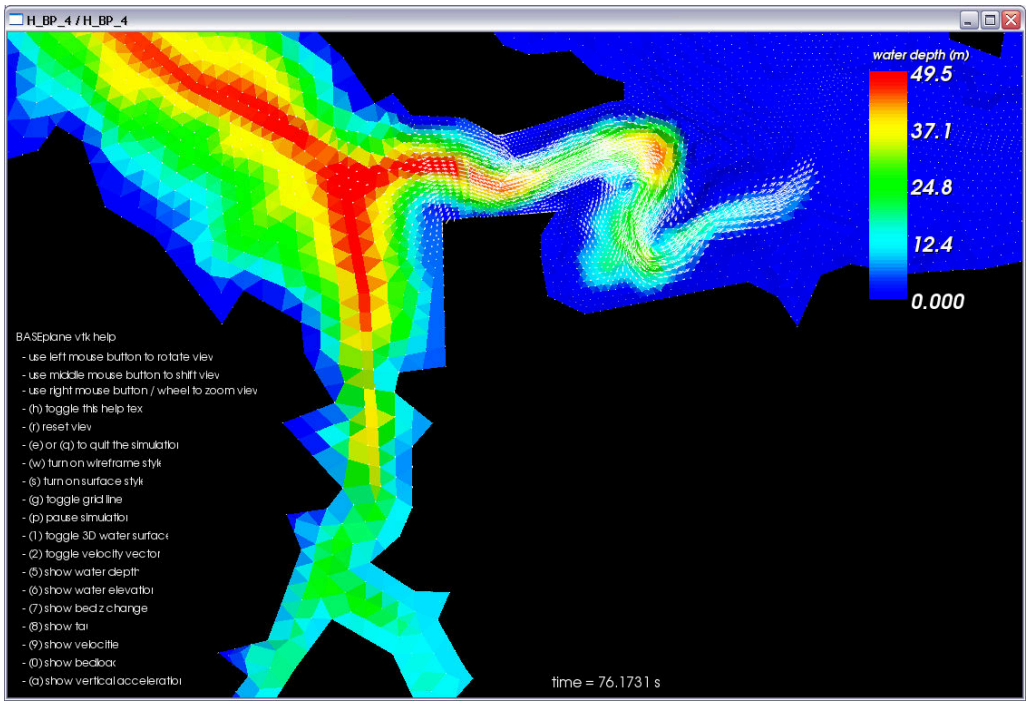

Figure 8.14 *Visualization of BASEplain with BASEviz*

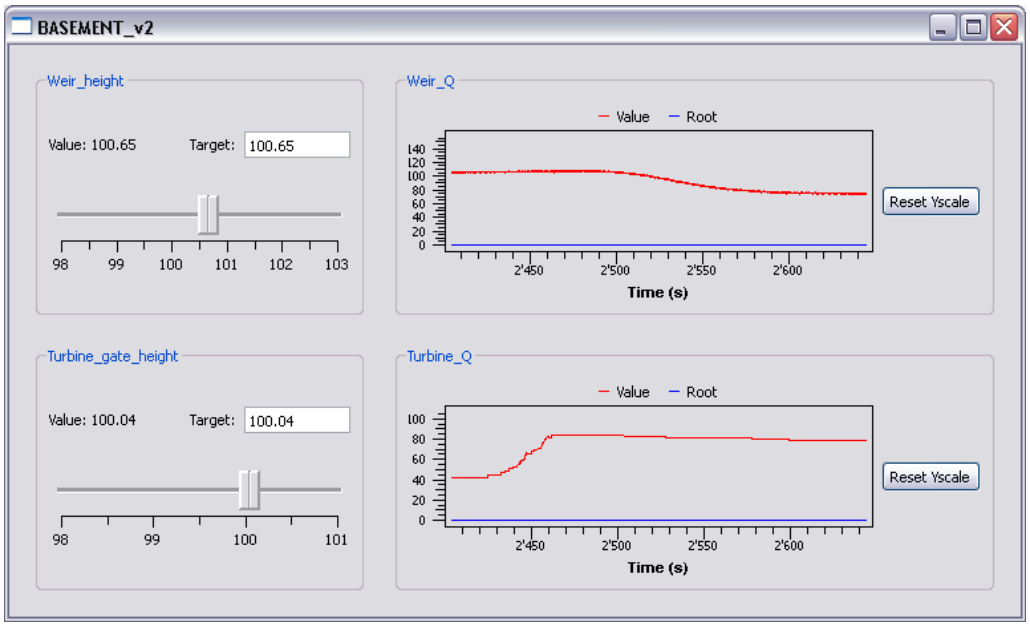

Figure 8.15 *Interface for the manual control and monitoring of the selected variables.*

8.5.2 Manual Controller Interface (HID)

In order to create a controller, a new CONTROLLER block is generated in the DOMAIN block. The HID controller provides an interface for the manual operation (Figure 8.15). The control window will pop up automatically after starting the simulation with the start button. In the CONTROLLER block several manipulated variables and controlled variables can be defined. The manipulated variables will appear on the left hand side of the controller interface, whereas the monitored variables will show up on the right hand side (Figure 8.15). In this example two manipulated variables (height of a weir and height of a gate) and two monitored variables (discharge over the weir and through the gate) are selected. With the cursor the slide can be moved within the predefined range of the manipulated variable. Additionally the target value can be entered directly into the white text box (Target). As the simulation proceeds the impact on the monitored variable is visualized on the chart on the right hand side. Additionally the output and the impact of your control measures can be visualised with BASEviz (Section 8.5.1).

9

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BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

APPENDIX

VERSION 4.1.0
JUNE 2024

1

Third Party Software

1.1 Third party software licenses

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```
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one; be sure to read it in full, and don't assume that anything in it is
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  The reason we have a separate public license for some libraries is that
they blur the distinction we usually make between modifying or adding to a
program and simply using it.  Linking a program with a library, without
changing the library, is in some sense simply using the library, and is
analogous to running a utility program or application program.  However, in
a textual and legal sense, the linked executable is a combined work, a
derivative of the original library, and the ordinary General Public License
treats it as such.

  Because of this blurred distinction, using the ordinary General
Public License for libraries did not effectively promote software
sharing, because most developers did not use the libraries.  We
concluded that weaker conditions might promote sharing better.

  However, unrestricted linking of non-free programs would deprive the
users of those programs of all benefit from the free status of the
libraries themselves.  This Library General Public License is intended to
permit developers of non-free programs to use free libraries, while
preserving your freedom as a user of such programs to change the free
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this as regards changes in header files, but we have achieved it as regards
changes in the actual functions of the Library.)  The hope is that this
will lead to faster development of free libraries.

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"work based on the library" and a "work that uses the library".  The
former contains code derived from the library, while the latter only
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works together with the library.

  Note that it is possible for a library to be covered by the ordinary
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which has been distributed under these terms.  A "work based on the
Library" means either the Library or any derivative work under
copyright law: that is to say, a work containing the Library or a
portion of it, either verbatim or with modifications and/or translated
straightforwardly into another language.  (Hereinafter, translation is
included without limitation in the term "modification".)

  "Source code" for a work means the preferred form of the work for
making modifications to it.  For a library, 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 library.

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and what the program that uses the Library does.

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    b) You must cause the files modified to carry prominent notices
    stating that you changed the files and the date of any change.

    c) You must cause the whole of the work to be licensed at no
    charge to all third parties under the terms of this License.

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    table of data to be supplied by an application program that uses
    the facility, other than as an argument passed when the facility
    is invoked, then you must make a good faith effort to ensure that,
    in the event an application does not supply such function or
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    table, the facility still operates, and performs whatever part of
    its purpose remains meaningful.

    (For example, a function in a library to compute square roots has
    a purpose that is entirely well-defined independent of the
    application.  Therefore, Subsection 2d requires that any
    application-supplied function or table used by this function must
    be optional: if the application does not supply it, the square
    root function must still compute square roots.)

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  Once this change is made in a given copy, it is irreversible for
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subsequent copies and derivative works made from that copy.

  This option is useful when you wish to copy part of the code of
the Library into a program that is not a library.

  4. You may copy and distribute the Library (or a portion or
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under the terms of Sections 1 and 2 above provided that you 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.

  If distribution of 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 satisfies the requirement to
distribute the source code, even though third parties are not
compelled to copy the source along with the object code.

  5. A program that contains no derivative of any portion of the
Library, but is designed to work with the Library by being compiled or
linked with it, is called a "work that uses the Library".  Such a
work, in isolation, is not a derivative work of the Library, and
therefore falls outside the scope of this License.

  However, linking a "work that uses the Library" with the Library
creates an executable that is a derivative of the Library (because it
contains portions of the Library), rather than a "work that uses the
library".  The executable is therefore covered by this License.
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Section 6 states terms for distribution of such executables.

  When a "work that uses the Library" uses material from a header file
that is part of the Library, the object code for the work may be a
derivative work of the Library even though the source code is not.
Whether this is true is especially significant if the work can be
linked without the Library, or if the work is itself a library.  The
threshold for this to be true is not precisely defined by law.

  If such an object file uses only numerical parameters, data
structure layouts and accessors, and small macros and small inline
functions (ten lines or less in length), then the use of the object
file is unrestricted, regardless of whether it is legally a derivative
work.  (Executables containing this object code plus portions of the
Library will still fall under Section 6.)

  Otherwise, if the work is a derivative of the Library, you may
distribute the object code for the work under the terms of Section 6.
Any executables containing that work also fall under Section 6,
whether or not they are linked directly with the Library itself.

  6. As an exception to the Sections above, you may also compile or
link a "work that uses the Library" with the Library to produce a
work containing portions of the Library, and distribute that work
under terms of your choice, provided that the terms permit
modification of the work for the customer's own use and reverse
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    a) Accompany the work with the complete corresponding
    machine-readable source code for the Library including whatever
    changes were used in the work (which must be distributed under
    Sections 1 and 2 above); and, if the work is an executable linked
    with the Library, with the complete machine-readable "work that
    uses the Library", as object code and/or source code, so that the
    user can modify the Library and then relink to produce a modified
    executable containing the modified Library.  (It is understood
    that the user who changes the contents of definitions files in the
    Library will not necessarily be able to recompile the application
    to use the modified definitions.)

    b) Accompany the work with a written offer, valid for at
    least three years, to give the same user the materials
    specified in Subsection 6a, above, for a charge no more
    than the cost of performing this distribution.

    c) If distribution of the work is made by offering access to copy
    from a designated place, offer equivalent access to copy the above
    specified materials from the same place.

    d) Verify that the user has already received a copy of these
    materials or that you have already sent this user a copy.

  For an executable, the required form of the "work that uses the
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reproducing the executable from it.  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.

  It may happen that this requirement contradicts the license
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restrictions of other proprietary libraries that do not normally
accompany the operating system.  Such a contradiction means you cannot
use both them and the Library together in an executable that you
distribute.

  7. You may place library facilities that are a work based on the
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library, provided that the separate distribution of the work based on
the Library and of the other library facilities is otherwise
permitted, and provided that you do these two things:

    a) Accompany the combined library with a copy of the same work
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    facilities.  This must be distributed under the terms of the
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  <signature of Ty Coon>, 1 April 1990
  Ty Coon, President of Vice

That's all there is to it!
```

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](README.ijg)

  This license applies to the libjpeg API library and associated programs
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- The Modified (3-clause) BSD License, which is listed below

  This license covers the TurboJPEG API library and associated programs, as
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- The [zlib License](https://opensource.org/licenses/Zlib)

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=========================================

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```

```
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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.
```

Liblzma

```
XZ Utils Licensing
==================

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Pegtl-2

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Qt5-base

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                           Version 1.0, January 1, 2003

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       and does not require the author to provide source
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       widgets against a user-supplied version of Qwt.

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       1, 2, and 4.

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       of the LGPL.


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           [program/widget] is based in part on the work of
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library does the same job as widely used non-free libraries.  In this
case, there is little to gain by limiting the free library to free
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    table, the facility still operates, and performs whatever part of
    its purpose remains meaningful.

    (For example, a function in a library to compute square roots has
    a purpose that is entirely well-defined independent of the
    application.  Therefore, Subsection 2d requires that any
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    be optional: if the application does not supply it, the square
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  This option is useful when you wish to copy part of the code of
the Library into a program that is not a library.

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under the terms of Sections 1 and 2 above provided that you accompany
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medium customarily used for software interchange.
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  If distribution of 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 satisfies the requirement to
distribute the source code, even though third parties are not
compelled to copy the source along with the object code.

  5. A program that contains no derivative of any portion of the
Library, but is designed to work with the Library by being compiled or
linked with it, is called a "work that uses the Library".  Such a
work, in isolation, is not a derivative work of the Library, and
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  However, linking a "work that uses the Library" with the Library
creates an executable that is a derivative of the Library (because it
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Section 6 states terms for distribution of such executables.

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that is part of the Library, the object code for the work may be a
derivative work of the Library even though the source code is not.
Whether this is true is especially significant if the work can be
linked without the Library, or if the work is itself a library.  The
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  If such an object file uses only numerical parameters, data
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functions (ten lines or less in length), then the use of the object
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  Otherwise, if the work is a derivative of the Library, you may
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Any executables containing that work also fall under Section 6,
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  6. As an exception to the Sections above, you may also combine or
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  You must give prominent notice with each copy of the work that the
Library is used in it and that the Library and its use are covered by
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    changes were used in the work (which must be distributed under
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    with the Library, with the complete machine-readable "work that
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    b) Use a suitable shared library mechanism for linking with the
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    rather than copying library functions into the executable, and (2)
    will operate properly with a modified version of the library, if
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    the user installs one, as long as the modified version is
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    c) Accompany the work with a written offer, valid for at
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  Ty Coon, President of Vice

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Shapelib

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[This is the first released version of the library GPL.  It is
 numbered 2 because it goes with version 2 of the ordinary GPL.]

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they blur the distinction we usually make between modifying or adding to a
program and simply using it.  Linking a program with a library, without
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analogous to running a utility program or application program.  However, in
a textual and legal sense, the linked executable is a combined work, a
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treats it as such.
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  Because of this blurred distinction, using the ordinary General
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sharing, because most developers did not use the libraries.  We
concluded that weaker conditions might promote sharing better.

  However, unrestricted linking of non-free programs would deprive the
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this as regards changes in header files, but we have achieved it as regards
changes in the actual functions of the Library.)  The hope is that this
will lead to faster development of free libraries.

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  Note that it is possible for a library to be covered by the ordinary
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    table of data to be supplied by an application program that uses
    the facility, other than as an argument passed when the facility
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    in the event an application does not supply such function or
    table, the facility still operates, and performs whatever part of
    its purpose remains meaningful.

    (For example, a function in a library to compute square roots has
    a purpose that is entirely well-defined independent of the
    application.  Therefore, Subsection 2d requires that any
    application-supplied function or table used by this function must
    be optional: if the application does not supply it, the square
    root function must still compute square roots.)

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  This option is useful when you wish to copy part of the code of
the Library into a program that is not a library.

  4. You may copy and distribute the Library (or a portion or
derivative of it, under Section 2) in object code or executable form
under the terms of Sections 1 and 2 above provided that you accompany
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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.

  If distribution of 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 satisfies the requirement to
distribute the source code, even though third parties are not
compelled to copy the source along with the object code.

  5. A program that contains no derivative of any portion of the
Library, but is designed to work with the Library by being compiled or
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work, in isolation, is not a derivative work of the Library, and
therefore falls outside the scope of this License.

  However, linking a "work that uses the Library" with the Library
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Section 6 states terms for distribution of such executables.

  When a "work that uses the Library" uses material from a header file
that is part of the Library, the object code for the work may be a
derivative work of the Library even though the source code is not.
Whether this is true is especially significant if the work can be
linked without the Library, or if the work is itself a library.  The
threshold for this to be true is not precisely defined by law.

  If such an object file uses only numerical parameters, data
structure layouts and accessors, and small macros and small inline
functions (ten lines or less in length), then the use of the object
file is unrestricted, regardless of whether it is legally a derivative
work.  (Executables containing this object code plus portions of the
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  Otherwise, if the work is a derivative of the Library, you may
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    with the Library, with the complete machine-readable "work that
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    to use the modified definitions.)

    b) Accompany the work with a written offer, valid for at
    least three years, to give the same user the materials
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That's all there is to it!
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Zlib

```
ZLIB DATA COMPRESSION LIBRARY

zlib 1.2.12 is a general purpose data compression library.  All the code is
thread safe.  The data format used by the zlib library is described by RFCs
(Request for Comments) 1950 to 1952 in the files
http://tools.ietf.org/html/rfc1950 (zlib format), rfc1951 (deflate format) and
rfc1952 (gzip format).

All functions of the compression library are documented in the file zlib.h
(volunteer to write man pages welcome, contact zlib@gzip.org).  A usage example
of the library is given in the file test/example.c which also tests that
the library is working correctly.  Another example is given in the file
test/minigzip.c.  The compression library itself is composed of all source
files in the root directory.

To compile all files and run the test program, follow the instructions given at
the top of Makefile.in.  In short "./configure; make test", and if that goes
well, "make install" should work for most flavors of Unix.  For Windows, use
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one of the special makefiles in win32/ or contrib/vstudio/ .  For VMS, use
make_vms.com.

Questions about zlib should be sent to <zlib@gzip.org>, or to Gilles Vollant
<info@winimage.com> for the Windows DLL version.  The zlib home page is
http://zlib.net/ .  Before reporting a problem, please check this site to
verify that you have the latest version of zlib; otherwise get the latest
version and check whether the problem still exists or not.

PLEASE read the zlib FAQ http://zlib.net/zlib_faq.html before asking for help.

Mark Nelson <markn@ieee.org> wrote an article about zlib for the Jan.  1997
issue of Dr.  Dobb's Journal; a copy of the article is available at
http://marknelson.us/1997/01/01/zlib-engine/ .

The changes made in version 1.2.12 are documented in the file ChangeLog.

Unsupported third party contributions are provided in directory contrib/ .

zlib is available in Java using the java.util.zip package, documented at
http://java.sun.com/developer/technicalArticles/Programming/compression/ .

A Perl interface to zlib written by Paul Marquess <pmqs@cpan.org> is available
at CPAN (Comprehensive Perl Archive Network) sites, including
http://search.cpan.org/~pmqs/IO-Compress-Zlib/ .

A Python interface to zlib written by A.M. Kuchling <amk@amk.ca> is
available in Python 1.5 and later versions, see
http://docs.python.org/library/zlib.html .

zlib is built into tcl: http://wiki.tcl.tk/4610 .

An experimental package to read and write files in .zip format, written on top
of zlib by Gilles Vollant <info@winimage.com>, is available in the
contrib/minizip directory of zlib.


Notes for some targets:

- For Windows DLL versions, please see win32/DLL_FAQ.txt

- For 64-bit Irix, deflate.c must be compiled without any optimization. With
  -O, one libpng test fails. The test works in 32 bit mode (with the -n32
  compiler flag). The compiler bug has been reported to SGI.

- zlib doesn't work with gcc 2.6.3 on a DEC 3000/300LX under OSF/1 2.1 it works
  when compiled with cc.

- On Digital Unix 4.0D (formely OSF/1) on AlphaServer, the cc option -std1 is
  necessary to get gzprintf working correctly. This is done by configure.

- zlib doesn't work on HP-UX 9.05 with some versions of /bin/cc. It works with
  other compilers. Use "make test" to check your compiler.

- gzdopen is not supported on RISCOS or BEOS.

- For PalmOs, see http://palmzlib.sourceforge.net/


Acknowledgments:

  The deflate format used by zlib was defined by Phil Katz.  The deflate and
  zlib specifications were written by L.  Peter Deutsch.  Thanks to all the
  people who reported problems and suggested various improvements in zlib; they
  are too numerous to cite here.

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  jloup@gzip.org          madler@alumni.caltech.edu

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  The requirement to provide Installation Information does not include a
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  Corresponding Source conveyed, and Installation Information provided,
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  If such an object file uses only numerical parameters, data
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functions (ten lines or less in length), then the use of the object
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work.  (Executables containing this object code plus portions of the
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  Otherwise, if the work is a derivative of the Library, you may
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    changes were used in the work (which must be distributed under
    Sections 1 and 2 above); and, if the work is an executable linked
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    with the Library, with the complete machine-readable "work that
    uses the Library", as object code and/or source code, so that the
    user can modify the Library and then relink to produce a modified
    executable containing the modified Library.  (It is understood
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    Library will not necessarily be able to recompile the application
    to use the modified definitions.)

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    rather than copying library functions into the executable, and (2)
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