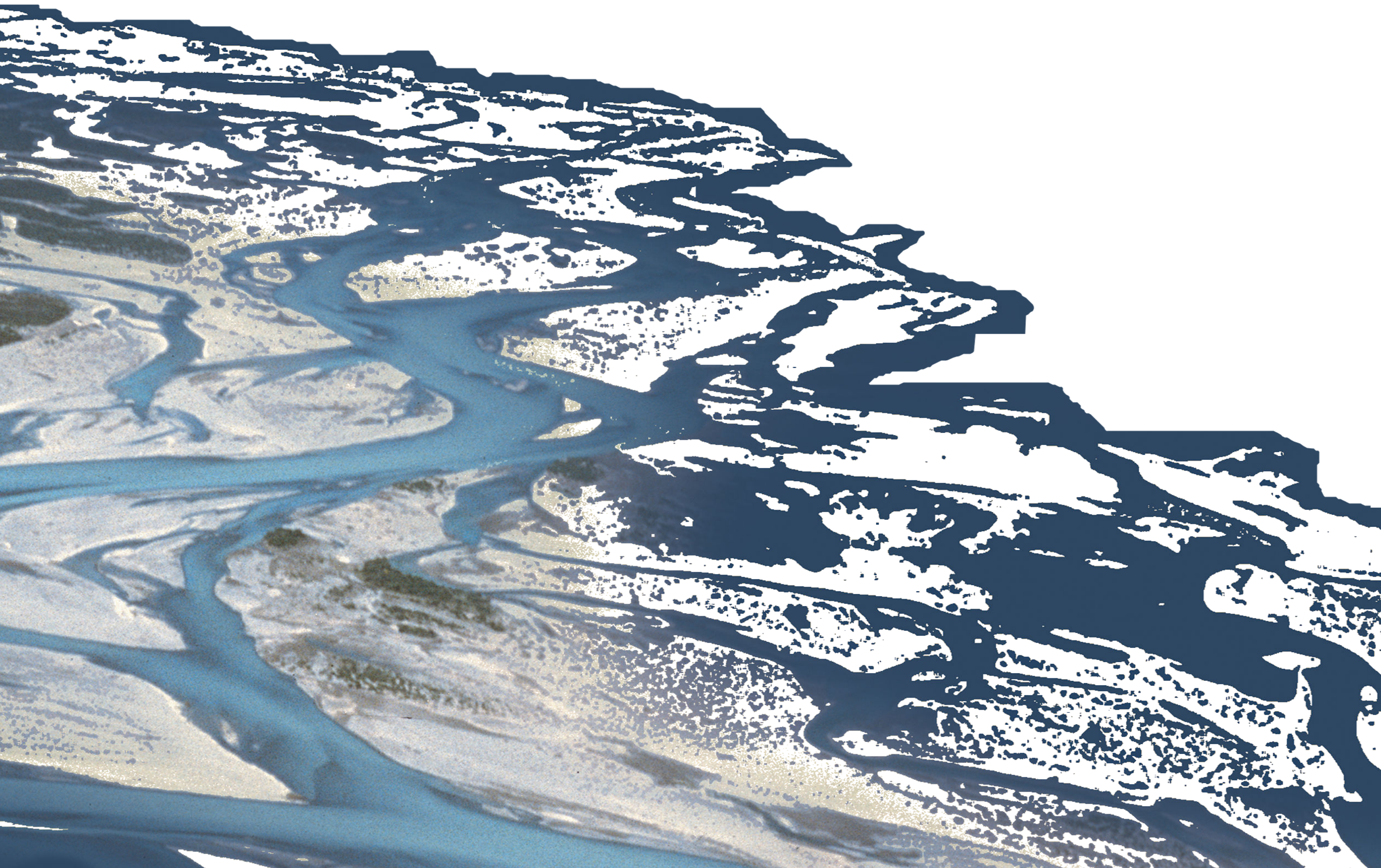
BASEMENT

BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

SYSTEM MANUALS

VERSION 4.0
FEBRUARY 2023



Preamble

VERSION 4.0.0

February 2023

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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Contact

Website: https://www.basement.ethz.ch
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Citation Advice

For System Manuals:

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For Website:

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For Software:

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BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

TUTORIALS

VERSION 4.0
FEBRUARY 2023

Contents

1

Introduction to BASEmesh

1.1 Introduction to BASEmesh

What is the goal of these tutorials? The following tutorials introduce the creation of computational meshes using BASEmesh and the integrated mesh generator Triangle. Besides mesh generation, features for loading and editing existing meshes are presented. Not all features of BASEmesh can be covered, but using the available tutorials will give you an impression of its workflow and its capabilities. For specific questions, a help function describing the necessary input layers and parameters is included in every tool of BASEmesh and can be accessed under the tab Help. Furthermore, these tutorials introduce several basic GIS - operations using QGIS. As all features and aspects of QGIS cannot be covered, we recommend the excellent documentation of QGIS for specific features or tasks.

What is the philosophy of mesh creation with BASEmesh? BASEmesh is a free and open source pre- and postprocessing QGIS plugin. It generates meshes for the numerical simulation software BASEMENT using Jonathan Richard Shewchuk's mesh generator 'Triangle'. The focus of BASEmesh is on the automatic generation of unstructured meshes based on specific quality criteria. BASEmesh follows the philosophy of separating the tasks of high-quality mesh generation and the generation/use of elevation models.

What is the workflow of BASEmesh? Please take a look at the figure below to see the workflow in BASEmesh. There are 3 main steps of the mesh generation process: (1) Create Elevation Mesh (2) Create Quality Mesh (3) Create Computational Mesh

For further details, please refer to Section 2.2 "2D grid generation with BASEmesh QGIS plugin" of the BASEMENT User Manual.

This tutorial covers the following BASEmesh workflow:

- Tutorial 1: Creation and export of a computational mesh for BASEMENT using pointwise elevation data.

Future tutorials will cover the following workflows in BASEmesh:

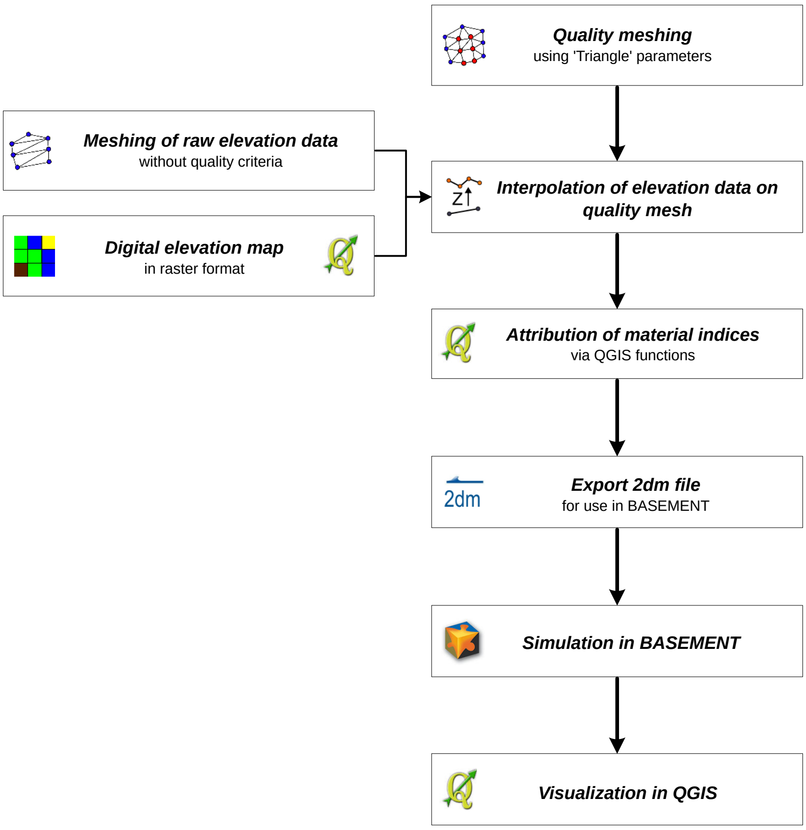


Figure 1.1 *General workflow for the creation of a computational mesh with BASEmesh.*

- Tutorial 2: Modifying of a computational mesh and using raster elevation data.
- Tutorial 3: Using dividing constraints along boundary cross sections and setting up a BASEMENT simulation.
- Tutorial 4: Create 1D cross sections with HEC-RAS and use BASEmesh to convert them into BASEMENT format.

1.2 Mesh Generation based on Pointwise Elevation Data

The following tutorial illustrates the consecutive steps to create a high-quality computational mesh based on pointwise elevation data stored in a text file. The elevation data in this tutorial is represented by cross section data, gathered in a river restoration project in Switzerland by terrestrial survey. All other files have been edited or created based on this elevation data. This tutorial exemplifies the mesh generation based on given river cross section data. Another typical task, e.g. for flood simulations with overland flow, is the generation of meshes based on a digital elevation model (DEM) in raster format.

Input Data The data needed to complete this tutorial comes as ZIP - file and needs to be extracted to a location of your choice. All screenshots and figures in this document were taken from QGIS version 3.16 Hannover. All data files have to be loaded into the QGIS - project before executing the different tools, as it is not possible to select files directly on the hard drive by browsing. Furthermore, those files must be activated in the QGIS Table of Contents (TOC- this abbreviation will be used often in this tutorial) on the left side of the screen. To prevent the selection of wrong shapetypes, the available fields are populated with the corresponding data type.

Rule of thumb Only data that is displayed on the map can be used for meshing.

Only 2 shapefiles are needed as input data for this tutorial. All other input files are created using BASEmesh and other QGIS functions. In case of difficulties, the result files for each step are additionally provided in the subfolder called ‘additional_files’.

1.2.1 Project Settings

(1) Start QGIS and make sure that the plugin BASEmesh is successfully installed (see Section 2.2.1 of the BASEMENT User Manual).

It is advisable to create a QGIS project with a meaningful name. The project’s name is used as basis for most of the files created with BASEmesh.

(2) Go to *Project* → *Project Properties*.

(3) Under *General* → *General settings* you will find the field *Project title*. Enter a name of your choice. Here the name ‘Tutorial’ was chosen.

In this tutorial we need the Swiss projection ‘CH1903 / LV03’. In the following steps, the project’s coordinate reference system (CRS) will be changed.

(4) Under *CRS* you can see the coordinate reference system settings for this project. Check *Enable* ’*on the fly CRS’ transformation* only to change the reference system.

(5) Enter the EPSG code ‘21781’ in the field *Filter*.

(6) Select the coordinate reference system ‘CH1903 / LV03’.

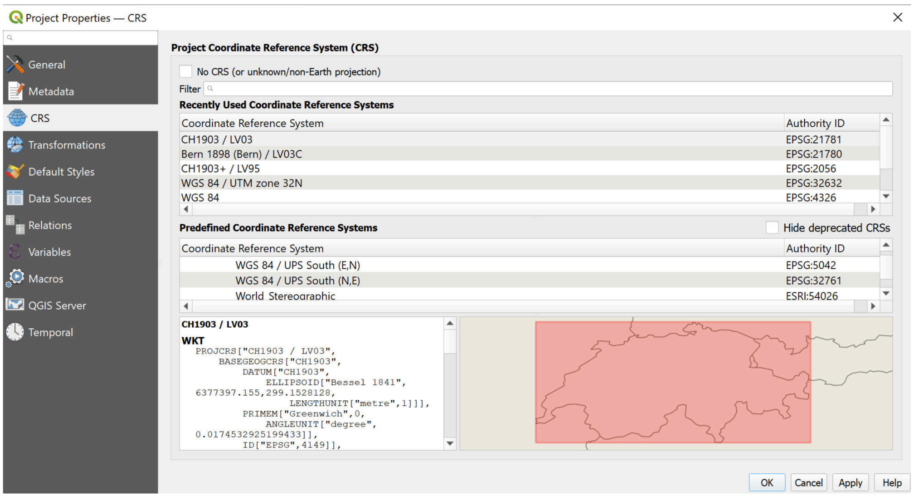


Figure 1.2 *Project Properties, CRS*

(7) Click *OK*.

(8) Again go to *Project* → *Project Properties* → *CRS*.

(9) Close the project properties window. If everything went well, you should see the chosen project name at the title of the QGIS main window and the EPSG code of your coordinate system at the lower right corner of the QGIS desktop.

(10) Now save the project: Go to *Project* → *Save*. The project name chosen before is automatically proposed.

1.2.2 Coordinate Reference System Configuration

Now we need to check how QGIS determines the coordinate system of added layers. This may vary between QGIS versions and operating systems.

(1) Go to *Settings* → *Options*

(2) Under *CRS* fill in the dialog as shown in Figure 1.3. Make sure that *Use project CRS* under *CRS for new layers* is checked.

(3) Close the dialog.

Now that the project and coordinate reference system properties have been set successfully, we can start adding data to the current project.

1.2.3 Loading Input Data for Elevation Model

In this tutorial the elevation model is represented by a triangulated irregular network TIN, refered to in the following sections as an 'elevation mesh'. Thus, our first step is loading the elevation data into our QGIS project. This data originates from cross sectional data and is stored in a delimited text file, where the values are separated by a comma. We will load this text file and convert it to a shapefile, which is more suitable for working in a GIS environment.

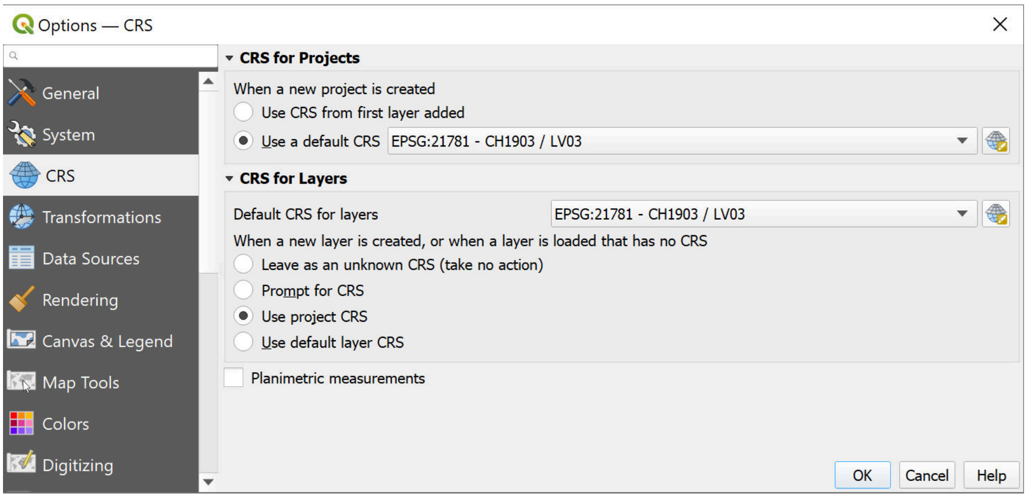


Figure 1.3 *Settings, CRS*

(1) Go to *Layer* → *Add layer* → *Add Delimited Text Layer*.

(2) Fill in the dialog that shows up (see Figure 1.4): Browse for the file containing the elevation data, 'XS_points_straightened.txt' provided with this tutorial. Be sure to select *Comma* as delimiter. Otherwise QGIS will not be able to separate the values found in the file. Under *Geometry definition* select *Point coordinates* and verify if the X, Y, and Z coordinates are set correctly.

(3) Be sure to check *Use spatial Index*.

(4) At the bottom of the dialog a preview of the file content using the selected delimiter and coordinate fields is given. If everything seems to be correct and according to Figure 1.4 , click *OK*.

(5) After successful import you will see the river cross sections displayed in the QGIS map canvas. The flow direction is from the bottom left corner to the upper right corner.

1.2.4 Converting Input Elevation Data to 3D Points

The loaded elevation data must be convereted into a format that can be used by BASEmesh. We will first convert the data into a shapefile.

(1) Right-click on layer 'XS_points_straightened' in the TOC.

(2) Go to *Export* → *Save Featues As...*

(3) Fill in the dialog according to Figure 1.5 and click *OK*.

(4) You will now see two layers in the TOC with the same name. The layer that represents the data from the text file can now be deleted by right-clicking on it in the TOC and selecting *Remove Layer*. If both layers have the same symbology, you can check its properties by right-clicking and selecting *Properties*.

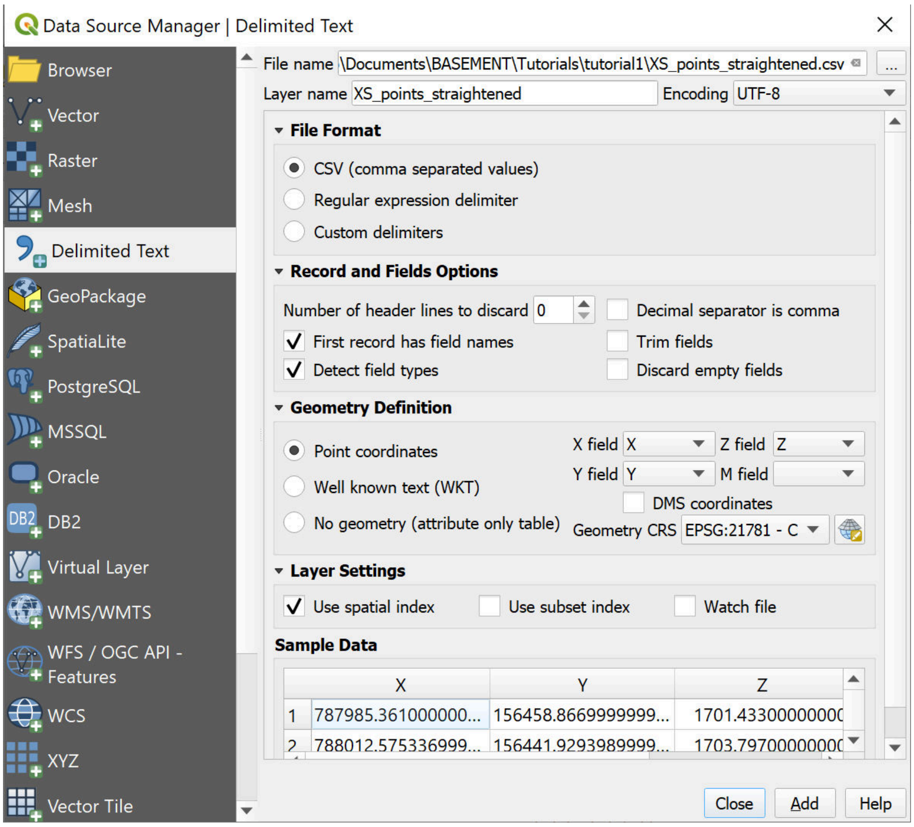


Figure 1.4 *Add delimited text layer*

The shapefile that we just generated contains 2D points. Now we will convert the 2D points into 3D points.

(1) Open the BASEmesh "Convert legacy layer (Point)" tool. *Processing Toolbox* → *BASEmesh* → *Converters* → *Convert legacy layer (point)*.

(2) Fill in the dialog according to Figure 1.6 and click run.

This 3D points file can be used in the BASEmesh *Elevation Meshing* tool.

1.2.5 Creating 3D Lines for Elevation Meshing

We will now use the elevation points to create 3D lines, which is another option for use in the BASEmesh *Elevation Meshing* tool. First, we create a digital elevation map using the points shapefile.

(1) Open the Natural neighbour tool from SAGA.

(2) Fill in the dialog according to Figure 1.7 and click run (this may take a few minutes).

Now we will use the elevation points to create 2D lines, which represent each cross section of the river.

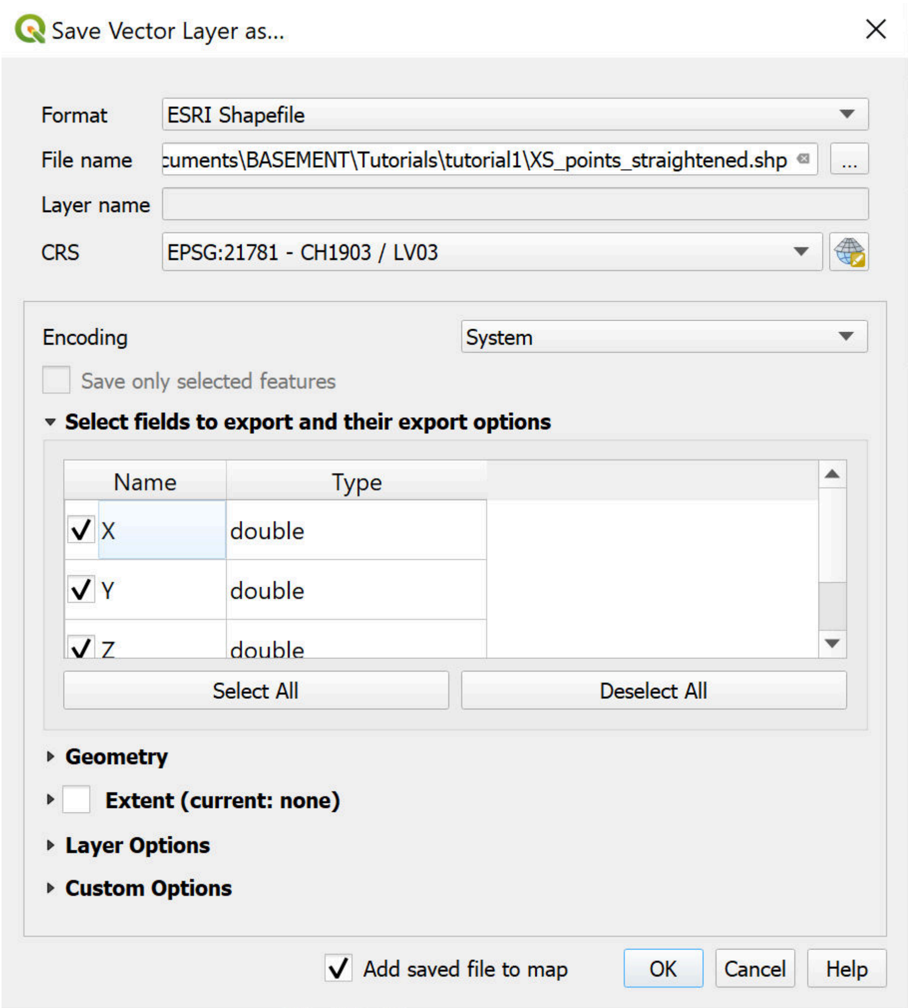


Figure 1.5 *Save vector layer*

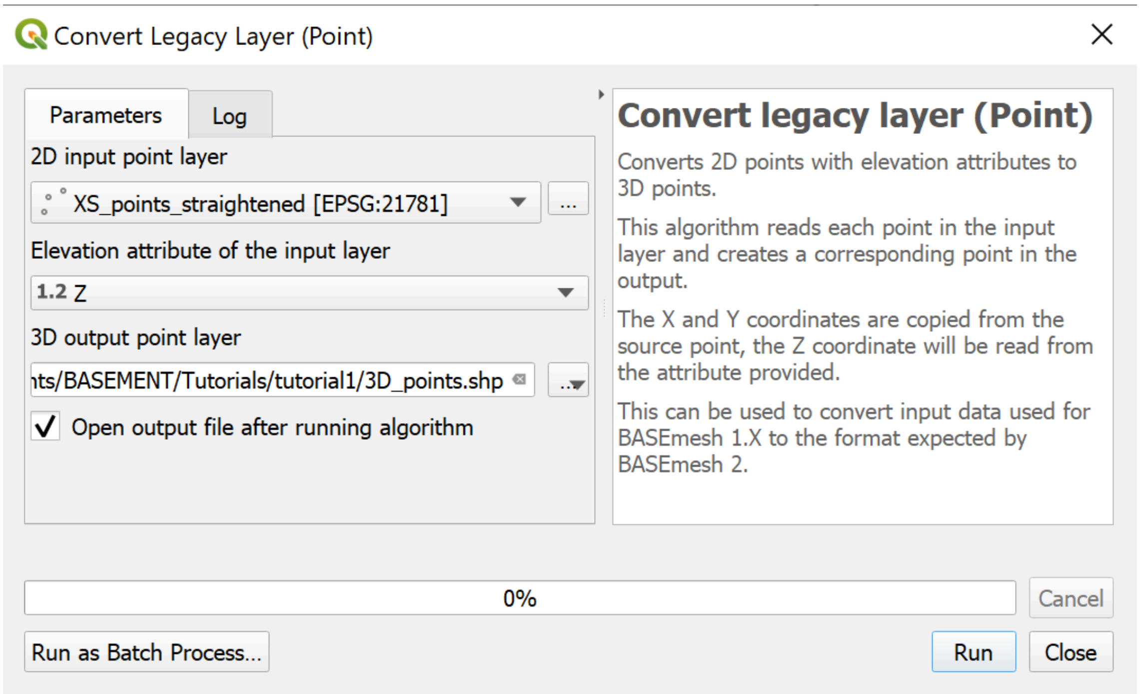


Figure 1.6 *Convert points to 3D*

(1) Open the QGIS points to path tool.

(2) Fill in the dialog according to Figure 1.8 and click run.

You will now see lines representing each cross section, plotted on top of the DEM, as in Figure 1.9. The 2D lines can now be converted to 3D lines, using the DEM.

(1) Open the QGIS drape tool

(2) Fill in the dialog according to Figure 1.10 and click run

1.2.6 Loading the Breaklines

(1) Go to *Layer* → *Add Layer* → *Add Vector Layer. . .* (or Ctrl-Shift-V).

(2) Browse for the shapefile provided with this tutorial 'breaklines.shp'.

(3) Click *Add*.

The color schemes of newly added layers are randomly chosen by QGIS. You can change them by double-clicking on a layer and selecting *Symbology*.

(4) Pull the newly added layer 'breaklines' below the initial file 'XS_points_straightened'. Your QGIS canvas should now look like in Figure 1.11.

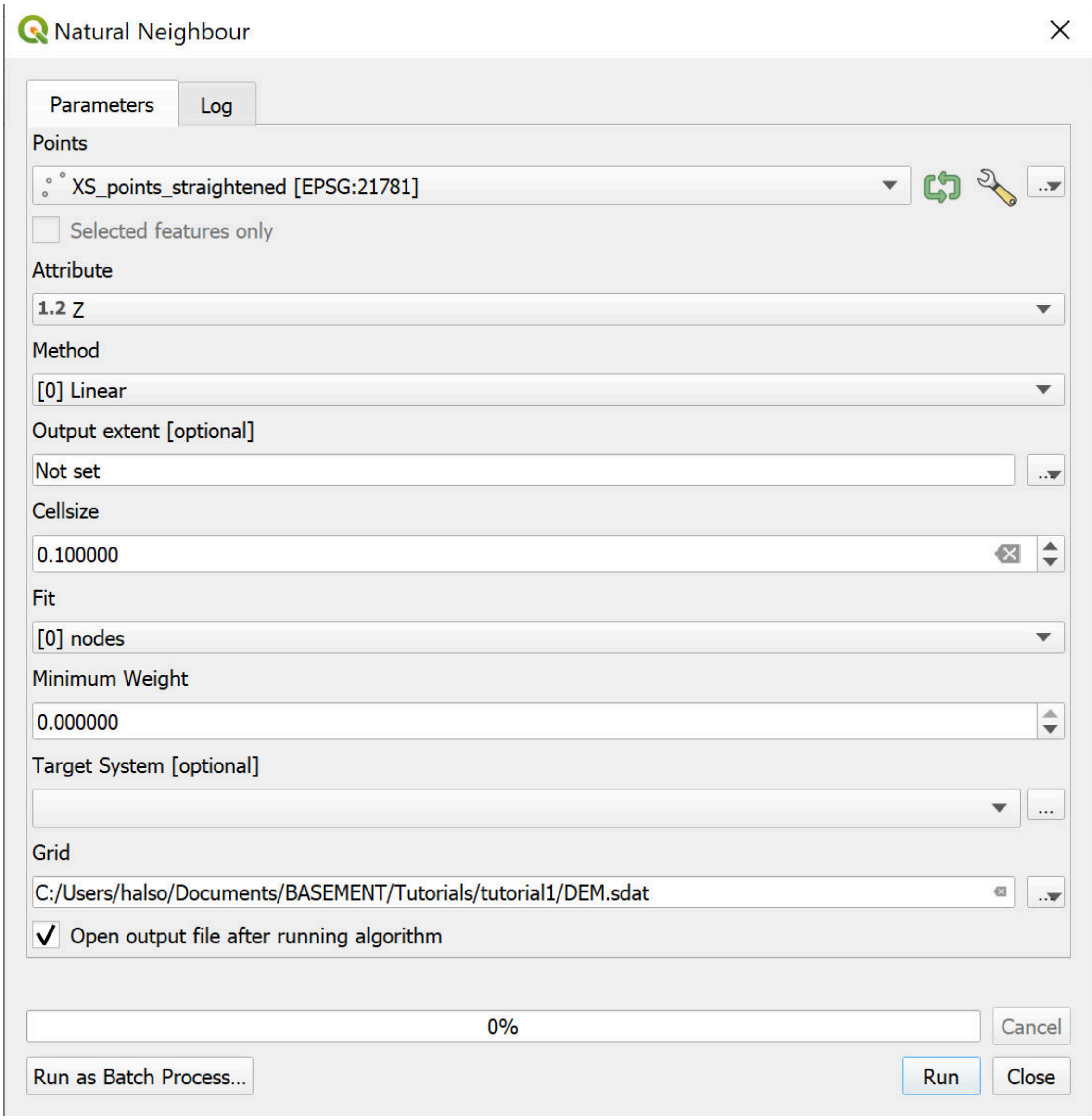


Figure 1.7 *Natural Neighbor*

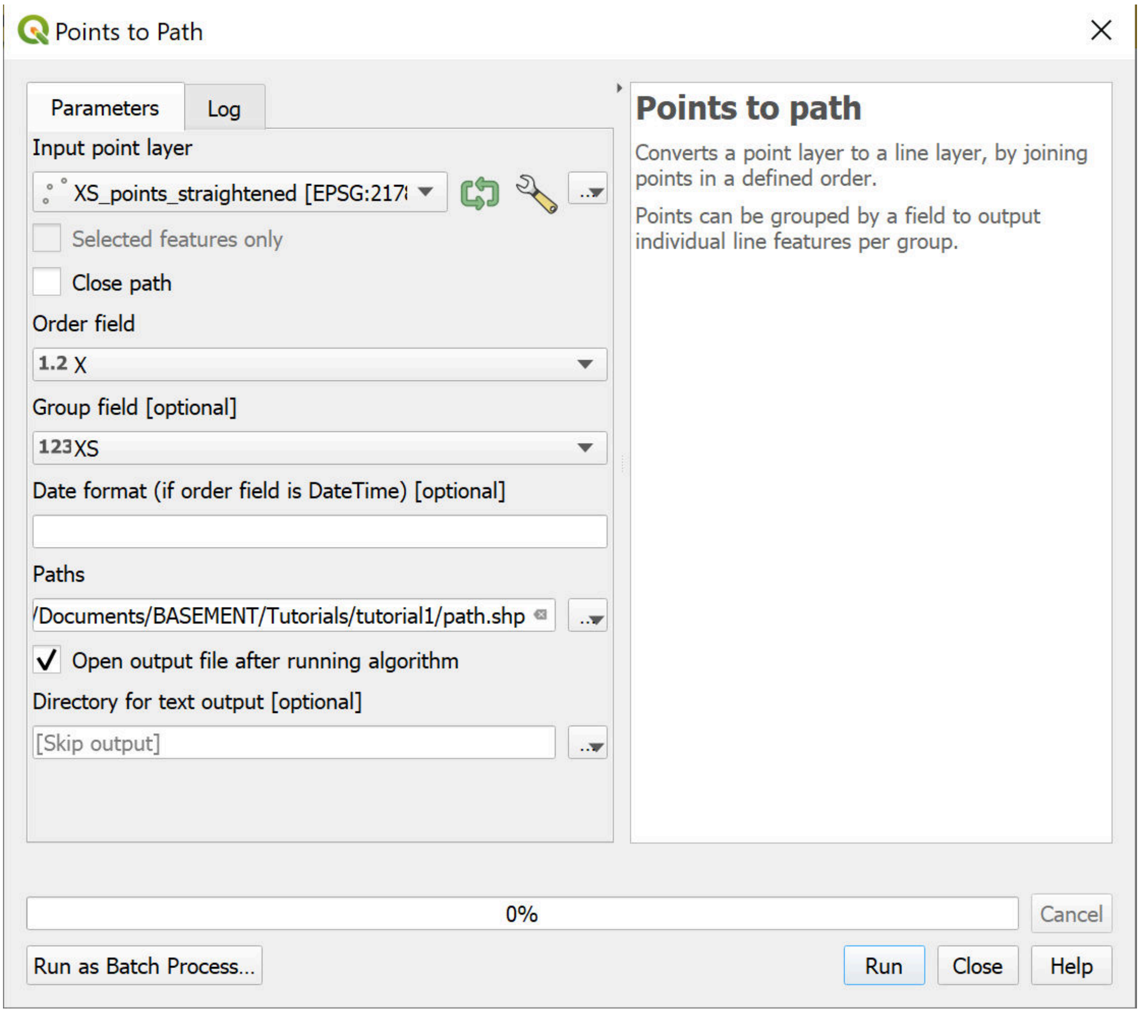


Figure 1.8 *Points to Path*

Figure 1.9 *2DLines on DEM*

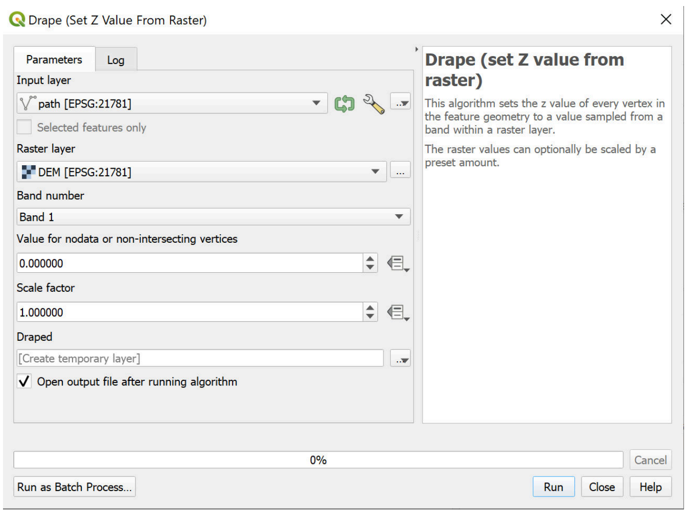


Figure 1.10 *Tutorial 1.1 Drape*

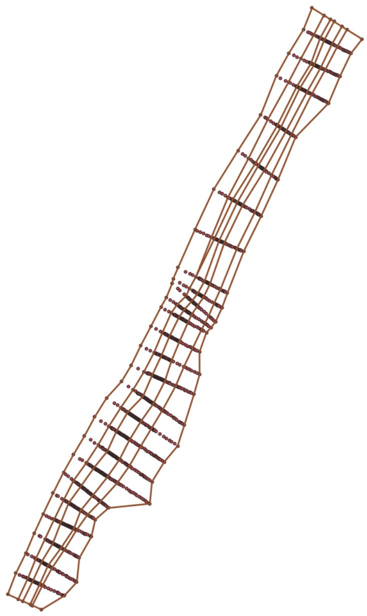


Figure 1.11 *Breaklines*

This breaklines shapefile contains several features, including one labeled 'model_boundary'. This feature gives the extents of the computational domain. Please note that for generating a computational mesh, the model boundary should not lie outside of the elevation points. Otherwise, there might be interpolation errors in the following meshing steps. A suitable model boundary can be created by using the *Convex hull(s)* feature of QGIS. For more information, please refer to the Tips and Tricks (Section 1.3) of this Tutorial.

1.2.7 Editing the Model Boundary

All vertices of the model boundary polygon **must** lie within the extents of the elevation points. Otherwise there might be interpolation errors in the following steps. In our example, a portion of the model boundary does not satisfy this criteria (see lower right region of the model data). Therefore we have to move/add nodes of the boundary layer:

(1) Right-click on layer 'breaklines' in the TOC and go to *Toggle Editing*. The layer can now be edited.

(2) Zoom into the area of interest. You should see small red 'x' for each polygon vertex.

We must ensure that the new/moved vertex will lie on an elevation point:

(3) Go to *Project* → *Snapping Options*. Fill in the form as shown in Figure 1.12 and click *OK*. Depending on your QGIS version and installation, the window with snapping and digitizing options might be docked. In this case, your edits are applied immediately and there are no *Apply* or *OK* - buttons available.

(4) Go to *Edit* → *Vertex Tool*.

(5) Click on the vertex of the boundary which is free. The polygon feature gets selected (all vertices turn to a red square).

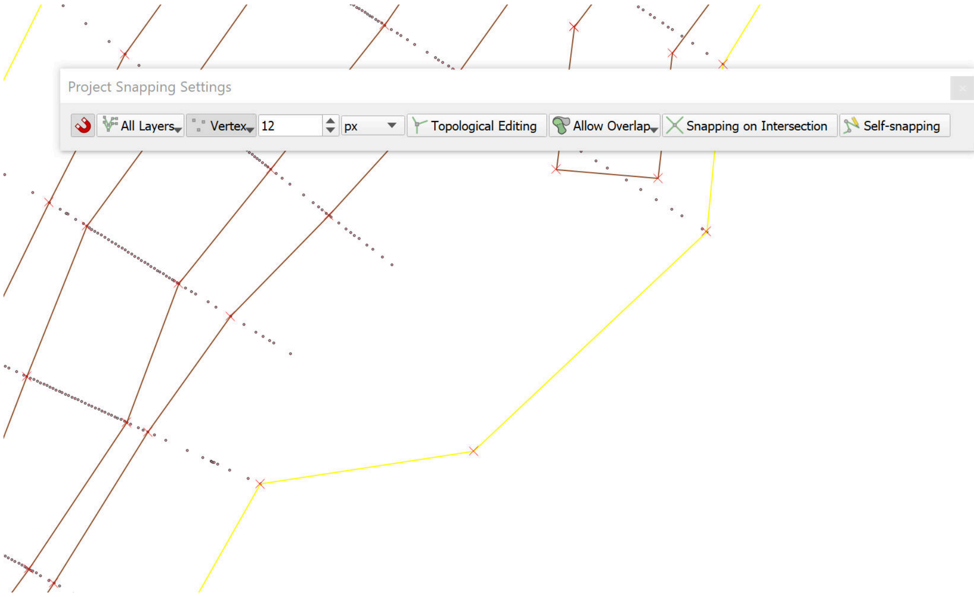


Figure 1.12 *Snapping*

(6) Drag & drop the free vertex to a neighbouring elevation points (see Figure 1.12).

We need to add a vertex to the polygon to include the remaining cross section end-point into the boundary:

(7) Hover over the segment somewhere between the two boundary vertices where you want to have the new one. In the middle of the segment, a small plus sign (+) will appear. Click on that plus sign to create a new node. (Be careful with clicking: as you may move the entire segment by mistake. This can lead to meshing errors or very fine triangulations in the following steps.)

(8) Again, drag and drop the vertex to the wished position.

(9) We are done with editing, go to *Layer* → *Toggle Editing*. Click *Save*.

The breakline shapefile is now ready for Quality Meshing. But first, the Region Markers must be defined.

1.2.8 Creation of the Elevation Mesh

Using the data that we have loaded and processed, we can now create the elevation model as a triangulated irregular network using the plugin BASEmesh. We call it *Elevation Meshing*. There are 3 methods for Elevation Meshing:

(1) Creation of the Elevation Mesh with 3D points

(2) Creation of the Elevation Mesh with 3D lines

(3) Using a DEM as the Elevation Layer

In this tutorial, we will show how to perform the first 2 methods.

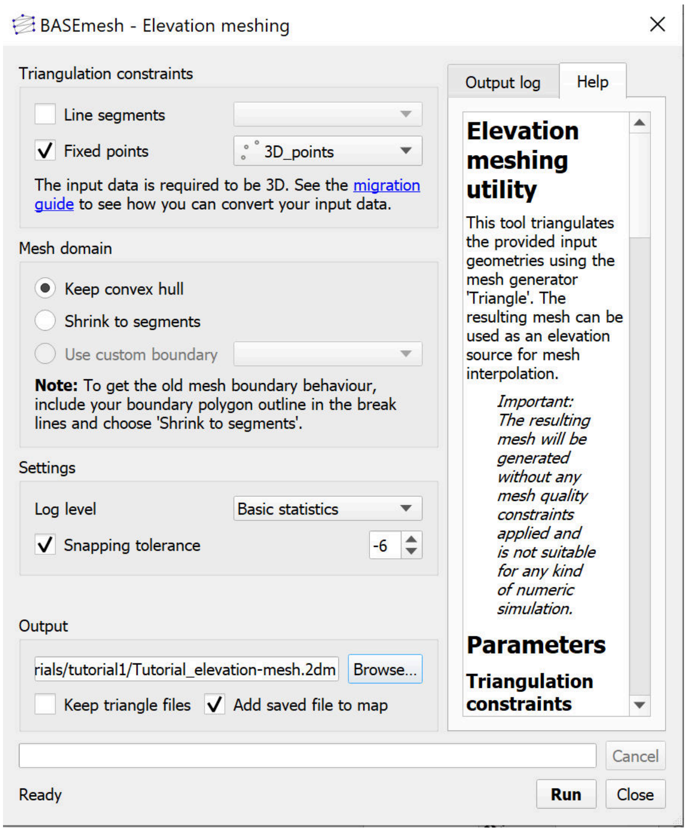


Figure 1.13 *BASEmesh Elevation Meshing*

1.2.8.1 Creation of the Elevation Mesh using 3D points

First, we will create an elevation mesh using the 3D lines that were created in Section 1.2.4.

(1) Go to *Plugins* → *BASEmesh* → *Elevation meshing*, or click the respective button in the toolbar.

On the left side of the dialog (Figure 1.13) you can define the input layers. See Section 2.2 “2D grid generation with BASEmesh QGIS plugin” of the BASEMENT User Manual for further explanations. On the right side status messages as well as Triangle’s output messages are displayed during meshing. Tool-specific help can be found in the *Help*-tab.

(2) Select the different fields according to Figure 1.13.

(3) Choose an output filename. The default is the name of the project.

(4) Click *run*.

This newly generated elevation mesh is an intermediate step and will be used as basis for the further interpolation of the elevation data. Due to it’s low mesh quality, it should **not** be used as computational mesh for any numerical simulations!

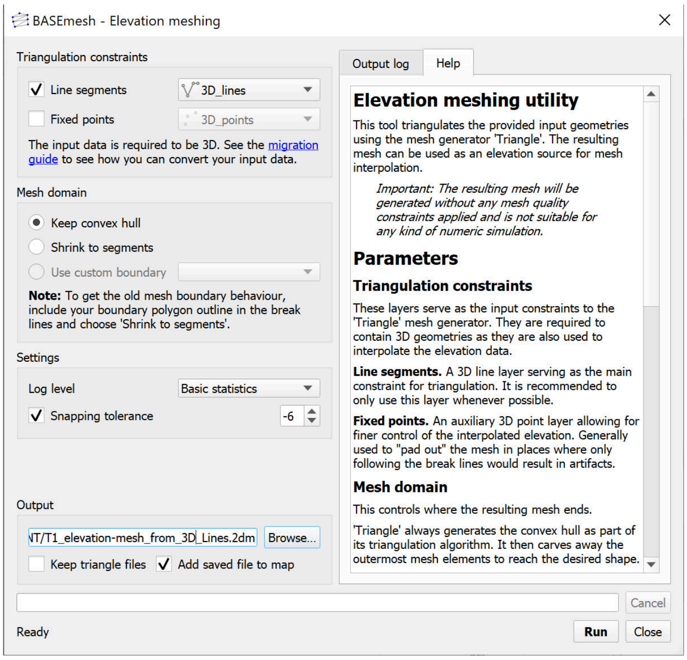


Figure 1.14 *BASEmesh Elevation Meshing with 3D Lines*

1.2.8.2 Creation of the Elevation Mesh using 3D Lines

Now we will create an elevation mesh using the 3d points that were created in Section 1.2.4.

(1) Go to *Plugins* → *BASEmesh* → *Elevation meshing*, or click the respective button  in the toolbar.

(2) Select the different fields according to Figure 1.14.

(3) Follow the same steps as in the previous section.

1.2.9 Adaption of the Breaklines for Quality Meshing

For most tasks, quality meshing requires the same basic breaklines as elevation meshing does. Neverthless, some content might be added, e.g. building outlines or lines along which we wish to have special outputs from the future numerical computations. In the following, the breakline layer used before will be duplicated and a building outline will be added:

(1) Right-click on the layer 'breaklines' in the TOC and go to *Export* → *Save Feature as. . .*

(2) In the next dialog choose an appropriate name and location for the new layer (e.g. 'breaklines_w_building.shp'). Be sure to check *Add saved file to map* at the bottom of the dialog.

(3) Load the shapefile 'building.shp' into QGIS (provided with this tutorial).

(4) Select the layer 'building' in the TOC.

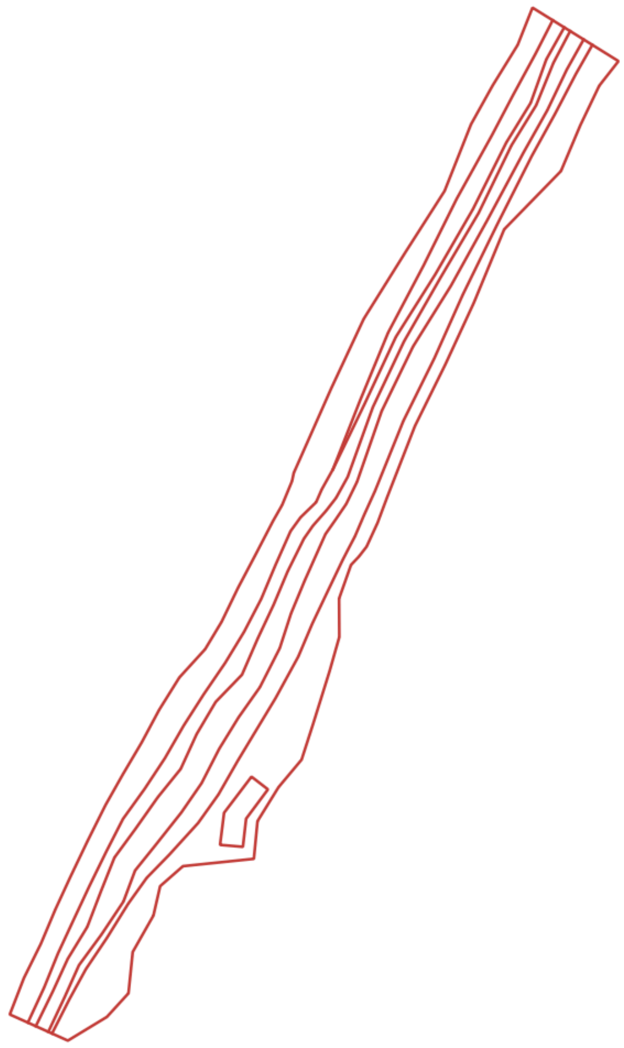


Figure 1.15 *Breaklines and building*

(5) Go to *View* → *Select* → *Select Single Feature*.

(6) Click on the building outline in the map (it should get colored differently).

(7) Go to *Edit* → *Copy Features* (or Ctrl-C).

(8) Right-click on the layer 'breaklines_qual_mesh' in the TOC and go to *Toggle Editing*.

(9) Go to *Edit* → *Paste Features* (or Ctrl-V).

(10) As copying the new line feature is completed, select *Edit Toggle Editing*. QGIS asks to save the changes. Click *Save*.

(11) Having activated only the 'breaklines_w_building' layer in the TOC, the lower part of your model should now look like Figure 1.15. If the building outline is still highlighted, select *View Select Deselect Features from all Layers*.

1.2.10 Creation of Region Marker Points

In this new Point-Shapefile, three attributes are defined that will be used for the *Quality meshing* (Figure 1.18) afterwards: *maximum area*, *material index* and *holes*. The atrributes have to be set individually for each region, which is embraced by breaklines or boundaries and are specified by placing a point into this area. Be careful, a misplaced region marker point can lead to very fine and computationally intensive meshes or wrong definition of Material Indexes respectively.

maximum area: The area attribute of the layer constraints the maximum area of the elements created during *Quality meshing*. If left blank, no maximum area constraints will be taken into acount for this particular region (see Figure 1.17)

material index: This attribute determines the material index of a certain region. If left blank, the material index is by default set to 1. The material indices are used in BASEMENT to group elements into zones with similar properties, e.g. to set different friction values or soil properties in certain mesh regions. These material indices are stored in the attribute field *MATID* of the mesh elements layer during mesh generation.

holes: These points define regions that will be neglected during meshing. These areas will be cut out and therefore not be integrated in the final mesh, preventing water flow through these regions.

(1) Create a new point layer: Go to Layer → Create Layer → New Shapefile Layer... .

(2) Fill in the form as shown in Figure 1.16. Be sure to define the correct CRS (EPSG:21781).

(3) Add an attribute for the *maximum area* with name e.g. 'max_area' and type 'Decimal Number' (e.g. *Length*=10 and *Precision*=3).

(4) Add a second attribute for the *material index* with name 'MATID' and type 'Whole Number' (e.g. *Length*=3).

(5) Add a third attribute for *holes* with name 'hole' and type 'Whole Number' (e.g. *Length*=1*).

(6) Optionally add another attribute with name 'Type' and type 'Text data' (e.g. *Length*=20) to assign a specific description for each region (e.g. 'River bed', ...)

(7) Save the layer with name 'regions_points'.

(8) Right-click on the layer 'regions_points' in the TOC and go to Toggle Editing.

(9) Go to *Edit → Add Feature*

(10) Add six features (points) inside the regions displayed in Figure 1.17

(11) Click somewhere inside the particular region. Enter an arbitrary *id* and fill in the attributes like shown in Figure 1.17

(12) Go to Layer → Toggle Editing and save the changes.

The value of the attributes 'max_area' (left) and 'MATID' (right) are used as label. In this example three different region 'Types' have been defined: 'river_bed', 'embankment' and 'surrounding'.

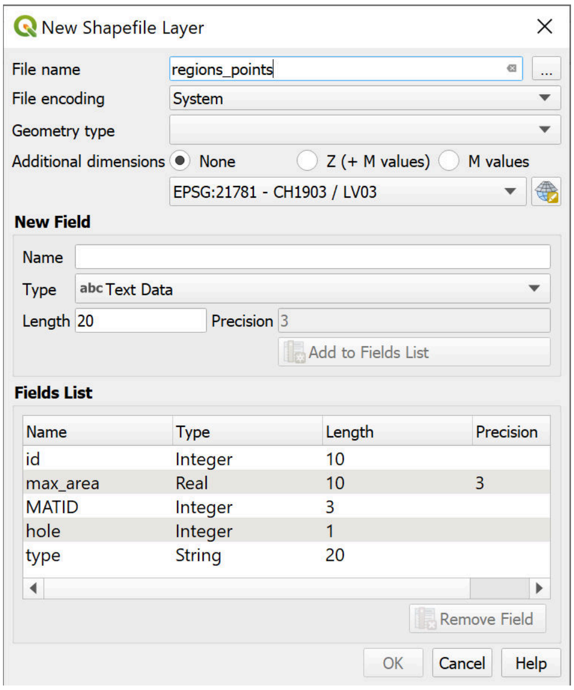


Figure 1.16 *New point layer 'region_points'*

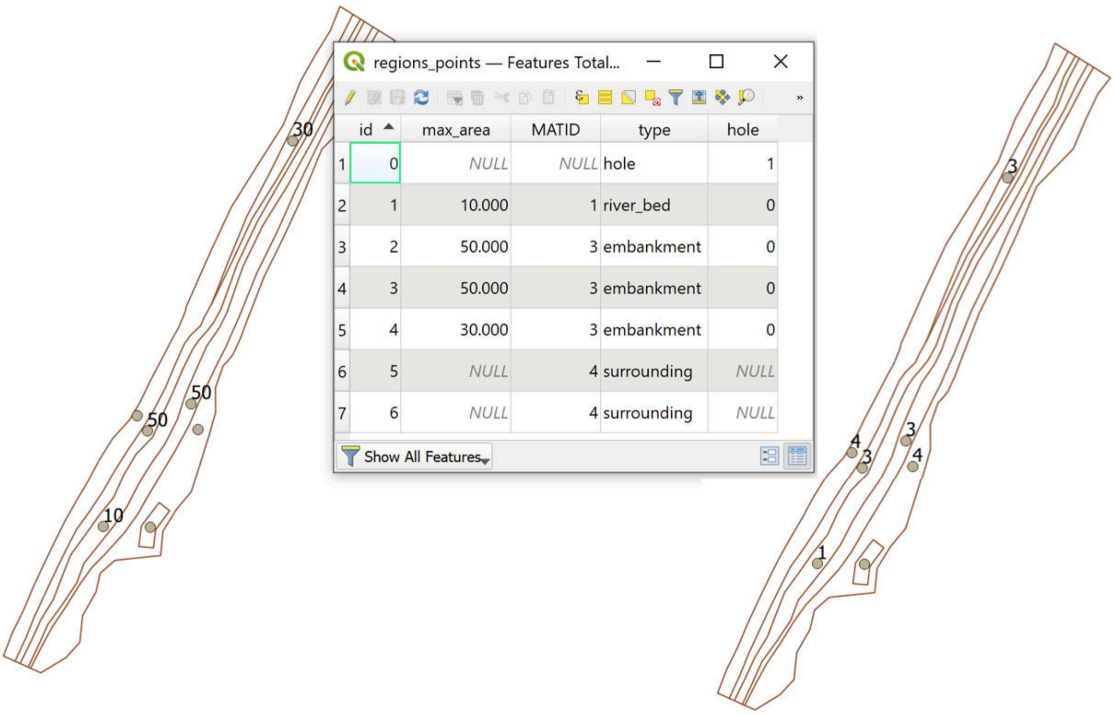


Figure 1.17 *Region marker points*

1.2.11 Creation of Quality Mesh

We can now use BASEmesh to generate a mesh with high quality properties by controlling cell sizes, using breaklines and holes and other parameters. Please note that the quality mesh created in this section does not incorporate any elevation data. This information will be added in the next step of the tutorial.

(1) Go to *Plugins* → *BASEmesh* → *Quality meshing*, or click the respective button in the toolbar.

On the left side of the dialog (Figure 1.18) you can define the input layers. See Section 3.2 “2D grid generation with BASEmesh QGIS plugin” of the BASEMENT User Manual for further explanations. On the rights side status messages as well as Triangle’s output messages are displayed during meshing. Tool-specific help can be found in the *Help*-tab.

(2) Select the different fields according to Figure 1.18

(3) Check the optional button for *Breaklines*, and *Regions*. Within the Layer ‘region_points’ check the attributes *maximum area*, *material index* and *holes* like shown in Figure 1.18.

In this tutorial a *minimum triangle angle* of 28 degrees was chosen. This means that no elements with angles smaller than 28 degrees are created. Therefore a smaller value leads to a smaller number of elements in the mesh, while a larger value leads to a higher number of elements but less distorted triangles.

(4) Finally, click on *run* to generate the quality mesh.

If the mesh contains regions with almost infinitely dense triangulation, again check the snapping of your model boundary and the breaklines used for quality meshing or increase the *Relative snapping tolerance* (see Tipps and Tricks Section 1.3).

1.2.12 Generation of the Computational Mesh

The quality mesh generated in the previous step still lacks any elevation data. Before it can be exported and used for simulations, elevation data has to be interpolated on the nodes of the quality mesh. For this purpose, the elevation mesh created in a previous step will be used. Alternatively, one could also use raster data as source for the elevation model.

(1) Go to *Plugins* → *BASEmesh* → *Interplolation*, or click the respective button in the toolbar. A new dialog will open (Figure 1.19).

(2) As input for *Mesh layer to interpolate* choose the quality mesh.

(3) To make the computational mesh using an elevation mesh, check the radio button *Interpolation via elevation mesh*, and select the desired elevation mesh. If you wanted to make the computational mesh using a DEM, you could check the radio button Interpolation via DEM (raster) and select the DEM.

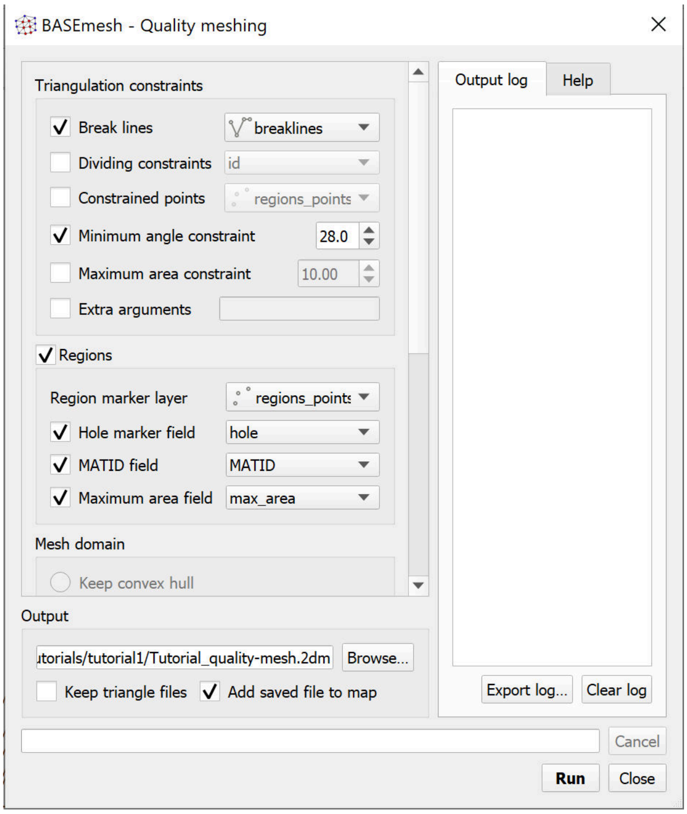


Figure 1.18 *BASEmesh Quality Meshing*

(4) Click on *Browse* and input a name for the computational mesh.

(5) Click on *run*. On Windows systems, the interpolation dialog might be marked as Not Responding. On Linux systems, the interpolation dialog might be darkened. This does not necessarily mean that the process stopped or had errors: The system is simply busy.

In case of a large number of elements (>10'000), the interpolation might take up several minutes. In general, the interpolation from raster data is faster than the interpolation from the elevation mesh. For every node of the quality mesh, the elevation has been interpolated based on the elevation mesh given. Therefore, the locations of the newly created interpolated nodes are identical to the nodes of the quality mesh, but contain the interpolated elevation data as attribute. The result can be checked for plausibility by labeling the elevation nodes layer and the interpolation result layer with their elevation attributes and comparing the values.

1.2.13 Viewing the computational mesh

During the interpolation step, elevation data has been added to the mesh. With this additional information we are now able to view both the elevation data and the mesh itself. This can be useful to check for plausibility.

(1) The elevation data of the computational mesh will be visible. To view the mesh, right click on the computational mesh in the layers toolbar, select *Properties* → *Symbology*

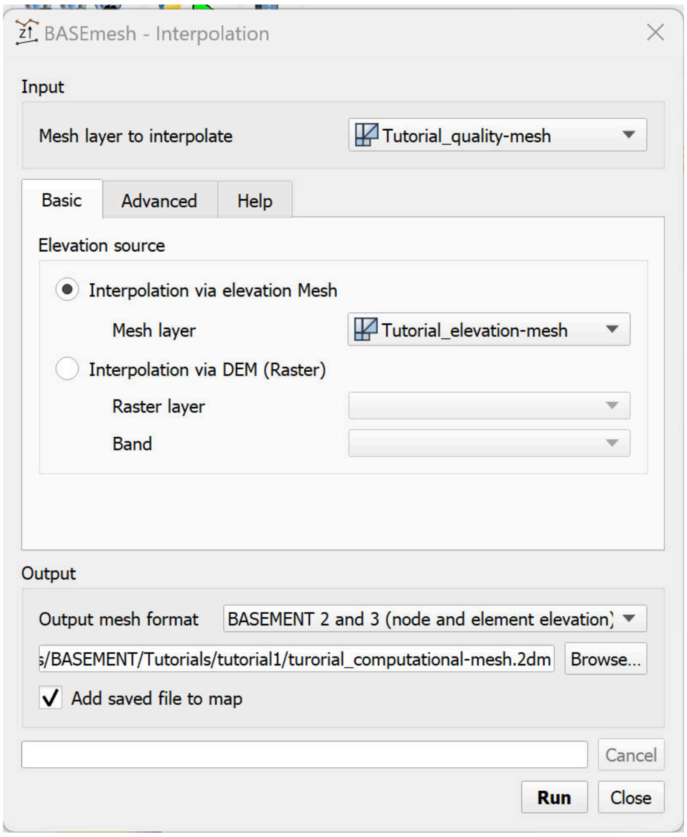


Figure 1.19 *BASEmesh Interpolation*

→ select *Native Mesh Rendering* → *OK*. The computational mesh for this tutorial should look as it does in Figure 1.20.

(2) The computational mesh is now ready for use in a BASEMENT simulation.

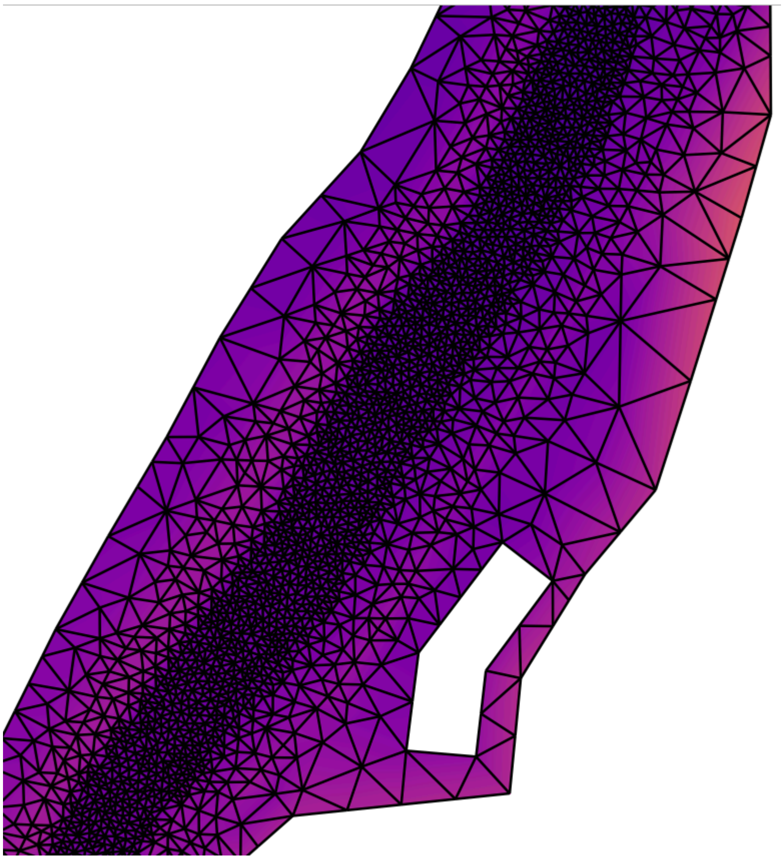


Figure 1.20 *Computational mesh*

1.3 BASEmesh Tips and Tricks

1.3.1 Recommended Plugins

QGIS offers the possibility to extend its features using plugins from various sources. We recommend in particular the following plugins.

Core plugins:

fTools This is the main plugin for many common vector-based GIS tasks. Core plugin, which can be activated in the plugin manager.

Spatial Query Plugin Core plugin of QGIS, which can directly be activated in the QGIS plugin manager without downloading. *Spatial Query* is comparable to ArcGIS' *Select by Location* feature and enables the user to select features in a target layer with reference to another layer. Possible operators are: contains / equals / overlap / crosses / intersect / touches / within.

Select Within Another spatial query plugin that runs through each geometry you want to select from and tests if the centroid falls within the selected geometry. This plugin is especially useful to select mesh elements for the assignment of material indices.

Processing Spatial data processing framework, which gives access to a large number of analysis algorithms. It can also connect external algorithms from other GIS packages, such as GRASS, SAGA or Orfeo Toolbox. One of the main features is the graphic modeler, where frequent workflows can be graphically represented by the user and executed automatically.

Python plugins:

Python plugins are mostly contributed by the worlwide QGIS user community. Most of them are stored in the official repository and available as stable or experimental versions.

Crayfish plugin Visualizes result data on structured or unstructured meshes using color maps and vectors. Crayfish is able to directly visualize result data from the numerical simulation software BASEMENT (see Post-Processing tutorial Section 2.1).

Point to One Converts a series of points to lines or polygons based on a common attribute or a sequence field.

Point Sampling Tool Samples polygon attributes and raster values from multiple layers at specified sampling points.

Dxf2ShpConverter Conversion and import of dxf files.

Interpolation plugin Very useful for interpolating raster maps of given elevation data, e.g. point clouds.

1.3.2 Tips and Tricks

The following list contains some basic tips and tricks for problem handling and the daily work with BASEmesh.

Creation of polygons out of intersection polylines: In many cases, polygons must be created out of intersecting polylines, e.g. for the definition of model boundary polygons based on breaklines. For completing this task, two features are available in QGIS:

- via fTools: Select *Vector* → *Geometry Tools* → *Lines to polygons*. Quite simple menu, no parameters or options can be chosen (standard option). Prone to errors with complex geometries.
- via the Processing toolbox: Select *Processing* → *Toolbox* → *QGIS geoalgorithms* → *Vector geometry tools* → *Polygonize*. Complex geometries are handled well by this tool, multiple options and a log are available.

Creation of a model boundary based on elevation data: When creating an elevation mesh, all vertices of a model boundary polygon must lie on elevation points. Otherwise, there might be interpolation errors in the following meshing steps. Therefore, it is advisable to create a model boundary using the *Convex hull(s)* - feature of QGIS. Below is a short example using the input data provided with Section 1.2.

- Select *Vector* → *Geoprocessing Tools* → *Convex hull(s)*
- As *Input vector layer* select 'XS_points_straightened'.
- Check the radio button *Create single minimum convex hull*.
- Select an appropriate name for the output shapefile.
- Check *Add result to canvas*.
- Select *OK*, after completion close the dialog. Your result should now look like Figure 1.21 .

What to do if Triangle creates (almost) infinitely dense triangulations:

- Polylines that are used for the segmentation of boundary polygons must end in vertices of the polygons. Otherwise, Triangle creates an almost infinitively dense triangulation to ensure its angle and area criteria.
- Be aware that using the *vertex editing tool* generates a new vertex point at each double-clickg. This can easily lead to the generation of two or more points at the same location or very near to each other. In such a case, Triangle creates a very dense triangulation due to its angle and area criteria.
- Prevent situations where breaklines (and corresponding vertices) have very short distances to each other. The resulting mesh will be very fine in these regions. Meshing sometimes requires to manually adapt the input data and to make compromises between mesh quality and accuracy in certain regions.
- Use the *Relative snapping tolerance* provided in the BASEmesh dialogues *Elevation meshing*, *Quality meshing* and *String definition* def. The mesh shown in Figure 1.22 on the right was generated with the default *Relative Snapping Tolerance* of -6. This led to a very dense triangulation at the intersection of breakline and

Figure 1.21 *QGIS Convex hull*

model boundary since the breakline is not exactly snapped to the vertex of the model boundary. Futhermore MATID 3 was not considered for the embankment as desired. To prevent such behaviour, increase the tolerance to -3 for example. This allows you to generate a proper mesh like shown in Figure 1.22 on the left.

Do not group layer in the table of contents (TOC): Grouping layers in the TOC may lead to errors because the resulting shapefiles cannot be generated after triangulation.

Conversion of 3D shapefiles to 2.5D shapefiles with elevation attributes This special kind of shapefile is sometimes used in ArcGIS. The 3rd dimension value is not stored in the attribute table (as in 2.5D shapefiles), but in the geometry definition itself. The x and y coordinates of such shapefiles can be displayed in QGIS, but the elevation information is inaccessible and lost. In the following, three workflows are illustrated how to convert 3D shapefiles to 2.5D shapefiles:

- *GDAL - ogr2ogr*: On Linux systems, this GDAL command line tool is directly accessible on the shell. On Windows systems, the tool can be used in the OSGEO4W-shell. For further information, please visit the GDAL homepage
- *Spatialite:*
  - Open QGIS, add your shapefile and save it as Spatialite (or alternatively use the QGIS DB Manager to drag and drop the shapefile to an already existing Spatialite Database).

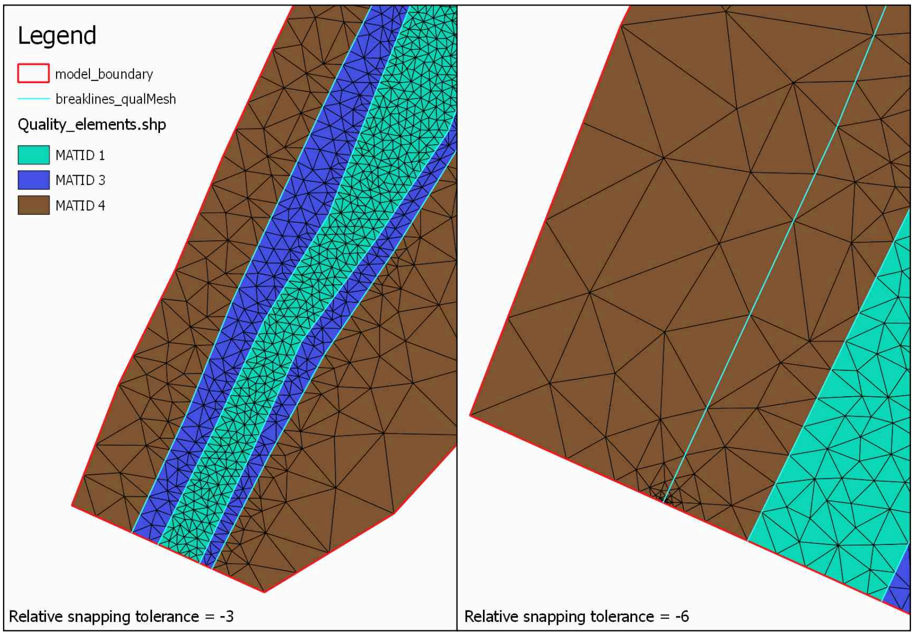


Figure 1.22 *Quality meshing using the Parameter 'Relative snapping tolerance'*

- Add the newly created Spatialite vector and through the QGIS vector properties ('fields' tab) add a new column, that will store the z-values.
- In the QGIS DB Manager SQL Window use this command: *update* ***tablename*** *set* ***columnname*** *= st_z(st_pointn(geom,1))*.
- If at the end of the process you really need to have a shapefile (shame on you) then just use the 'save as. . . ' function of QGIS.

- *PostGIS:*
  - Import the shapefile to your PostGIS database
  - ogr2ogr -f "PostgreSQL" PG:"host=yourhost user=user dbname=dbname password=*****" shapename.shp
  - Connect to your database
  - psql -h yourhost -U user dbname
  - Add a column
  - ALTER TABLE tablename ADD COLUMN columnname numeric(19,11);
  - Fill the column with the z-values
  - update tablename set columnname=st_z(ST_PointN(wkb_geometry,1));
  - Save result as shapefile

2

Post-Processing of 2D simulation results

2.1 Introduction

In the following tutorials it is demonstrated how to do the post-processing of 2D results generated by a BASEMENT simulation. For this purpose the free and open source GIS software QGIS is applied.

In addition, the free and open source application ParaView is used to generate 3D views of the BASEMENT simulation results.

2.2 2D result visualization with QGIS

2.2.1 Input data

The data needed to complete this tutorial comes as ZIP-file and needs to be extracted to a location of your choice. All screenshots and figures in this document were generated with QGIS version 3.16 'Hannover'. Along with the computational grid (Flaz_mesh.2dm), the results of the unsteady flow simulation of the tutorial 'Hydrodynamics and sediment transport at the river Flaz' (Section 4.1) are used for visualization. In the *SPECIAL_OUTPUT* Block of the BASEMENT model file select *format* 'sms' to generate result files that can be visualized in QGIS (see Figure 2.1). QGIS can handle both types *node_centered* and *element_centred* results. Be aware that most of the data (e.g. depth, velocity, wse,...) is calculated on the elements during simulation. When chosing type *node_centered*, these results are interpolated to the nodes by BASEMENT and written to the solution files (*.sol).

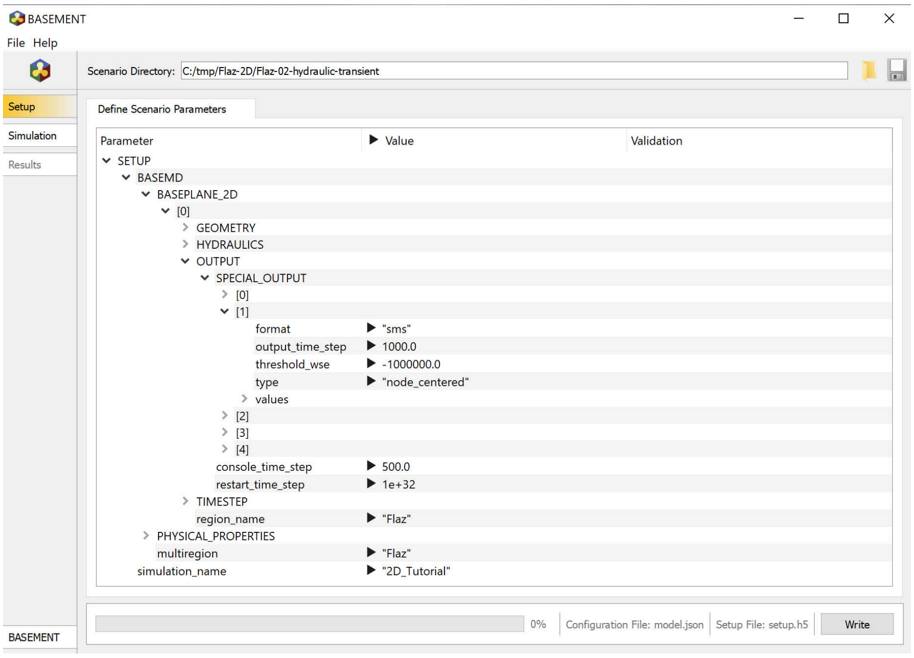


Figure 2.1 *Settings defined in the* SPECIAL_OUTPUT *Block of BASEMENT to generate time dependend result-files (*.sol) of a 2D simulation*

2.2.2 About Crayfish

Crayfish is a plugin (extension) developed by Lutra Consulting for the free and open source GIS platform QGIS. The Crayfish plugin aspires to be a complete set of post-processing tools to support numerical modelling within QGIS. With the functionalities of Crayfish, users can load time varying mesh into QGIS. In more recent editions of QGIS version 3, the Crayfish functionalities come incorporated automatically into the QGIS core. Currently, QGIS supports a number of hydraulic modelling software packages including BASEMENT.

The functionalities of Crayfish allow for loading and rendering of results directly, rather than converting them to other GIS formats before viewing. This allows users to flick quickly through the various output steps in the result files and to create animations.

2.2.3 Installation

For recent editions of QGIS version 3, the Crayfish functionalities come incorporated automatically into the QGIS core. Therefore, installation of a separate plugin is not needed.

For older versions of QGIS, Crayfish can be installed from the official QGIS plugin repository. It requires binary libraries specific to your platform. Lutra consulting distributes Windows (32-bit and 64-bit) DLL files and Linux libraries (64-bit) for Debian-based distributions (Ubuntu, Debian, Linux Mint, etc). If your operating system is one of these, the plugin should automatically download the required libraries. To install Crayfish from the QGIS plugin repository, follow these steps:

(1) Start QGIS

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

(3) In the tab *All* type 'Crayfish' into the search field and click *Install plugin*

Once Crayfish is installed successfully, a new icon should be added to your Layers toolbar.

2.2.4 Load and visualize data

2.2.4.1 Project Settings

In order the display the provided geodata correctly, some settings regarding the coordinate reference system (CRS) have to be defined. In this tutorial we use the same CRS (CH1903/LV03) like in the tutorial of BASEmesh (Section 1.1). With the following steps, the project's CRS can be changed:

(1) Go to *Project* → *Properties*.

(2) Under the tab *CRS* you can see the coordinate reference system settings for the current project.

(3) Enter EPSG code '21781' into the field *Filter*.

(4) Select the coordinate reference system 'CH1903 / LV03' and click *OK*.

(5) Again go to *Project* → *Project Properties* → *CRS*.

(6) Define a *Project title* under the tab *General* → General Settings*.

(7) Close the Project Properties window. If everything went well, you should see the chosen project name at the title of the QGIS main window and the EPSG code of your coordinate system at the lower right corner of the QGIS desktop.

2.2.4.2 Loading results of unsteady flow simulation (river Flaz)

The provided data is stored in the 'QGIS' subfolders 'background_data', Flaz_mesh' and '2D_results'. You can either use these data or visualize your own mesh and/or simulation results of the BASEMENT 2D tutorial 'Hydrodynamics and sediment transport at the river Flaz'.

Loading geodata

(1) Go to *Layer* → *Add Layer* → *Add Raster Layer* (Alternatively press Ctrl+Shift+R or use the *Add Raster Layer* icon in the Manage Layers toolbar).

(2) Browse to the folder 'background_data' and load the areal image 'Flaz_si25.tif'.

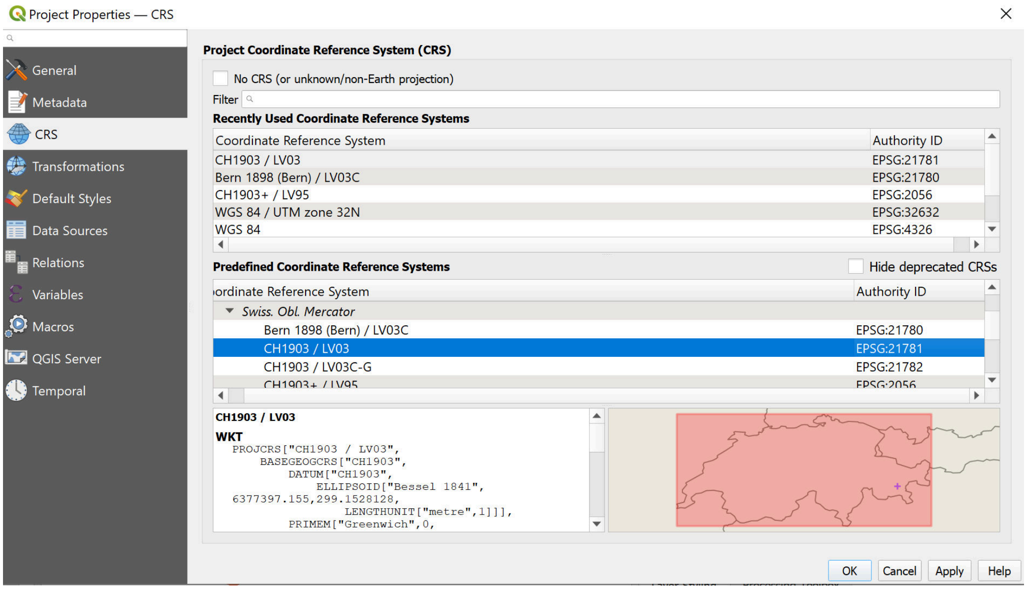


Figure 2.2 Project Properties, CRS

(3) Go to *Layer* → *Add Layer* → *Add Vector Layer* (Alternatively press Ctrl+Shift+V or use the *Add Vector Layer* icon in the Manage Layers toolbar).

(4) Browse to the folder 'Flaz_mesh_data' and load the provided shapefiles (*.shp).

The color schemes of newly added layers are randomly chosen by QGIS. You can change them by right-clicking on a layer → Style → select a color from the palette. QGIS displays the loaded layers according to their order in the Layers control panel.

Adding Results layers

To view 2D results, first, we load the computational mesh of the 2D simulation. If you use your own data, make sure to load the latest mesh file (*.2dm) you used for your simulations. Otherwise the node ids of the mesh won't match those of the result files and the visualization won't be correct.

(1) Go to *Layer* → *Add Layer* → *Add Mesh Layer* or use the *Add Raster Layer* icon in the Manage Layers toolbar).

(2) Browse to the folder '03_2D_results' and load the mesh 'Flaz_mesh.2dm'.

Now load the result files of the 2D simulation:

(1) Double-click on the mesh layer. Go to *Source* → Available Datasets *Layer* → *Assign extra dataset to mesh*

(2) Browse to the folder '03_2D_results' and load the solution files 'Flaz_nds_depth.sol' and 'Flaz_nds_velocity.sol'

The appropriate mesh file should be loaded automatically when the user opens a .dat or .sol file. If the mesh file is named differently, users will be prompted to locate the mesh file

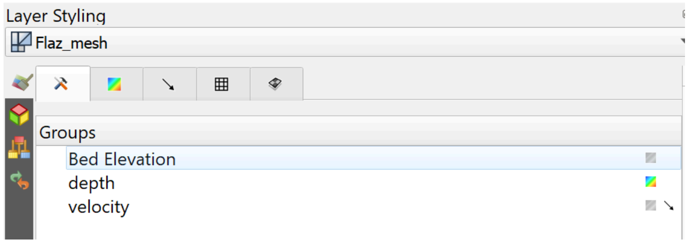


Figure 2.3 *Layer Styling Panel Groups*

manually. In this case, browse to the location of your mesh and double-click on the file (*.2dm).

If a quantity contains time-varying data, you will be able to browse through the output times defined by the 'output_time_step' in the BASEMENT command file (see Figure 2.1) and change the timing through the time control.

2.2.4.3 Display properties

The style of the displayed quantities can be modified in the Layer Styling panel. On the 1st tab of the Layer Styling Panel, you can select which layer associated with your 2dm that you would like to edit. To select a layer, click on the icon to the right of the layer name (see Figure 2.3).

Contour styles

Styling of contours can be done in the 2nd tab of the Layer Styling Panel (see Figure 2.4). In this tab you can:

- Create your own color ramp
- Set the interpolation in the color ramp
- Save and load color settings
- Fill values below or above min/max

Vector Styles

To activate the vectors, *Go to the 1st tab of the Layer Styling Panel → Click on the arrow to the right of 'velocity'*. Vector styling of the velocity vectors can then be done in the 3rd tab of the Layer Styling Panel (Figure 2.5).

In this tab you can:

- Set the color, length, and width of the vectors
- Filter by min/max
- Set vector head size
- set an arbitrary grid, where vectors will be displayed by activating *Display on User Grid*. This is particularly useful to view a smoother vector interpolation.

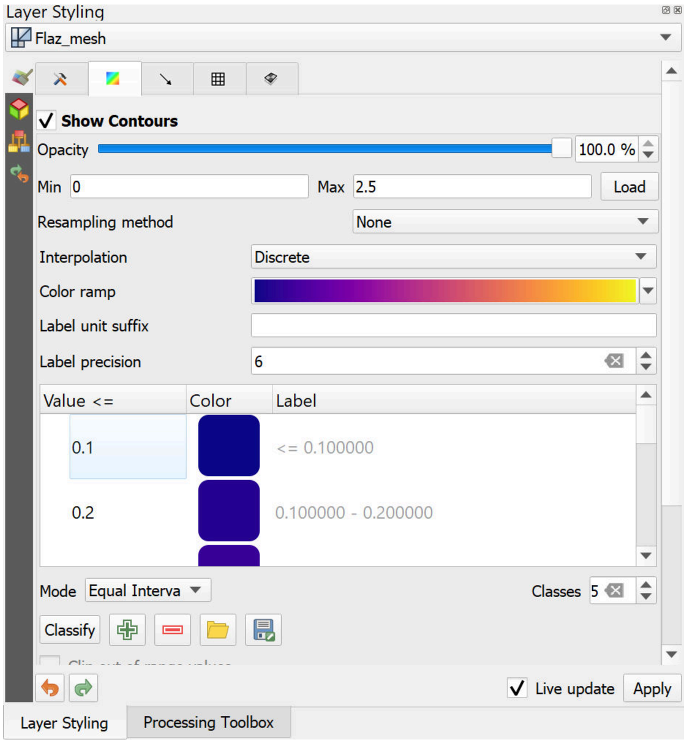


Figure 2.4 *Layer Styling Panel*

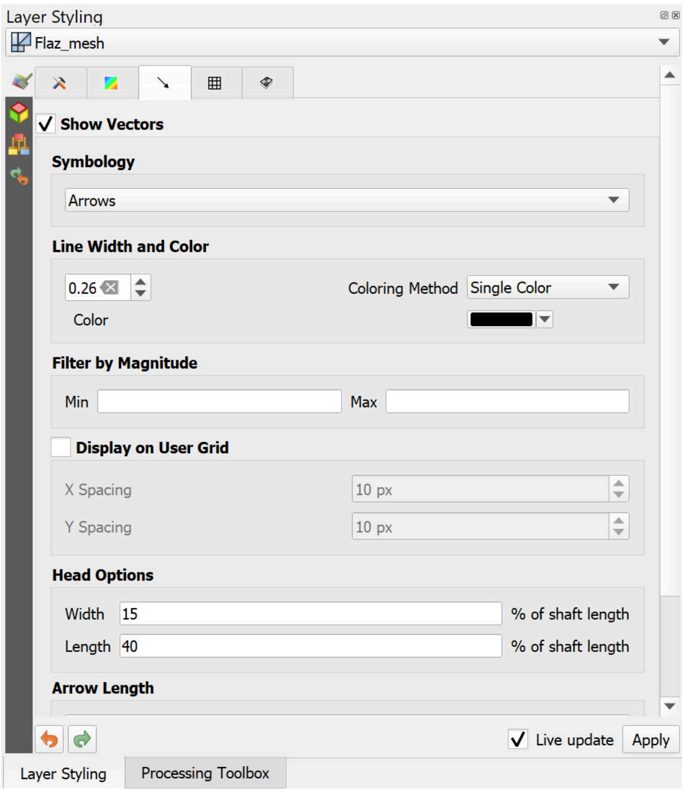


Figure 2.5 *Vector Options window of the Layer Styling panel*

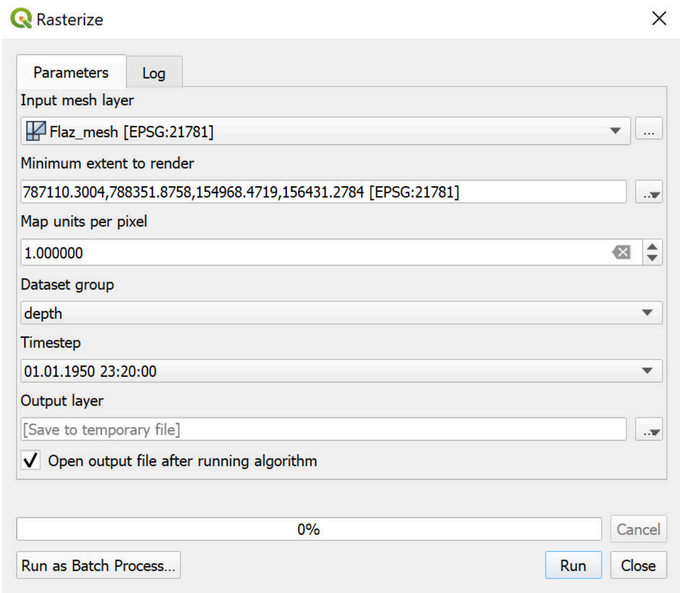


Figure 2.6 *Rasterize*

2.2.4.4 Export results to raster

For further results analysis, it might be useful to export the simulation results into raster format. Crayfish offers the possibility to directly resample the results data at a desired output time step on a desired output resolution.

(1) In the *Processing Toolbox*, search for 'Rasterize.' Select the Crayfish Rasterize tool. (Figure 2.6)

(2) Set the "Minimum extent to render" based on *Calculate from layer* → *Flaz_model_boundary* (make sure QGIS window is zoomed to show entire model domain).

(3) Select the mesh layer that contains the results data.

(4) Select the desired data, timestep, and grid resolution.

(5) Click OK .

(1) *Right click on the newly created layer* → *Click Export* → *Save as...*

(2) Save the raster layer as a GeoTIFF (Figure 2.7)

The generated raster is stored in Geo-Tiff format (*.tif) and will cover the extent defined by the model boundary. The flexible raster format allows further post processing steps of the simulation results. After having exported both quantities depth and velocity, you can easily calculated the product depth * velocity using the QGIS *Raster Calculator* for example. This might be of particular interest when generating flood hazard maps for example.

(1) Go to *Raster* → *Raster Calculator*.

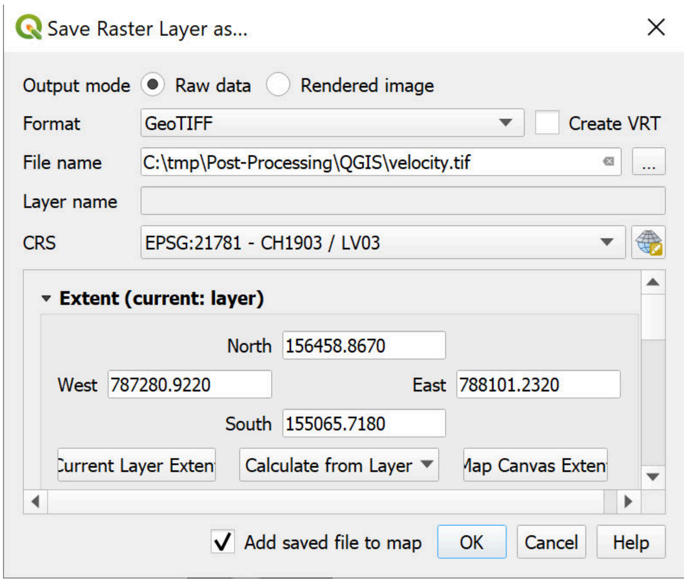


Figure 2.7 *Save as GeoTIFF*

(2) Specify the *Raster calculator expression* as shown in Figure 2.8 by double-clicking on the *Raster bands* depth and velocity in combination with the required *Operators*.

(3) Define the *Output layer* and press *OK*.

The new calculated raster dataset will cover the same extent like the two input datasets and will be stored in Geo-TIFF format as well.

2.2.4.5 Profile tool

If you want to analsye the temporal change of a variable along a certain cross section of a river reach during a BASEMENT simulation, in principle there are two options:

- Define a *STRINGDEF* along the desired location within your computational grid and chose a *SPECIAL_OUTPUT* of type *stringdef_history* with the reqiured *stringdef_values*.
- Use the QGIS plugin 'Profile Tool' and analyse the results of a Crayfish layer.

The advantage of option two is a fast and easy evaluation at any location of the modelled domain, without having definied any stringdef_history outputs beforehand.

Installation

The Profile Tool plugin can be installed via the official QGIS repository:

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

(2) In the tab *All* type 'Profile tool' into the search field and click Install plugin.

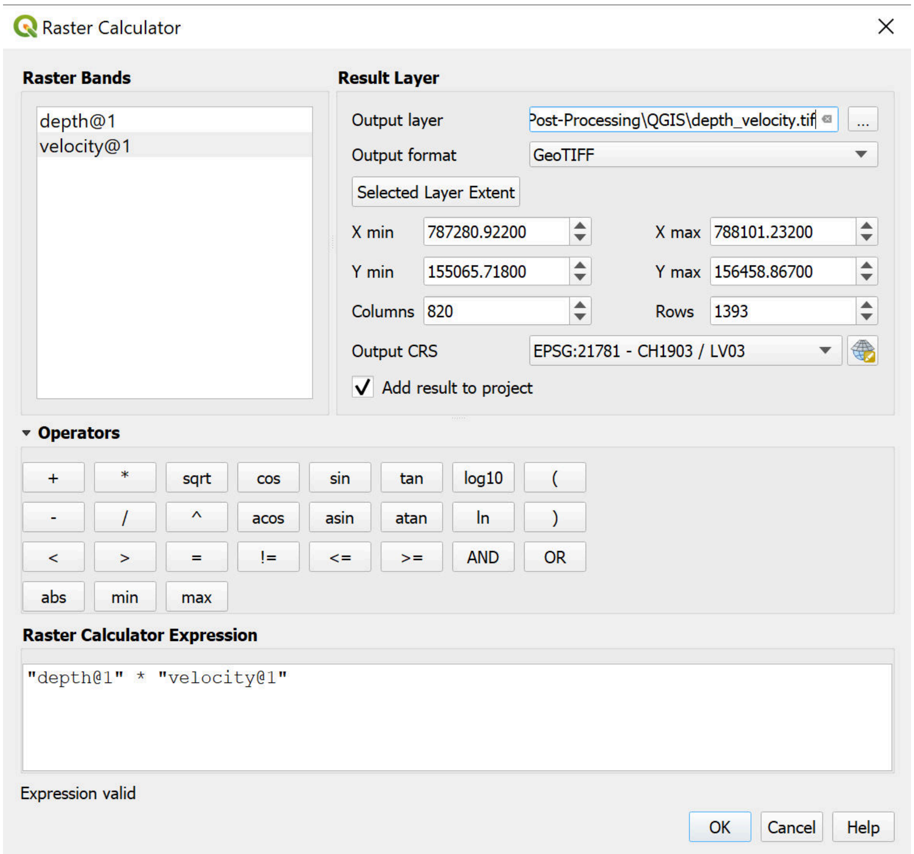


Figure 2.8 *Applying QGIS Raster Calculator*

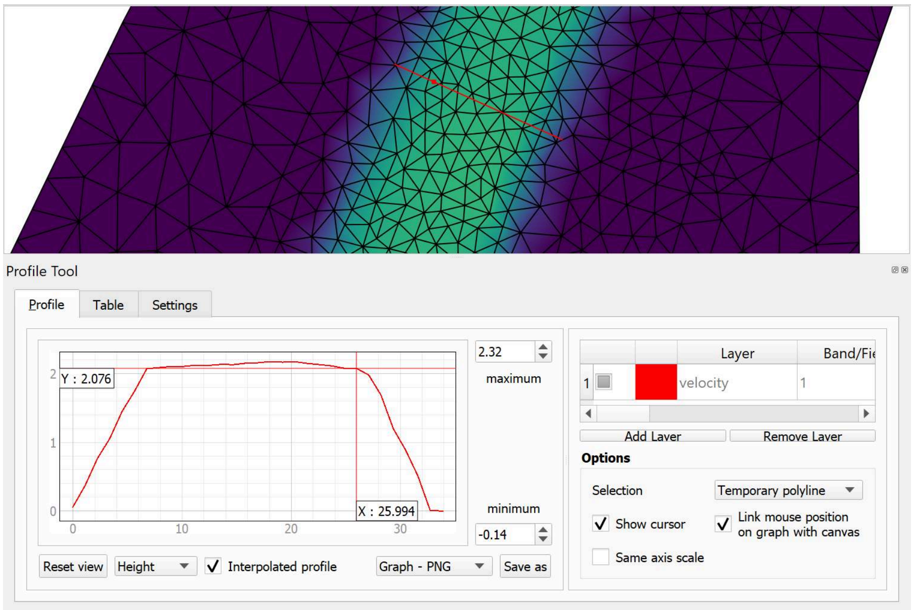
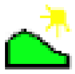


Figure 2.9 *Velocity profile along a temporary polyline generated with the 'Profile Tool' plugin*

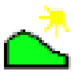
Once the 'Profile Tool' is installed successfully, a new icon  should be added to your Layers toolbar.

Usage

In general, there are two options to use the 'Profile Tool':

1. Using a temporary polyline:

   With this option, you can draw an arbitrary polyline at the location of your choice. Along this line the data of the selected *Quantity* will be extracted.

   (1) Click on the *Terrain profile* icon  and the Profile Tool window pops up.

   (2) In the field *Selection* chose *Temporary polyline* from the dropdown menu.

   (3) Use the black cross to draw a red line along the desired location of your displayed Quantity (see Figure 2.9).

   (4) Start drawing the line with a click and finish the line with a double-click

   Now the profile of the chosen quantity should be displayed in the *Profile Tool* window (see Figure 2.9 below). From there you can save the graph in different formats or export the raw data via the tab *Table*.

2. Using a selected polyline:

   With this option you can chose an existing polyline feature e.g. a certain cross section to extract the desired quantities.

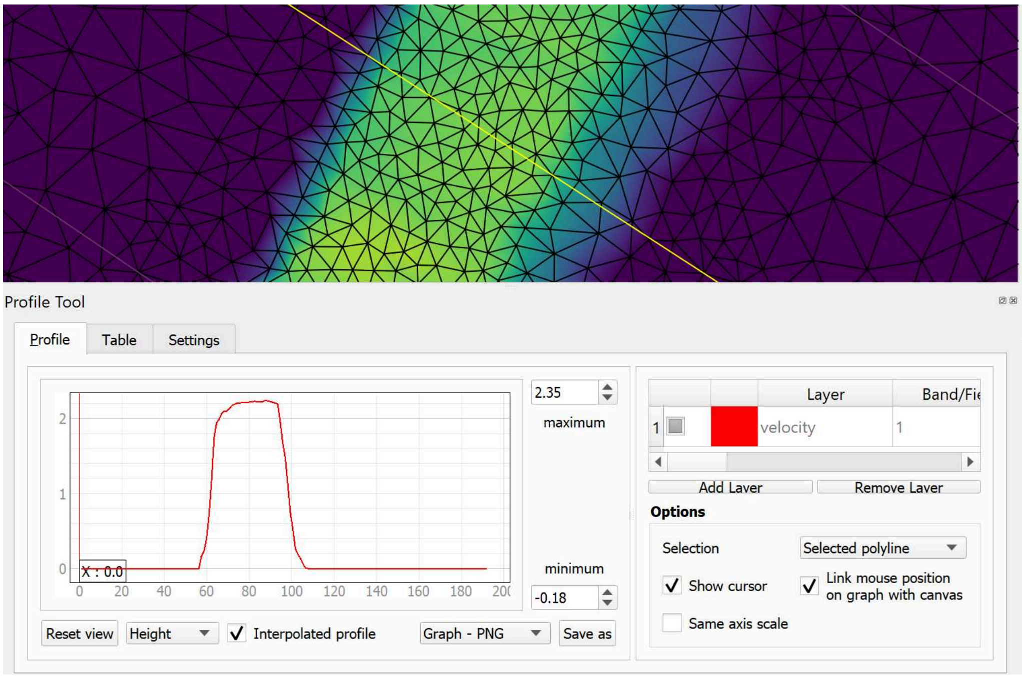
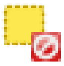
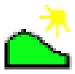


Figure 2.10 *Velocity profile along the red line drawn at the location of cross section 'CS10' generated with the 'Profile Tool' plugin*

(1) First make sure to *Deselect Features from All Layers* pressing the respective toolbar button 

(2) Again click on the *Terrain profile* icon  and the Profile Tool window pops up.

(3) In the field *Selection* now chose *Selected polyline* from the dropdown menu.

(4) Right-click on the layer 'Flaz_cross_sections' and go to *Open Attribute Table.*

(5) Select the feature with *name* 'CS10' and left-click into the map displayed in the QGIS main canvas.

Again the profile of the chosen quantity should be displayed in the *Profile Tool* window (see Figure 2.10). Note that the profile also contains entries with value 0 since the extent of the cross section is wider than the wetted main channel.

2.2.5 Creating maps and animations

An important step of the post processing of simulation results is the creation of maps for example of flow depths or velocities to be published in reports or presentations. For this purpose QGIS offers a powerful tool called 'Print Layout which allows you to take your GIS layers and package them to create professional maps including legend, scale bar or text boxes. It is possible to display and export BASEMENT results layers using the QGIS 'Print Layout. This tutorial can't cover the whole functionality of the 'Print Layout, but some of the main features, needed to create proper figures and animations of 2D simulation results are explained subsequently. Check the online User Guide of the software QGIS for further documentation.

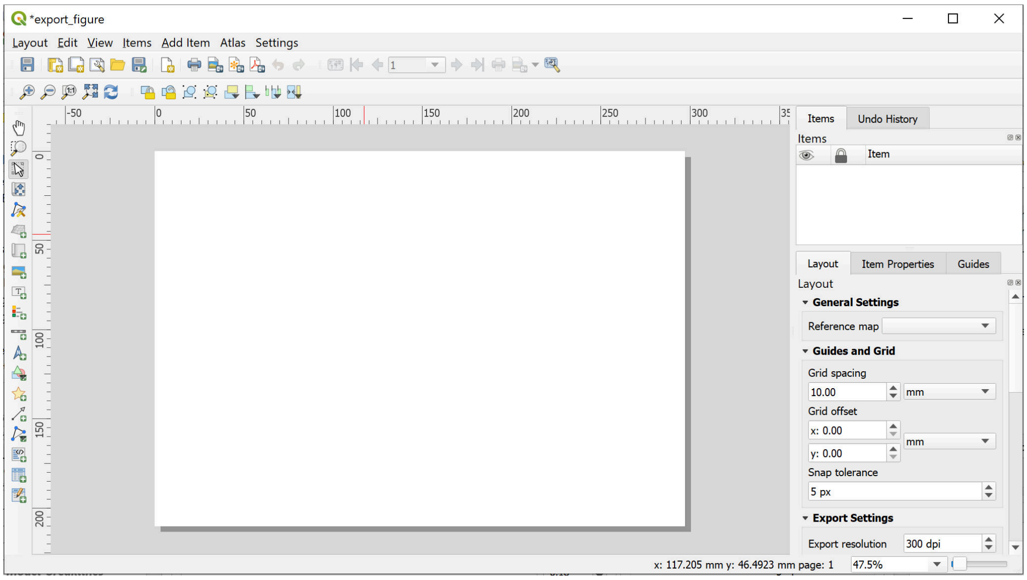


Figure 2.11 *QGIS Print Layout with some of the basic control features*

2.2.5.1 Customized layout (QGIS print Layout)

After loading all the layers to be exported in a map into the main QGIS canvas, we can start to assemble our map. Note, that only layers which are checked / enabled in the *Layers control panel* of the main canvas can be displayed in the *Print Layout*.

(1) Go to *Project* → *New Print Layout* or press the New Layout icon in the toolbar.

(2) You will be prompted to enter a title for the layout e.g. 'export_figure'. If left blank, a default name will be applied.

A new Print Layout opens up (see Figure 2.11). The main control buttons to add and modify maps can be found in the toolbar on the left site. You can also specify the layout and export resolution in the tab *Layout* on the right site.

After defining a proper layout a new map can be added:

(1) Press the *Add map button* , hold the left mouse button and drag a rectangle where you want to insert the map.

The rectangle window will be rendered with the currently active map from the main QGIS canvas. In this example the 'depth' results shall be displayed together with the background areal image, breaklines and mesh elements (see Figure 2.12). The rendered map might not cover the desired extent of interest. To alter the displayed map extent and/or zoom:

(1) Select *Move item content* to pan the map in the window to desired position.

(2) Once *Move item content* is active, you can change the map zoom using the mouse wheel.

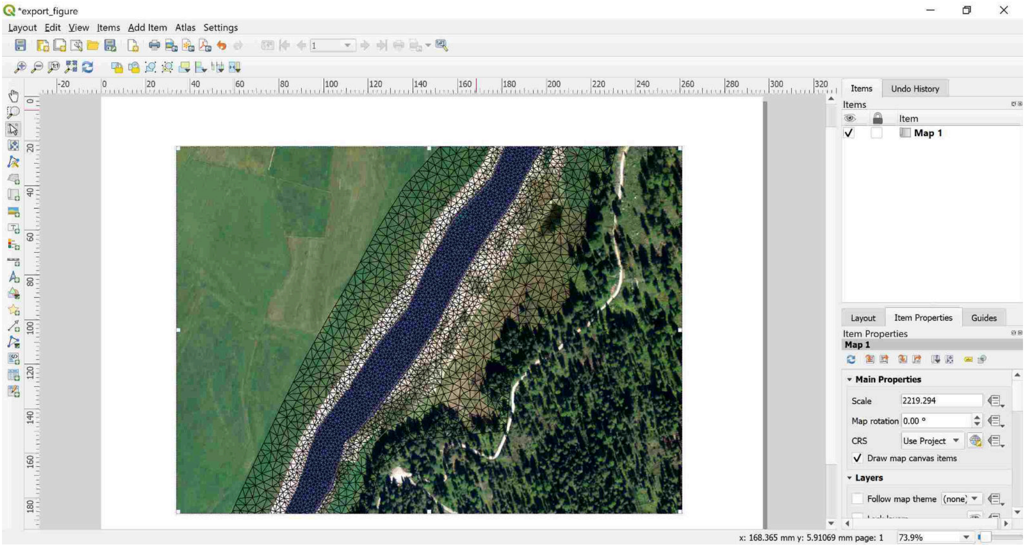


Figure 2.12 *QGIS Print Layout with displayed results layer 'depth'. Orthophoto: © 2016 swisstopo (JD100041)*

The map is now listed as 'Map 1' in the *Item* dialogue box. Further map properties can be defined via the tab *Item properties*. Additionally, we want to add a legend to our map:

(1) Press *Add legend* , hold the left mouse button and drag a rectangle where you want to insert the legend.

(2) The legend will appear as new *Item* 'Legend' in the Items dialogue box (see Figure 2.13). Go to *Item properties* in order to modify the legend entries.

(3) Under *Legend items* uncheck/disable the *auto update* function. Now you can remove the legend items that shall not be displayed using the *minus* button . In this example everything but the 'Flaz_mesh' and the 'model_boundary' is removed. The order of the legend items can be changed with the *up* and *down* buttons.

So far no units of the 'depth' are displayed in the legend. Furthermore, we want to add scale bar and a north arrow to our map:

(1) Click on 'depth' in the *Legend items* dialogue box and press *edit* .

(2) Type 'depth [m]' and press *OK*

(3) With the additional *Item properties* you can modify Fonts size and style of the legend entries as well as the size of the symbols or spacing of the columns and rows.

(4) To insert a scale bar press the *Add new scalebar* button and click to the map at the desired position.

(5) A new *Item* 'scale bar' appears in the Items dialogue box and again properties of the scale bar can be modified via the *Item properties* tab.

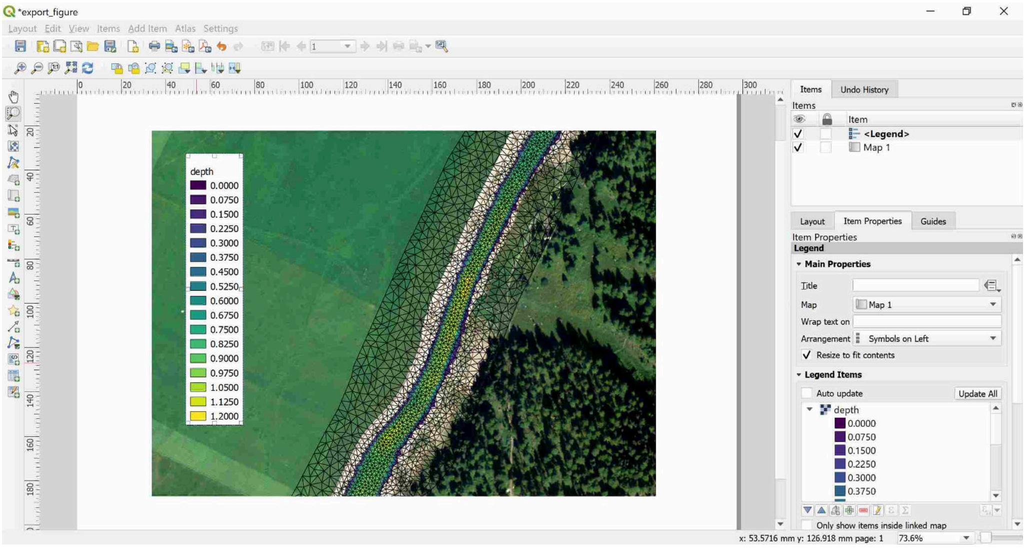


Figure 2.13 *QGIS print layout with displayed results layer 'depth' after inserting the legend. Orthophoto: © 2016 swisstopo (JD100041)*

(6) To insert a north arrow, press the *Add image* button and click to the desired location.

(7) A new *Item* 'picture' is listed in the Items dialogue box.

(8) A new *Item* 'Picture' appears in the Items dialogue box. In the *Item properties* tab you will find a preview of different arrow styles offered by QGIS, it is also possible to *Add* and *Remove Image search paths* manually.

If everything went well, your Print Layout should now look like shown in Figure 2.14. The map is now ready to be exported or printed. You can add additional features like text or images to the map at your convenience. Just use the *Add image* or *Add label* buttons . You can save your map properties as template for further QGIS projects.

(image.png) Go to *Layout* → *Save as Template* or use the button in the main toolbar.

In general the Print Layout is stored together with the main QGIS Project. If you open a project in which you defined a Print Layout in, you will always be able to access it via the main QGIS canvas.

(1) Go to *Project* → *Layout manager* where you can find a table of all print layouts defined within the main QGIS Project.

For the export of your map several formats are available in the Print Layout.

(1) Go to *Laout* → *Export as Image* to export the map as raster image e.g. png, jpeg, tif,. . .

(2) Alternatively chose export as PDF or export as SVG to save the map in vector format.

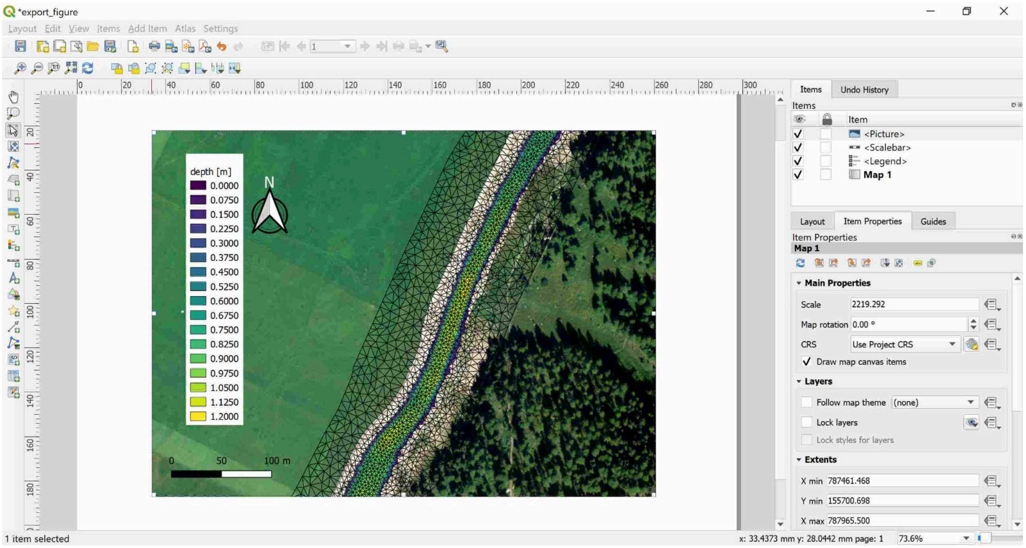


Figure 2.14 *QGIS print Layout with displayed results layer 'depth' after inserting legend, scalebar and north arrow. Orthophoto: © 2016 swisstopo (JD100041)*

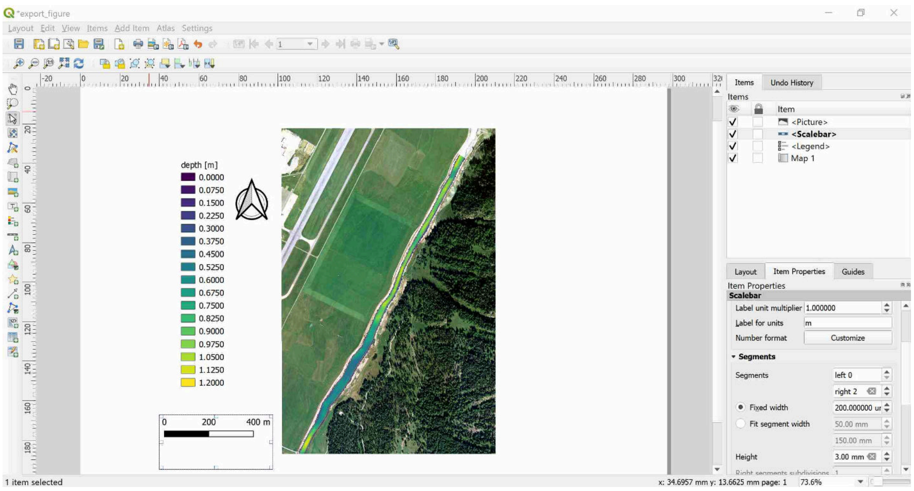


Figure 2.15 *QGIS print layout with displayed results layer 'depth' zoom to the full extent of the model for export as animation. Orthophoto: © 2016 swisstopo (JD100041)*

2.2.5.2 Export animation

If your simulation results are time dependent like those provided in this tutorial, you might not just want to export selected time steps as maps, but rather create an animation over the whole run time of the simulation. Before exporting your time-dependent result, you have to define the layout of your animation in the QGIS Print Layout.

We can continue from the Print Layout of the previous section (Section 2.2.5.1). Using the *Move item content* , zoom the map out to see the entire model domain. You may want to change the size of the scale bar, which can be done in the *Item properties* tab. You may also set the paper size and orientation: *Right click on the map → select "Page Properties"*.

In order to display the runtime of the simulation some additional steps are required:

(1) Press *Add label* and add a text field below the Legend.

(2) Go to *Item properties* and type 'run time:' into the *Main properties* field.

(3) Define *Font size*, *Frame*, and *Background* as desired.

(4) Again press *Add new label* and insert a second text field to the right of the first.

(5) Don't change the default expression 'Lorem ipsum' in the Main properties field.

(6) Go down to *Item ID* and type 'time' into the *ID* field

Now the text field is linked to the simulation runtime, which will be displayed during the animation.

(1) Go to *Layout* → *Save as Template* or use the button in the main toolbar.

The customized layout of the animation is saved as QGIS layout template (*.qpt) and will be used during the animation export.

The final export of the animation is done from the QGIS main canvas:

(1) Right click the 'Flaz_mesh' layer, select *Export animation...* and a new window will appear (see Figure 2.16).

(2) In the tab *General* you have to specify the start and end times of the animation, the frame rate in frames per second (fps), and the output directory.

(3) In the tab *Layout* chose *Custom layout (.qpt)* and browse to the location where you saved the Print Layout template (step 56).

(4) In the tab *Video* you can chose the Quality of the animation. The choice will affect the time to generate the animation as well as the resulting file size.

(5) *Under Video encoding utility (FFmpeg) to use:* chose custom.

(6) Press *OK* to begin generation of the animation.

A window may pop up saying that "The tool for video creation (FFmpeg) is missing ..." (Figure 2.17). Follow the instructions depending on your system (Windows or Linux).

(1) Finally press *OK*. QGIS will inform you that the export of the simulation was successful.

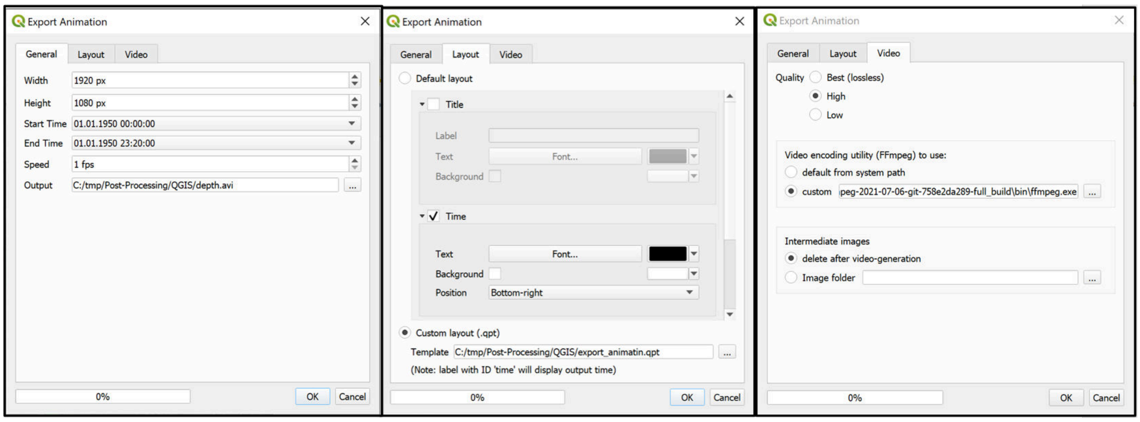


Figure 2.16 QGIS Export Animation window

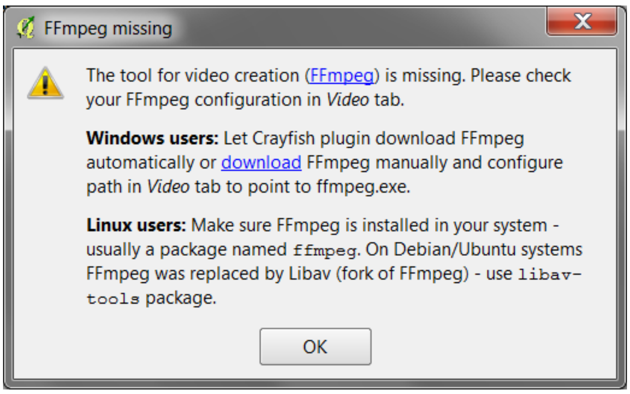


Figure 2.17 QGIS Export Animation FFmpeg

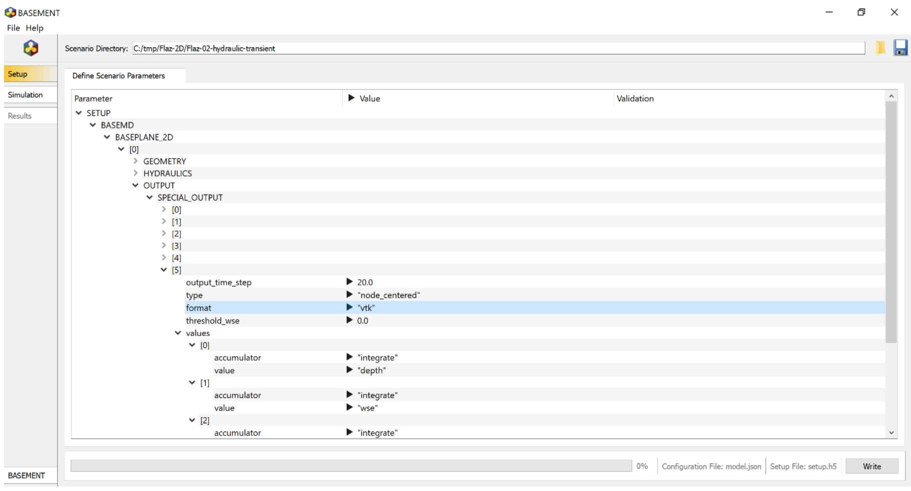


Figure 2.18 *Settings defined in the* SPECIAL_OUTPUT *Block of BASEMENT to generate time dependend result-files (*.vtk) of a 2D simulation*

2.3 3D result visualization with Paraview

2.3.1 Input data

The data needed to complete this tutorial comes as ZIP-file and needs to be extracted to a location of your choice. All screenshots and figures in this document were generated with ParaView version 4.3.

The result files (*.vtk) used for visualization in this tutorial come from the River Flaz. In the *SPECIAL_OUTPUT* Block of the BASEMENT command file select *format* 'vtk' to generate result files that can be visualized with ParaView (see Figure 2.18).

2.3.2 About Paraview

ParaView is an open source application for visualizing 2- and 3-dimensional data sets. The size of the data sets ParaView can handle varies widely depending on the architecture on which the application is running. The platforms supported by ParaView range from single-processor workstations to multiple-processor distributed-memory supercomputers or workstation clusters. Using a parallel machine, ParaView can process very large data sets in parallel and later collect the results.

More Information

In this tutorial, only a very small part of the enormous functionality of ParaView will be covered. The documentation as well as a number of tutorials is available online as Public Wiki. ParaView also offers an online help that can be accessed by clicking the help button  in the application.

2.3.3 Installation

To use ParaView on your own computer simply go to the Download page of ParaView. The software is available for Windows, Linux and Mac.

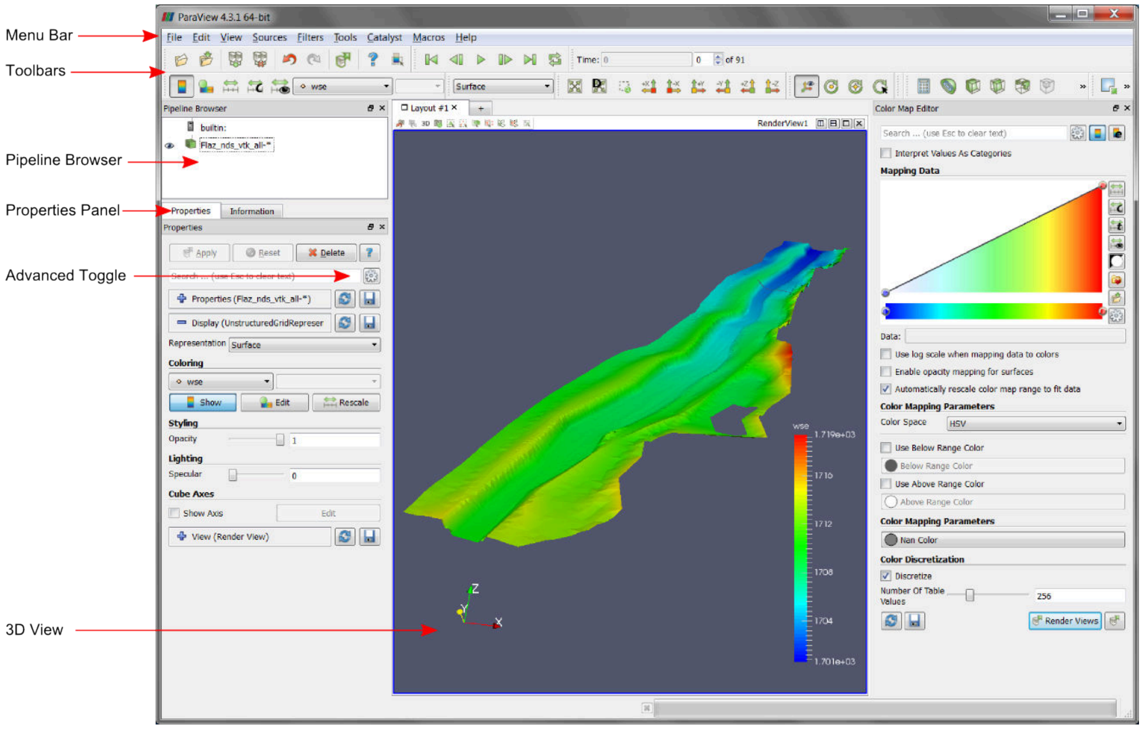


Figure 2.19 *ParaView GUI*

2.3.4 User Interface

The layout shown in Figure 2.19 is the default layout given when ParaView is first started. The GUI comprises the following components:

Menu Bar As with any other program, the menu bar allows you to access the majority of the features.

Toolbars The toolbars provide quick access to the most commonly used features within ParaView.

Pipeline Browser ParaView manages the reading and filtering of data with a pipeline. The pipeline browser allows you to view the pipeline structure and select pipeline objects for visualization. To toggle visibility of single objects, click on the 'eye-symbol'.

Properties Panel The properties panel allows you to view and change the parameters of the current pipeline object. Use the *Toggle advanced properties* button to show and hide advanced options. The properties are by default coupled with an **Information** tab that shows a basic summary of the data produced by the pipeline object.

3D View The remainder of the GUI is used to present the data so that you may view, interact with and explore your data. This area is initially populated with a 3D view that will provide a geometrical representation of the data.

Note that the GUI layout is highly configurable. To toggle the use of a toolbar, go to *View* → *Toolbars* and check/uncheck the available options.

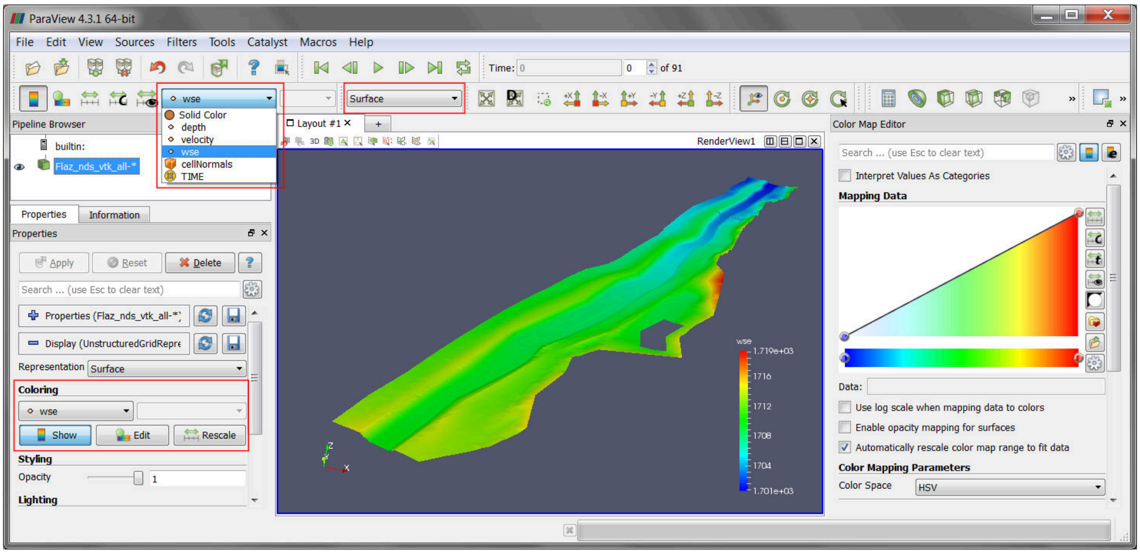


Figure 2.20 *ParaView GUI with 3D view of the domain Flaz*

2.3.5 Import Data

The provided results are stored in the subfolder 'ParaView'. Although the folder contains 91 vtk-file representing 91 output timesteps, we can load the results as one single data package:

(1) Go to *File* → *Open* or use the *Open* button  in the toolbar.

(2) Browse to the 'ParaView' folder, select the file 'Flaz_nds_vtk_all-..vtk' and press *OK*.

Note that opening a file is a two step process in ParaView, so you don't see any data yet.

(3) In the *Properties Panel*, click on *Apply* to load the data.

Now a 3D preview of the domain Flaz should be rendered to the 3D view. From the dropdown in the toolbar, we can select, which quantity shall be visualized. Alternatively, the quantities can also be selected under *Coloring* in the *Properties* panel. In this example the quantities 'depth', 'velocity' and 'wse' are available (see Figure 2.20). With the option 'Solid Color', just the geometry of the domain without any time depending quantity can be displayed. To visualize the mesh elements, select 'Surface with edges' instead of 'Surface' from the dropdown menu. The color of the mesh elements can by modified under *Edge Styling*, which is enabled by toggeling the advanced properties (see Figure 2.20).

2.3.6 ParaView Filters

2.3.6.1 Overview

In ParaView a large number of so called *Filters* can be applied. *Filters* are functional units that process the data in order to generate, extract or derive features from the data. Here are some of the most common, which are available by clicking the respective icon in the filters toolbar.

Calculator  Evaluates a user-definied expression on a per-point or cell basis.

Contour  Extracts the points, curves, or surfaces where a scalar field is equal to a user-definied value. This surface is often also called an isosurface.

Clip  Intersects the geometry with a half space. The effect is to remove all the geometry on one side of a user-defined plane.

Slice  Intersects the geometry with a plane. The effect is similar to clipping except that all that remains is the geometry where the plane is located.

Threshold  Extracts cells that lie within a specified range of a scalar field.

Extract Subset  Extracts a subset of a grid by defining either a volume of interest or a sampling rate.

Glyph  Places a glyph, a simple shape, on each point of the mesh. The glyphs may be oriented by a vektor and scaled by a vector or scalar. With this *Filter* it is possible to visualize velocity vector for example.

For further information about available *Filters*, please refer to the documentation of ParaView.

2.3.6.2 Applying Filters to data

After introducing the basic concept of *Filters*, we are now ready to apply three different *Filters* to our dataset. The goal is, to generate a 3D view of the time depending water surface elevation (wse) superimposed on the mesh geometry. First we want to display the geometry with vertical exaggeration for better contrast.

(1) In the toolbar chose 'Solid Color' and 'Surface' from the dropdown menu (see Figure 2.21)

(2) Go to *Transforming* in the *Properies* panel (advanced properties) and alter the *Scale* in the third column (z-direction) from 1 to 2 and press Enter.

(3) Reload the 3D view by clicking on the eye symbol in the *Pipeline Browser*.

Filter: Warp by Scalar

This *Filter* moves point coordinates along a vector by a distance determined by a user defined scalar for the active data set.

(4) Select the data set 'Flaz_nds_vtk_all-*' from the *Pipeline Browser*.

(5) In the menu bar go to *Filters* → *Alphabetical* and select *Warp By Scalar*.

(6) In the *Properties* panel chose 'depth' as *Scalars* and press *Apply* (see Figure 2.22)

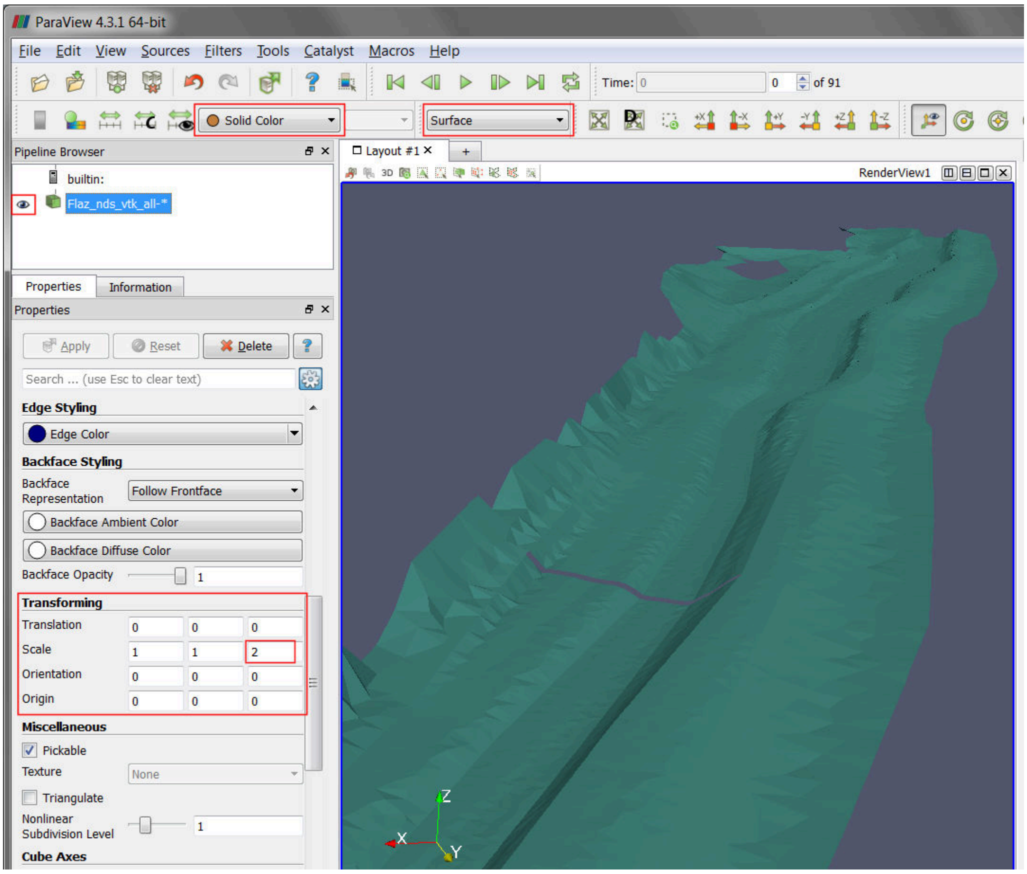


Figure 2.21 *Vertical exaggeration of solid mesh*

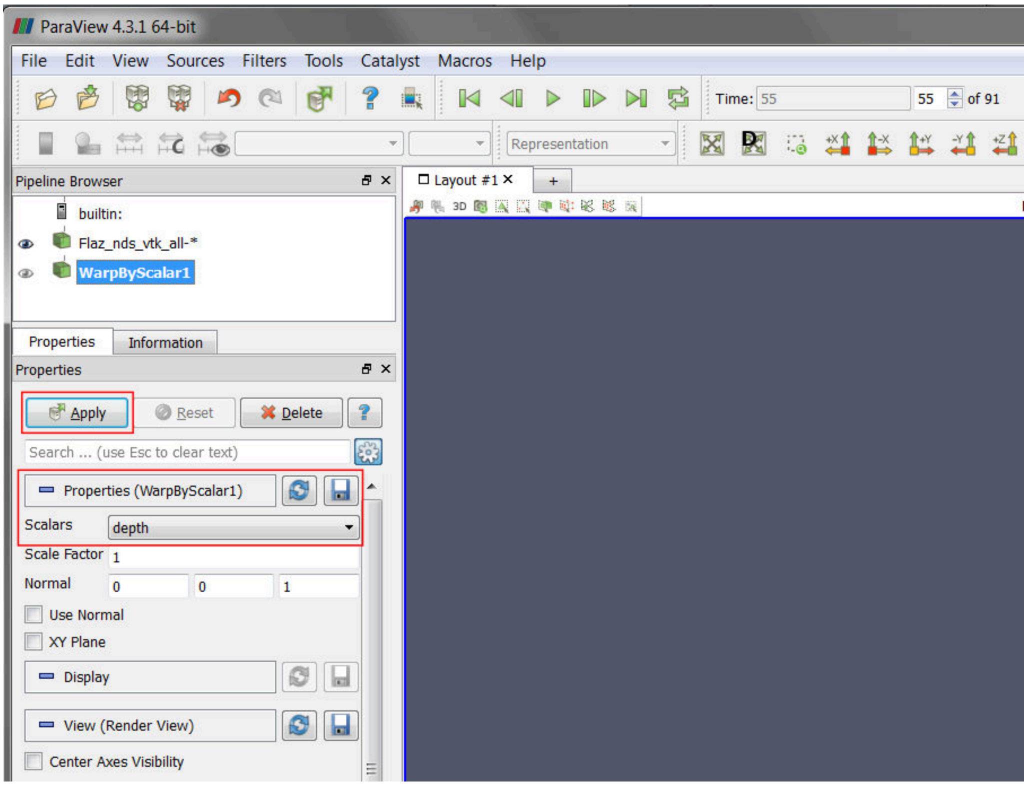


Figure 2.22 *Filter, Warp by Scalar*

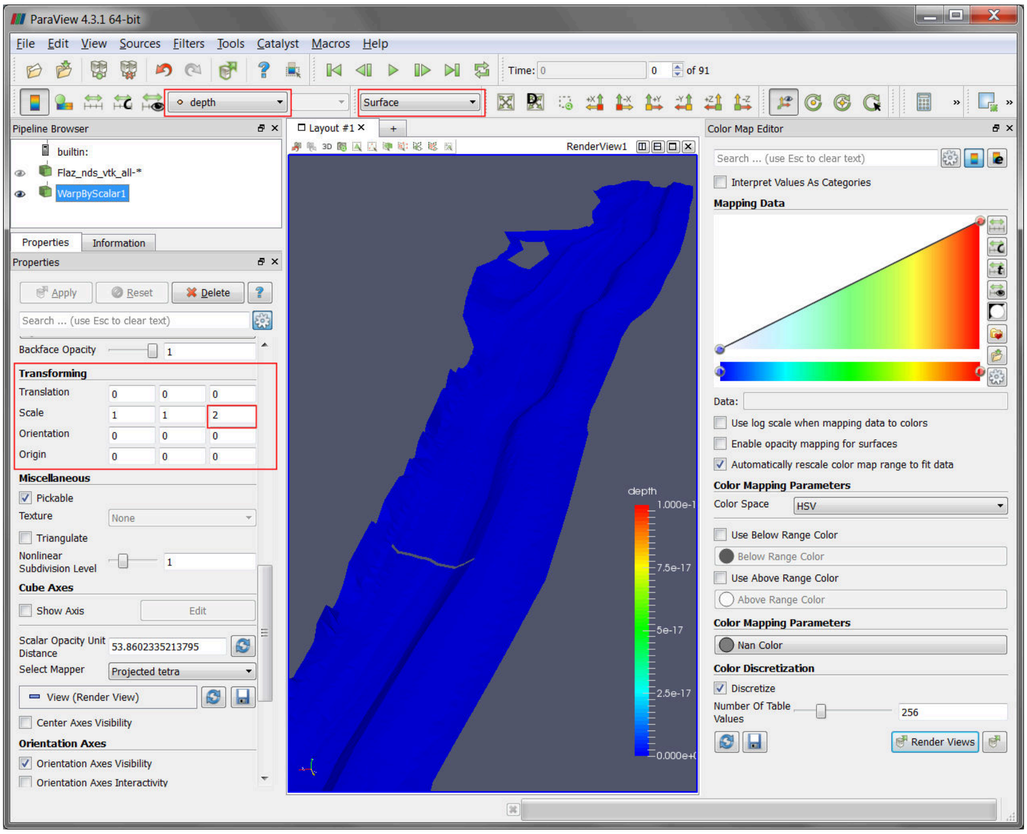


Figure 2.23 *Warp by Scalar, properties*

(7) Select the data set ‘WarpByScalar1’ from the *Pipeline Browser*.

(8) In the toolbar chose ‘depth’ and ‘Surface’ from the dropdown menu (see Figure 2.23)

(9) Again alter the *Scale* in z-direction from 1 to 2.

Filter: Threshold

Applying a Threshold *Filter*, we are able to blank out elements with a water depth below a certain threshold:

(10) Select the data set ‘WarpByScalar1’ from the *Pipeline Browser*.

(11) In the menu bar go to *Filters* → *Alphabetical* and select *Threshold* or directly access the *Filter* pressing the respective button  in the toolbar.

(12) In the *Properties* panel for ‘Threshold1’ chose ‘depth’ as *Scalars* and specify the *Minimum* and *Maximum* as shown in Figure 2.24, than press *Apply*.

(13) Repeat the steps 1-3 for the layer ’Threshold1’in order to adjust the coloring and the vertical exaggeration.

(14) Toggle visibility of the layers ‘Flaz_nds_vtk_all-*’ and ‘Threshold1’ in the *Pipeline Browser*.

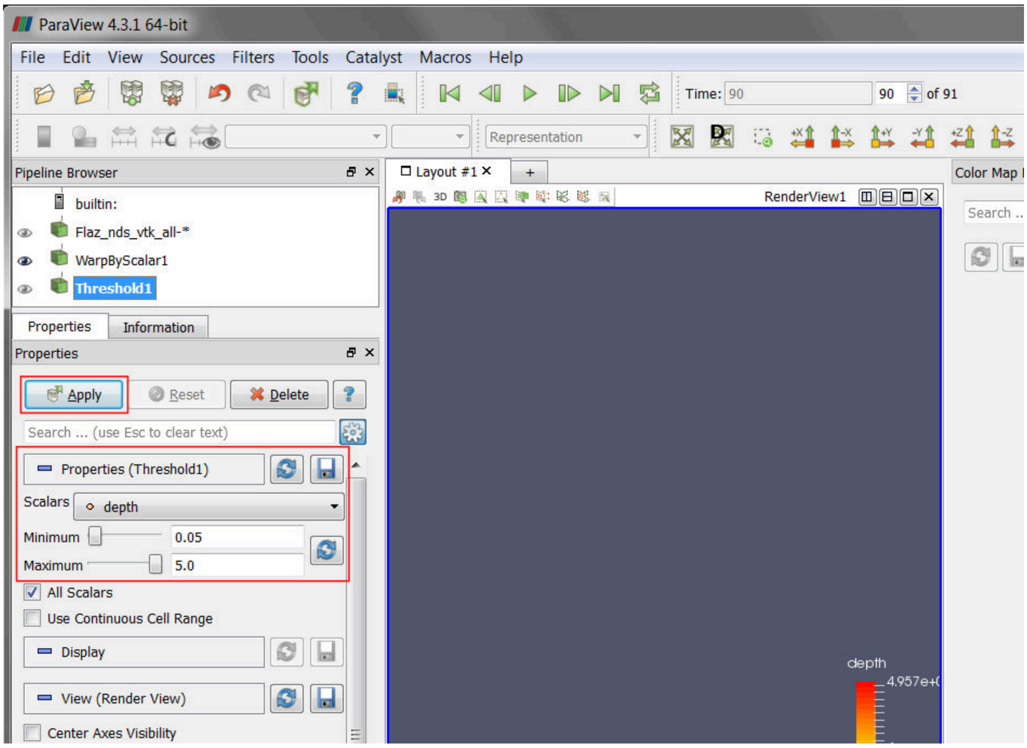


Figure 2.24 *Filter, Threshold*

Annotate Time Filter

So far our 3D preview of the simulation results is missing a time annotation, which shows the current simulation runtime of the selected output timestep. To add this information:

(15) Select the data set 'Threshold1' from the *Pipeline Browser*.

(16) In the menu bar go to *Filters* → *Alphabetical* and select *Annotate Time Filter*

(17) Specify the *Properties* like shown in the *Properties* panel of Figure 2.25 and press *Apply*.

Note that the definition of *Format*, *Shift* and *Scale* is highly dependent on the data you want to visualize. For the provided data a runtime of 1800 seconds and an output timestep of 20 seconds have been defined in the *SPECIAL_OUTPUT* Block of the BASEMENT command file. This leeds to 90 time steps you can browse through with the time control buttons in the toolbar (see Figure 2.25).

- Format %4.0f: Double with a width of 4 characters and a precision of 0 decimal places.
- Shift 0: Time annotation starts at 0.
- Scale 20: The timespan between the single output steps in 20 seconds.

If everything went well, your 3D view should no like like Figure 2.26. At the beginning (Time: 0) only the geometry is visible due to the initial condition 'dry'. From time step 1

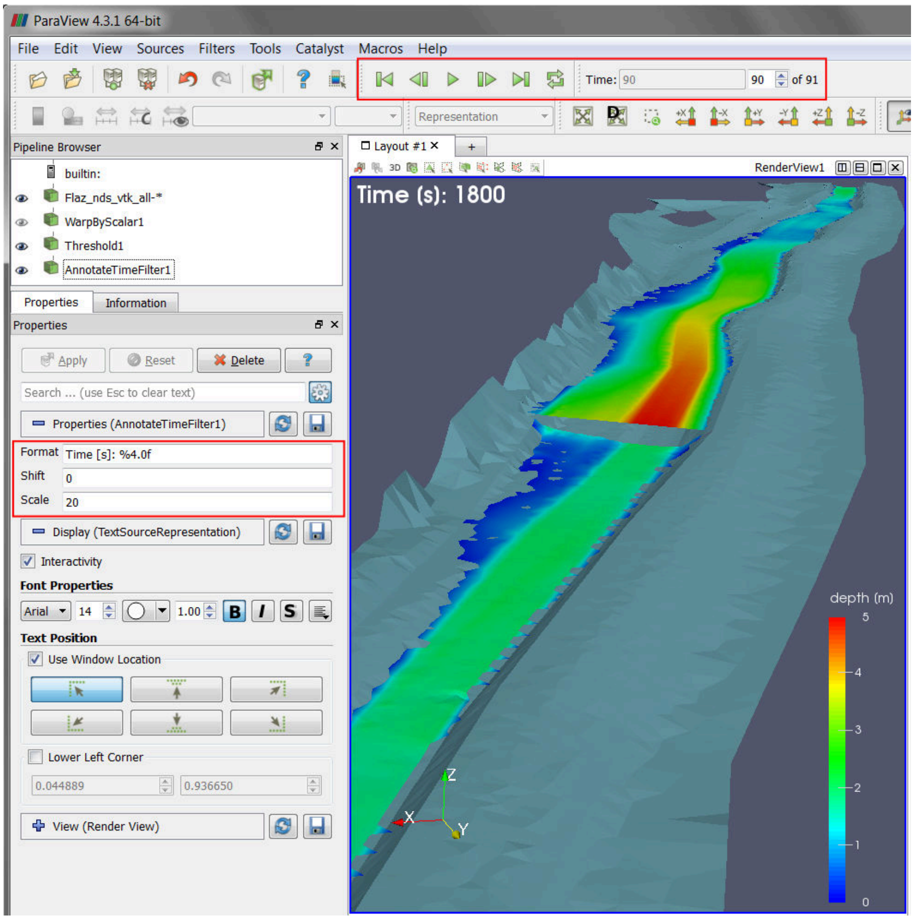


Figure 2.25 *Annotation Time Filter*

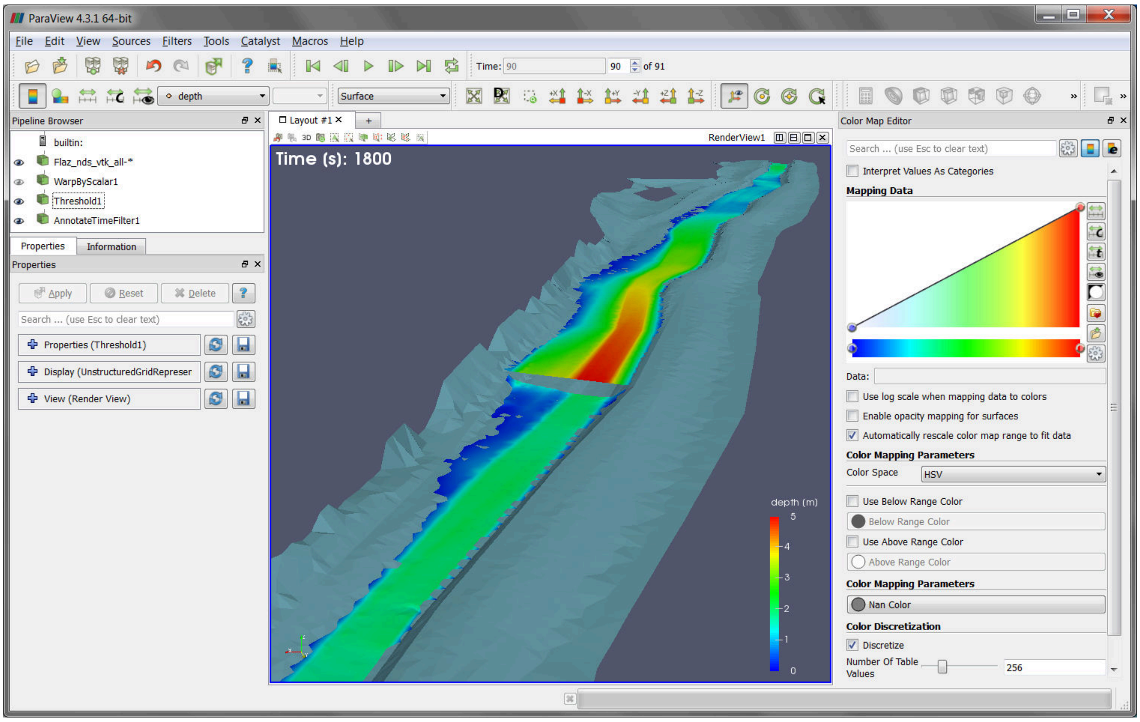


Figure 2.26 *Water depth at the steady state of the simulation*

to 27 water enters the domain at the upstream boundary and a backwater profile appears upstream of the inner weir boundary. After time step 28 the weir is overtopped and water is visible also downstream of the weir boundary.

2.3.7 Exporting figures and animations

One of the most important products of any visualization is screenshots and movies that can be used for reports and presentations.

2.3.7.1 Save Screenshot (picture)

(1) Go to *File* → *Save Screenshot* and a new window with several controls will appear. (see Figure 2.27)

The *Select resolution for the image to save* entries allows you to create an image that is larger (or smaller) than the current size of the 3D view.

(2) Press *OK* and specify a location for the file to be exported. From the dropdown you can select several file types. It is recommended to save images as PNG file though.

The save screenshot option saves the image as a raster graphic, which is natural for rendered images and very efficient for large data sets. Howerver, elements like text and other labels often become disfigured. These elements are better represented as vector graphics, which use geometrical primitives to draw the shapes. To create a vector graphic:

(3) Go to *File* → *Export Scene* and specify an output location. Several file types are available e.g. *.pdf or *.svg.

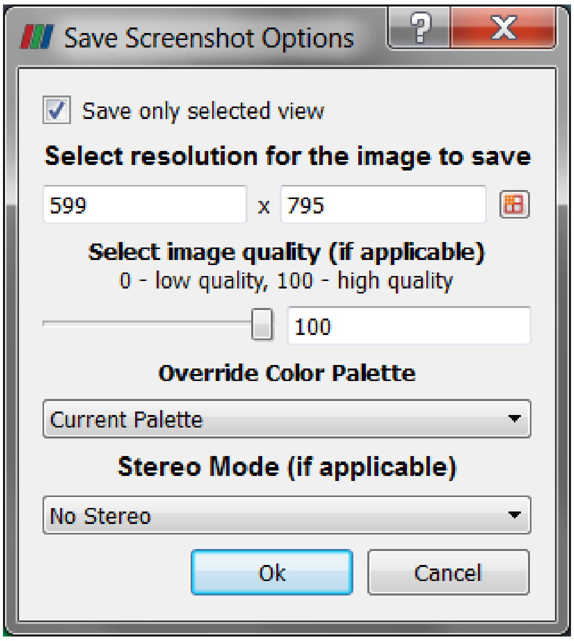


Figure 2.27 *Export Screenshot*

2.3.7.2 Save Animation (movie)

(1) Go to *File* → *Save Animation* and a new window with several controls will appear. (see Figure 2.28)

Again, you can create an animation that is larger (or smaller) than the current size of the 3D view modifying the *Resolution (pixels)* entries. It is advisable to reduce the *Frame Rate (fps)* from 15 to 8, otherwise the animation might run to fast.

(2) Press *Save Animation* and specify an output location.

(3) Select AVI files (*.avi) as file type and press *OK*.

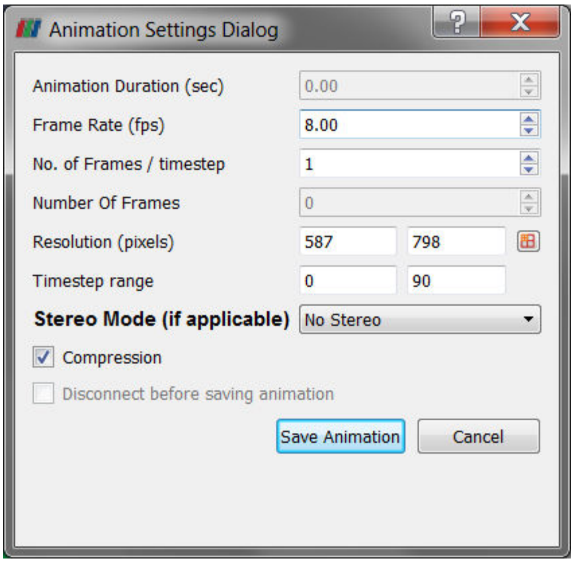


Figure 2.28 *Export Animation*

3

Hydrodynamics and sediment transport at the river Flaz with BASEHPC

3.1 Hydrodynamics and sediment transport at the river Flaz with BASEHPC (2D)

3.1.1 Introduction

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

3.1.2 Computational Mesh

The computational mesh of the Flaz is imported from the tutorial of BASEMENT version 2.8. The 2dm file has been modified as explain in the pre-processing tutorial for small meshes in the User manual. There are two stringdefs for the inflow and outflow boundaries. The mesh has 14'457 cells, 7'446 vertices and the interpolation method "weighted" is used to convert the mesh from version 2.8 to a 3 compatible computational mesh. Figure 3.1 shows the bottom elevation of the river Flaz used in this tutorial.

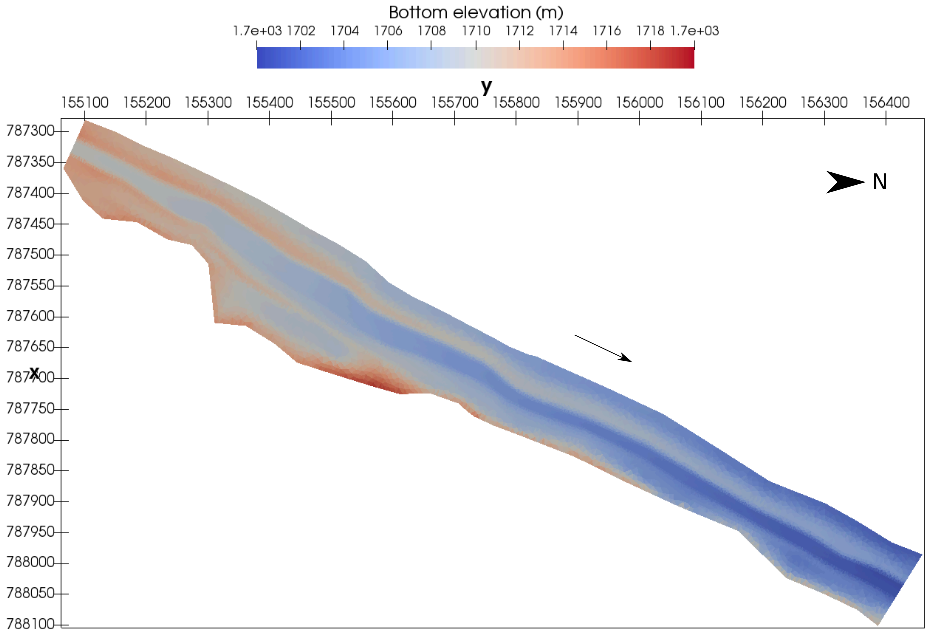


Figure 3.1 *Planar view of the initial bottom elevation of the river Flaz*

3.1.3 Hydraulics

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

3.1.3.1 Setup the Configuration File model.json

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

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

```
}
```

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

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

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

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

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

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

```
"PARAMETER": {
                        "CFL": 0.95,
```

```
                        "minimum_water_depth":0.002,
                        "fluid_density": 1000.0,
                        "max_time_step": 100
                    }

"FRICTION": {
                    "type": "strickler",
                    "default_friction": 30,
                    "regions": [
                            {"region_name": "one",
                             "friction": 28.0},
                            {"region_name": "two",
                             "friction": 30.0},
                            {"region_name": "three",
                             "friction": 35.0},
                            ...
                        ]
                    }

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

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

"INITIAL":{
```

```
                "type": "dry"
            }
```

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

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

3.1.3.2 Setup the Configuration File simulation.json

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

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

3.1.3.3 Set up the Configuration File results.json

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

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

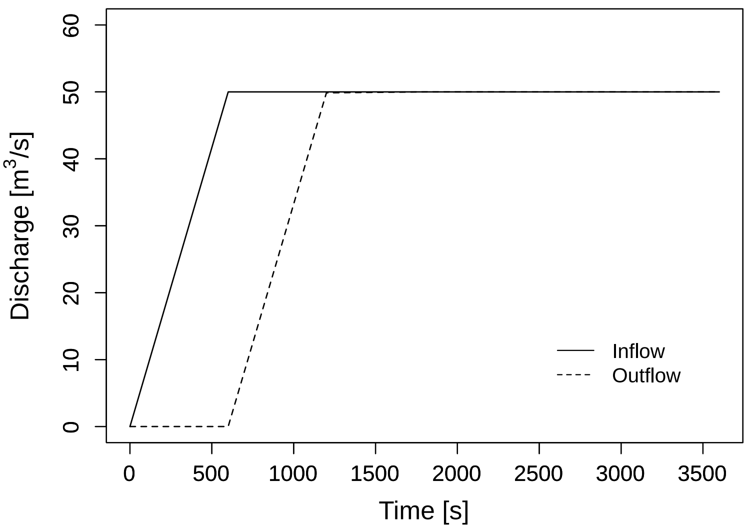


Figure 3.2 *Inflow and outflow hydrograph at boundaries*

3.1.3.4 Steady Flow Simulation

The simulation results are stored inside the results.h5 binary. By calling the python script BMv3NodestringResults.py available on the BASEMENT Website, the discharge values at boundaries are extracted and stored in the Discharge.csv file, where the rows are the time steps and the columns represents the stringdef in their definition order (inside the .2dm file). The steady state is reached after 1200 seconds (Figure 3.2).

3.1.3.5 Model Calibration

The calibration of the friction value is done by comparing the water surface elevation between BASEMENT version 3 and version 2.8 at a cross section located in the middle of the channel (Figure 3.3). The water surface elevation and the water depth values along the cross section were obtained using the software ParaView.

The resulting water depth and water surface elevation are compared in Figure 3.4. The steady flow simulation of BASEMENT version 3 provides similar results to those obtained with BASEMENT version 2.8. There is no need to modify the friction value defined in Section 3.1.3.1.

3.1.3.6 Unsteady Flow Simulation

The hydrograph based on the flood event of July 2004 provides unsteady flow conditions for the numerical simulation. The results of the steady flow simulation are stored in the binary Flaz_steady_state_results.h5 inside the run/ folder and taken as initial state. The other parameters defined in Section 3.1.3.1 don't change, except for the boundary block where the new discharge file (Inflow_transient.txt) replaces the stationary hydrogrpah. The initial block:

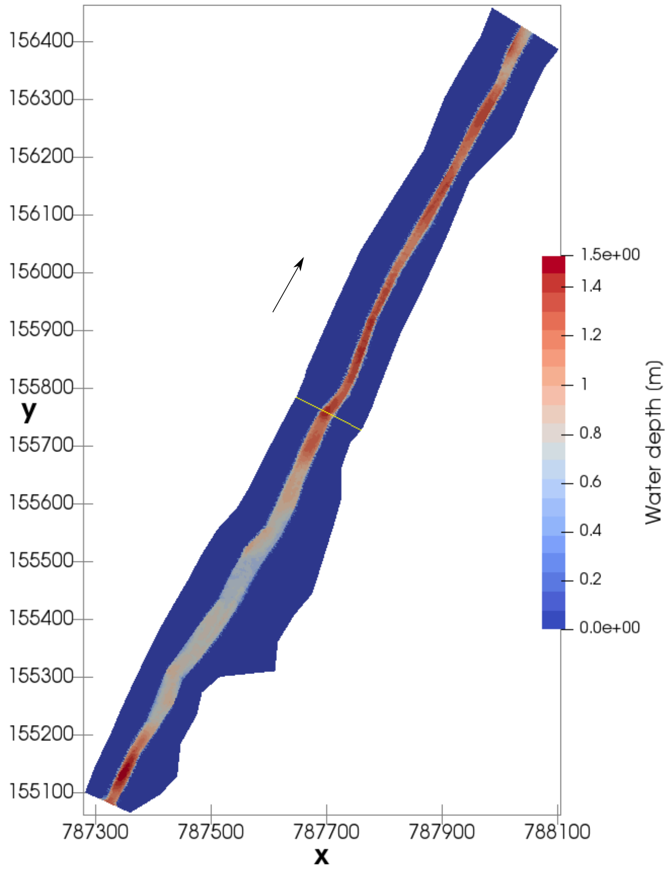


Figure 3.3 *Water depth at the end of the steady flow simulation (t=3600 s) with the cross section location (yellow line)*

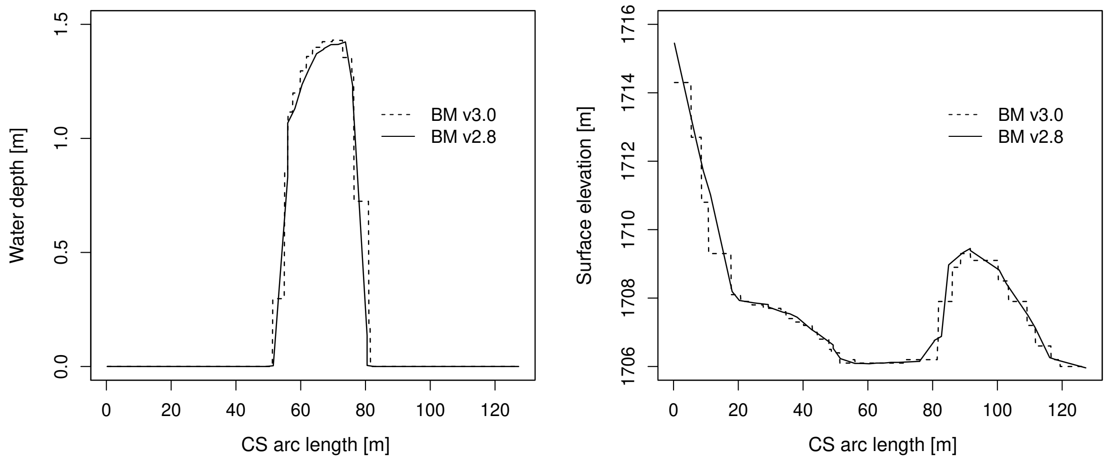


Figure 3.4 *Cross sectional view of the water depth and surface elevation facing the opposite flow direction at the end of the steady flow simulation (t=3600 s)*

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

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

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

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

3.1.4 Morphology

3.1.4.1 Setup the Configuration File model.json

The unsteady flow simulation is now converted into a morphodynamic simulation with a morphology block and starting from the results of the steady flow simulation. The inflow hydrograph and the initial blocks are the same as described in Section 3.1.3.6. Additionally, the block morphology is defined inside the model.json file with the following structure

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

Inside the morphology block, the initial conditions look like:

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

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

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

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

```
"BEDMATERIAL": {
                        "GRAIN_CLASS": {
                            "diameters": [0.050]
                        },
                        "FIXED_BED": {
                            "type": "region_defined",
                            "correction_accuracy": 0.0,
                            "max_iteration": 300,
                            "regions": [
                                {"region_name": "one",
                                 "z_rel": -0.8},
                                 {"region_name": "two",
                                 "z_rel": 0.0},
                                 {"region_name": "three",
                                 "z_rel": 0.0},
                                 {"region_name": "four",
                                 "z_rel": -2.0},
                                 {"region_name": "five",
                                 "z_rel": 0.0},
                                 {"region_name": "six",
                                 "z_rel": -2.0},
                                 {"region_name": "seven",
                                 "z_rel": -2.0},
                                 {"region_name": "eight",
                                 "z_rel": 0.0},
                                 {"region_name": "nine",
                                 "z_rel": 0.0},
                                 {"region_name": "ten",
                                 "z_rel": 0.0},
```

```
                    {"region_name": "eleven",
                    "z_rel": -0.2},
                    {"region_name": "twelve",
                    "z_rel": -0.4}
                ]
            }
        }
```

In the bedload block, the bedload transport formula is chosen and the morphological boundary conditions are defined. The boundary condition is defined as transport_capacity at the inflow boundary. The value of the sediment flux is averaged over the stringdef length and equally distributed (same value) among the edges. The outflow boundary has been reduced to the bed width composed of 6 nodes only. Therefore, the nodes located on the channel levee of the outflowing stringdefs have been removed from the .2dm file (computational mesh) manually using a text editor. The stringdef definition remains unchanged and the outflow boundary is defined as equilibrium_out with the reference bottom elevation set to 1700.68 m. Additionally, lateral transport due to local slope bed slope is considered with a default value of 1.5 (see Reference Manual).

```
"BEDLOAD": {
            "FORMULA": {
                "type": "MPM_like",
                "factor":1.0,
                "coefficient":3.2,
                "exponent":1.6,
                "critical_value":0.047
            },
            "BOUNDARY":{
                "STANDARD": [
                    {
                        "name": "inflow_MOR",
                        "string_name": "Inflow",
                        "type": "transport_capacity",
                        "boundary_factor": 0.8
                    },
                    {
                        "name": "outflow_MOR",
                        "string_name": "Outflow",
                        "type": "equilibrium_out",
                        "reference_bed_elevation": 1700.68
                    }
                ]
            },
            "DIRECTION": {
                "LATERAL_SLOPE": {
                    "factor": 1.5
                }
            }
        }
```

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

```
"SUSLOAD": {
  "PARAMETER": {
    "suspended_diffusivity": [0.1],
  },
  "BOUNDARY": {
    "STANDARD": [
      {
        "name": "inflow_SUS",
        "string_name": "Inflow",
        "type": "concentration_in",
        "data1": 0.0001
      },
      {
        "name": "outflow_SUS",
        "string_name": "Outflow",
        "type": "zero_gradient_out"
      }
    ]
  },
  "INITIAL": {
    "type": "zero"
  },
  "SETTLING_VELOCITY": {
    "closure_model": "van_rijn"
  },
  "SHEAR_PARTITION": {
    "default_friction_susp": 67.0
  },
  "EROSION_RATE": {
    "closure_model": "van_rijn",
    "constants": {
      "critical_shields": 0.125
    }
  },
  "DEPOSITION_RATE": {
    "closure_model": "lin",
    "constants": {
      "param_m": 1.0
    }
  }
}
```

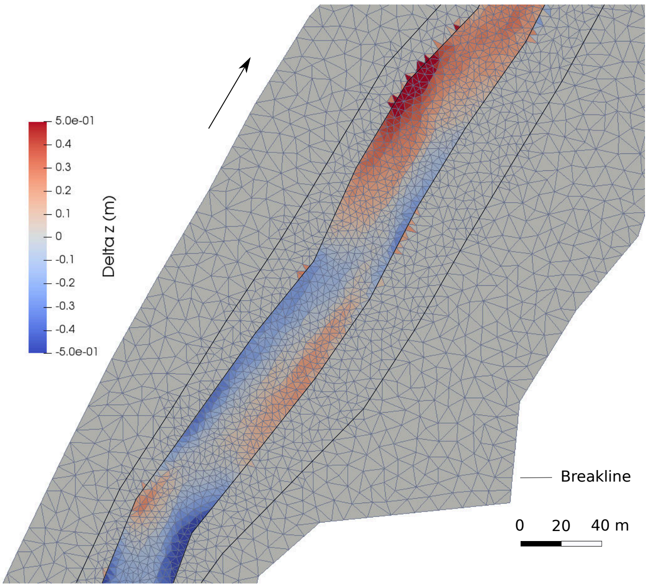


Figure 3.5 *Planar view of the widening part of the river Flaz with the change in bed elevation (Delta z) due to the flood event at the end of the morphodynamic simulation (t= 84'000 s)*

3.1.4.2 Setup the Configuration File simulation.json

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

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

3.1.4.3 Results

The morphological changes of the river bed are observed on Figure 3.5. The software ParaView was used for the post-processing of the output file (.xdmf).

3.1.5 Passive tracers

3.1.5.1 Setup the Configuration File model.json

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

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

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

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

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

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

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

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

"INITIAL":{
  "type": "uniform",
```

```
  "tracers": [0.0,0.25,0.5]
}

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

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

A source block within the tracers block would look like:

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

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

3.1.5.2 Setup the Configuration File simulation.json

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

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

```
            "flow_velocity_abs",
            "ns_hyd_discharge",
            "bottom_elevation",
            "spec_discharge",
            "water_depth",
            "tracer1",
            "tracer2",
            "tracer3"
        ]
    }
}
```

3.1.5.3 Set up the Configuration File results.json

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

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

4

Hydrodynamics and sediment transport at the river Flaz with BASEMD

4.1 Hydrodynamics and sediment transport at the river Flaz with BASEMD (2D)

4.1.1 Introduction

This tutorial gives an introduction to the capabilities of the 2D modelling module BASEplane of BASEMENT. It provides a step-by-step guidance on how build up a model for BASEplane.

4.1.1.1 Case study description

The tutorial for the 2D modelling module is based on an extract of the case study of the River Flaz in Graubünden. Within the framework of a high water protection project for the village Samedan a completely new section of the River Flaz was built. On a length of 4.1 km morphologically different kind of river subsections can be distinguished (Figure 4.1). The numerical modelling of the whole domain is carried out within the river monitoring project Flaz of the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). In order to reduce the model size (and thus computational running time) only the three most interesting sub-sections are modelled in this tutorial, such as the lower part of the section enriched with roughness elements, the widening part and the part with alternating bars shown in Figure 4.1.

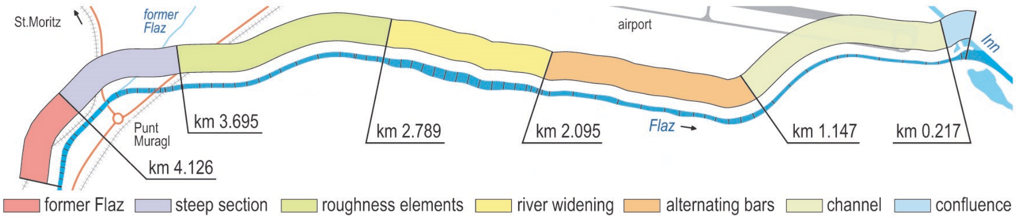


Figure 4.1 *Different morphological river subsections of the new section of the river Flaz*

4.1.1.2 Tutorial structure

In a first step the important properties of the mesh file are shown. The tutorial is designed to run BASE_MD_ with the help of the free and open source Geographic Information System QGIS as pre- and post-processor. The computational grid used in this tutorial (Flaz_mesh.2dm) covers the same perimeter like the one generated in the tutorial of BASEmesh (see Section 1.1). However the position of the breaklines differs slightly from the version of the BASEmesh tutorial. Furthermore the material indices have been changed for the definition of friction factors and soil properties.

How to visualize the results of the 2D simulations using QGIS and how to generate the graphics shown in this tutorial is demonstrated in the post-processing tutorial (Section 2.1) . The main focus of this tutorial lies on the setup the command file for the numerical simulation with BASEMENT.

The structure of this tutorial reflects the recommended steps to go from a hydraulic simulation to a morphodynamic simulation. A hydraulic simulation is initially set up. Based on this simulatio,n the morphological part can be added with a single-grain model. An outline of outputs is given and possible visualization is shown for each step.

4.1.2 Computational grid

The computational mesh is generated with the QGIS plugin BASEmesh. Here, only a few important features and characteristics of the computational mesh for modelling with BASEMENT are mentioned. The mesh discretizes the topography of the river in such a way that the important topographical information is maintained. Breaklines in the mesh are ensuring that important features of the topography such as the river bed and dike crests are represented correctly (Figure 4.2).

An important feature is the assignment of the material indexes to the different groups of elements. By the material index different properties such as the friction factor and the soil properties can be assigned. The material index is mainly used to assign the friction factor to the different river sections separately. For example it is usual to assign different values for the main channel, embankments, and surrounding floodplain (Figure 4.3).

The mesh file is saved as Flaz_mesh.2dm and has the following structure:

```
MESH2D
.
E3T    eN    n1    n2    n3      eMi        (triangle element)
.
ND      ni  x    y    z
.
```

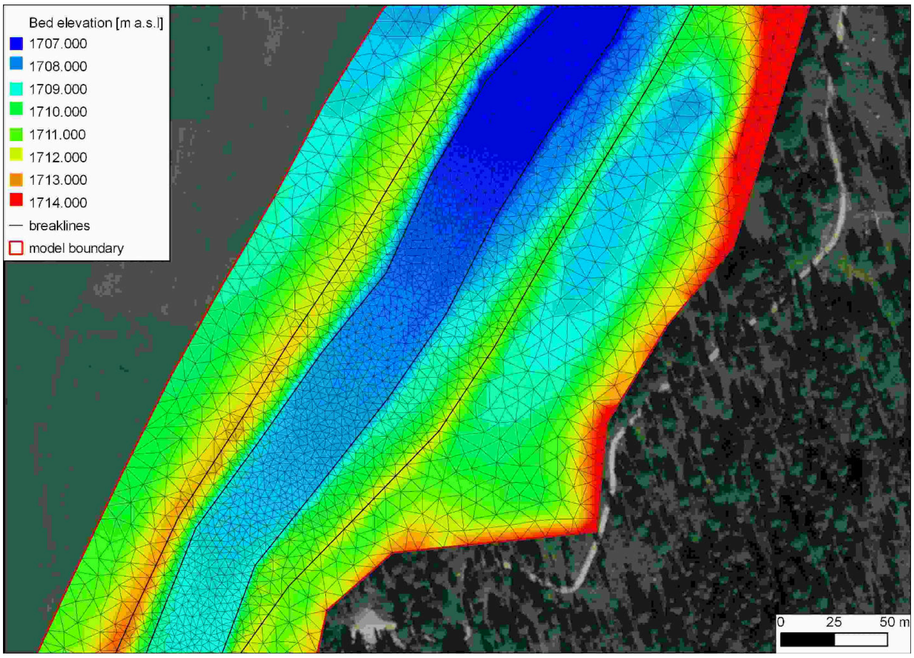


Figure 4.2 *Computational mesh generated with BASEmesh for a section in the widening part. The bold black lines are breaklines for the mesh.*

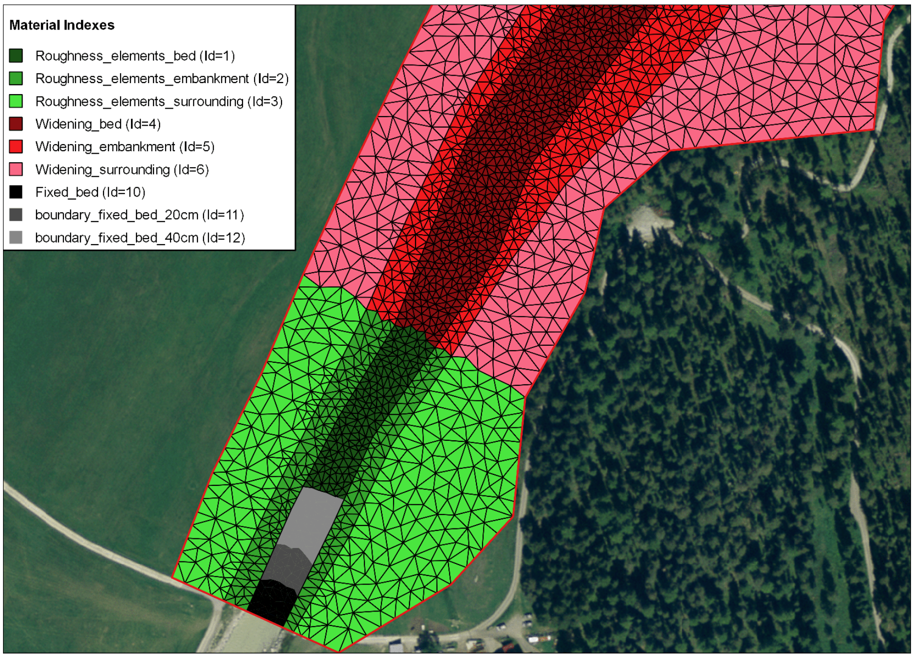


Figure 4.3 *Material indices used for assignment of the friction factor and the soil properties.*

Where E3T is the flags for the triangular elements; eN denotes the element number; n1, n2 and n3 denote the node numbers of the element and eMi is the material index of the element. The elements are defined in a counter-clockwise direction. The coordinates of the nodes are defined in the second block. ND is the flag for a node; ni denotes node number and x, y and z are the coordinates of the node.

4.1.3 Setting up the model file

The configurations files (model.json, simulation.json and results.json) can be created and modified with the graphical user interface (GUI) or any text editor. The configuration files must all be located in one folder.

Open the model setup file *model.json* via the menu of the BASEMENT GUI (File → Open Scenario Directory → select the folder that contains the configuration files). The structure of the model setup file looks like this:

```
SETUP
{
    "simulation_name": "2D_Tutorial"
    BASEMD
    {
        multiregion = Flaz
        PHYSICAL_PROPERTIES
        {...}
        BASEPLANE_2D
        {
            region_name = Flaz
            GEOMETRY
            {...}
            HYDRAULICS
            {...}
            TIMESTEP
            {...}
            MORPHOLOGY
            {...}
            OUTPUT
            {...}
        }
    }
}
```

4.1.3.1 BASEMD

The BASEMD-block includes all necessary blocks for a simulation.

```
BASEMD
{
    multiregion = Flaz
```

```
    PARALLEL
    {...}
    PHYISICAL_PROPERTIES
    {...}
    BASEPLANE_2D
    {...}
}
```

4.1.3.2 Physical properties

The physical properties are global constants in a project.

```
PHYSICAL_PROPERTIES
{
    gravity = 9.81              // [m/s2]
    viscosity = 1.0e-6          // [m2/s]
    rho_fluid = 1000            // [kg/m3]
}
```

4.1.3.3 Two dimensional domain

The *BASEPLANE_2D*-block within the BASEMD-block contains all information concerning the two dimensional model domain.

```
BASEPLANE_2D
{
    region_name = Flaz
    GEOMETRY
    {...}
    HYDRAULICS
    {...}
    TIMESTEP
    {...}
    MORPHOLOGY
    {...}
    OUTPUT
    {...}
}
```

4.1.3.4 Geometry

The GEOMETRY-block defines the mesh file and necessary strings of nodes. Strings are used for inflow and outflow boundaries and can also be used for discharge control. The node ids of the inflow and outflow string can be read out from the mesh in Figure 4.4 and Figure 4.5 respectively.

```
GEOMETRY
```

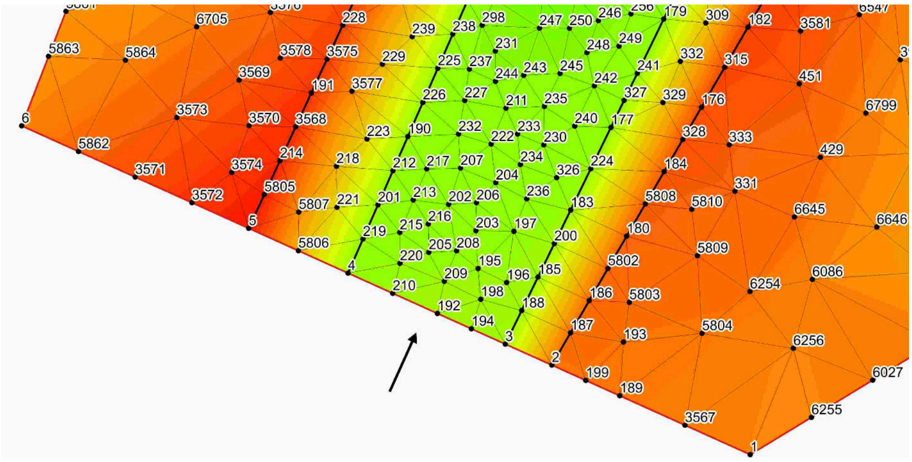


Figure 4.4 *Node id numbers for the definition in the STRING_DEF block for the inflow boundary.*

```
{
    type = 2dm
    file = Flaz_mesh.2dm

    STRINGDEF
    {
        name = Inflow
        node_ids = ( 2 3 194 192 210 4 5806 5 )
        upstream_direction = left
    }
    STRINGDEF
    {
        name = Outflow
        node_ids = ( 38 5568 5569 5570 37 5565 5538 5521 5551 36 6004 35 )
        upstream_direction = left
    }
}
```

4.1.3.5 Define the hydraulics

The HYDRAULICS-block includes all the information necessary for the hydraulic part of the simulation. This block is divided into the following sub-blocks:

```
HYDRAULICS
{
    BOUNDARY
    {...}
    INITIAL
    {...}
    FRICTION
    {...}
    PARAMETER
```

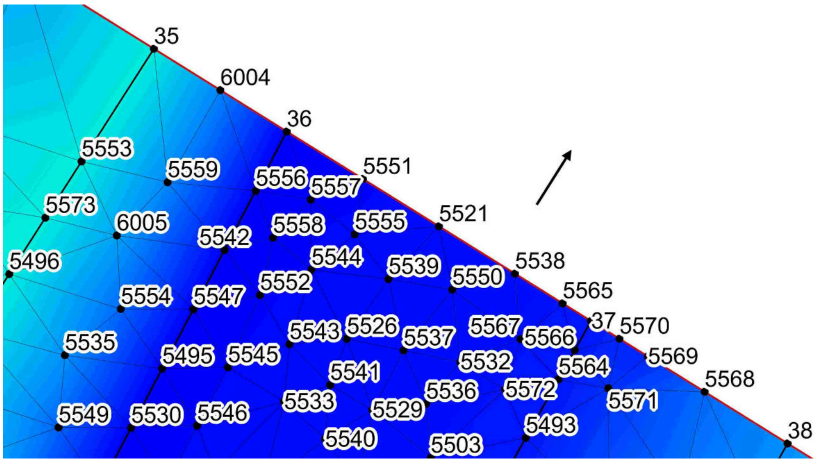


Figure 4.5 *Node id numbers for the definition in the STRING_DEF block for the outflow boundary.*

```
    {...}
}
```

4.1.3.5.1 Hydraulic boundary conditions

For the upper (inflow) and lower (outflow) boundary condition we have to refer to the predefined STRINGDEFs (see Section 4.1.3.4). If the boundary condition is not defined explicitly a wall boundary is considered for those edges. Except for the explicitly defined inflow and outflow boundary the model boundary is basically an impermeable wall.

The inlet boundary condition is defined across the predefined string *Inflow*. The hydraulic condition at the boundary is set by the use of a hydrograph and a corresponding slope. The normal slope is used in order to calculate the normal flow depths and the normal flow velocities at the boundary and can be considered as a calibration parameter.

```
BOUNDARY
{
    type = hydrograph
    string_name = Inflow
    file = Inflow_stationary.txt
    slope = 10.0                // [per mill]
}
```

The hydrograph is saved in a text file *Inflow_stationary.txt* in which the first column is the time and the space separated second column is the discharge (Figure 4.6). As a first step, a steady inflow hydrograph is an appropriate choice in order to test the mass conservation of the model. After a certain run time, depending on the size of the model domain, the outflow should counterbalance the inflow. There should be no uncontrolled mass loss within the model domain.

Usually the discharge is taken as the mean annual discharge or the beginning discharge of a flood event. In this case a steady discharge of 50 m^3/s is chosen in order to continue later on with a flood hydrograph which starts in this range.

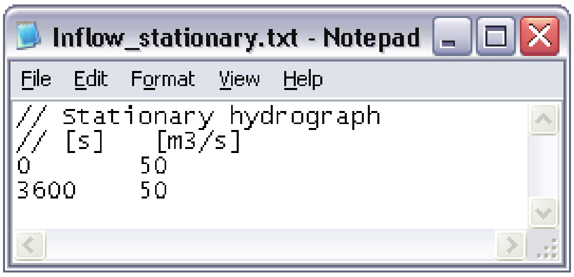


Figure 4.6 *Stationary hydrograph file saved as Inflow_stationary.txt.*

The outlet boundary condition is defined across the predefined string *Outflow*. The normal slope is used in order to calculate the normal flow depths and the normal flow velocities at the boundary and can be considered as a calibration parameter. A sensitivity analysis of this parameter should always be done. In any case the upper and lower model boundary should be far away enough from the river section of interest, in order to minimise the influence of the boundary conditions.

```
BOUNDARY
{
    type = hqrelation
    string_name = Outflow
    slope = 2.0         // [per mill]
}
```

4.1.3.5.2 Initial condition

The INITIAL-block defines the flow variables at the beginning of the simulation. In a very first step the simulation is started with a dry initial condition.

```
INITIAL
{
    type = dry
}
```

4.1.3.5.3 Friction

The FRICTION-block defines everything related to the friction term in the shallow water equations. Within the computational mesh, a material index is assigned to all elements. By the use of this material index (see Figure 4.3) a friction factor can be assigned. The default friction is used whenever there is no friction assigned to an element.

```
FRICTION
{
    type = strickler
    default_friction = 30
    input_type = index_table
    index = ( 1 2 3 4 5 6 7 8 9 10 11 12 )
    friction = ( 28 30 35 30 30 30 32 32 35 28 28 28 )
    wall_friction = off
}
```

4.1.3.5.4 Computational parameters

The PARAMETER-block defines the control parameters for the numerical simulation of the hydraulic part. The numerical simulation is performed using explicit time integration and the exact Riemann solver for flux computation. The elements with a water depth below the minimum water depth will be considered as dry elements due to stability reasons.

```
PARAMETER
{
    simulation_scheme = exp
    riemann_solver = exact
    minimum_water_depth = 0.05
}
```

4.1.3.5.5 Define the timestep

The simulation is performed with a total runtime of 3000 seconds. Later on, it has to be tested that after this runtime the flow in the model domain has reached a steady state, meaning that the outflow counterbalances the inflow (see Section 4.1.3.7).

```
TIMESTEP
{
    start_time = 0.0
    total_run_time = 3000
    CFL = 0.95
    minimum_time_step = 0.0001
}
```

4.1.3.5.6 Define the output

In the OUTPUT-block, the desired output has to be defined. During the simulation, output can also be visualized with BASEviz. In order to visualize the 2D results with QGIS, chose the output format 'sms'. For ParaView visualization chose type 'vtk'.

```
OUTPUT
{
    console_time_step = 100
    SPECIAL_OUTPUT
    {
        type = BASEviz
        output_time_step = 10
    }
    SPECIAL_OUTPUT
    {
        format = sms
        type = node_centered
        values = ( depth velocity wse )
        output_time_step = 500
    }
```

```
    SPECIAL_OUTPUT
    {
        format = vtk
        type = node_centered
        values = ( depth velocity wse )
        output_time_step = 500
    }
    SPECIAL_OUTPUT
    {
        type = balance
        balance_values = ( timestep )
        output_time_step = 100
    }
    SPECIAL_OUTPUT
    {
        type = boundary_history
        boundary_values = ( Q )
        history_one_file = yes
        output_time_step = 100
    }
}
```

4.1.3.6 Write the setup file

Once all the inputs have been set in the in the *model.json* file, a setup file must be written. Click *write* in the bottom right corner of the GUI. This will combine the model file with the computational mesh and external data, and store it in a binary file named *setup.h5*.

4.1.3.7 Perform hydraulic simulations

4.1.3.7.1 Setting up the simulation file

To set up the simulation file, switch to the *simulation* tab on the left. Select whether the simulation should be run on a single core (select *Single-threaded on CPU*) or on multiple cores (selected *Multi-threaded on CPU*). If multiple cores are selected, you must enter the *number of CPU cores*. This selection should depend on the number of threads your computer has available.

4.1.3.7.2 Perform steady flow simulation

Run the simulation with the *Run* button of the BASEMENT window. If the SPECIAL_OUTPUT of the type *BASEviz* is chosen press the keyboard button p to start the simulation. Be aware that the configuration files, computational mesh, and all other input files have to be in the same folder. The output files are stored in this same folder. In order to check the mass conservation of the model, the files *Flaz_bnd_Inflow_th.dat* and *Flaz_bnd_Outflow_th.dat* are used. After approximately 1600 seconds the outflow counterbalances the steady inflow (Figure 4.7).

In the file *Flaz_balance.dat* the run time of the simulation, the computational time steps and the element which is limiting the computational time step are stored. The identification

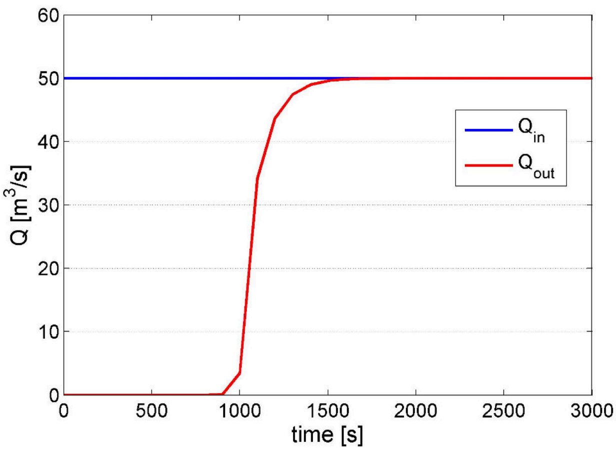


Figure 4.7 *Steady inflow hydrograph and outflow hydrograph.*

of the limiting element allows for improvement of the mesh. In order to identify the element location, load the computational mesh into QGIS.

The solution files with the ending *.sol* can be imported into the program QGIS (see Section 2.1) and the water depth and flow velocities can be visualized as shown in Figure 4.8. At the end of the simulation the flow variables of the last time step (t = 3000 s) are stored in the *Flaz_restart.h5* binary file. This file can be used later on to continue the simulation or to use it as an initial condition for a new simulation.

4.1.3.7.3 Perform unsteady flow simulation

The unsteady flow simulation is based on the flood event of July 2004 (Figure 4.10). Compared to the steady flow simulation the command file needs some minor changes. First, the last time step of the steady simulation is taken as initial condition for the unsteady simulation. Therefore the file *Flaz_restart.h5* from the steady simulation can be renamed and saved for example as *Initial_Condition.h5*. This file now can be used as an initial condition for the unsteady flow simulation. Therefore we have to consider two things:

1. Choose the solution time to be used as initial condition (note: restart file may contain several solution times).
2. Define the start time for the new simulation.

In this case we set the tag *restart_solution_time* equal to the solution of the last time step of the stationary simulation (*restart_solution_time* = 3000.027 sec). In order to start the simulation from time = 0 again, we have to set the *start_time* in the TIMESTEP block to zero. Be aware that if the *start_time* flag is not defined the *restart_solution_time* defined in the INITIAL block is used (in this case 3000.027 sec).

```
INITIAL
{
    type = continue
    file = Initial_Condition.h5
    restart_solution_time = 3000.022
```

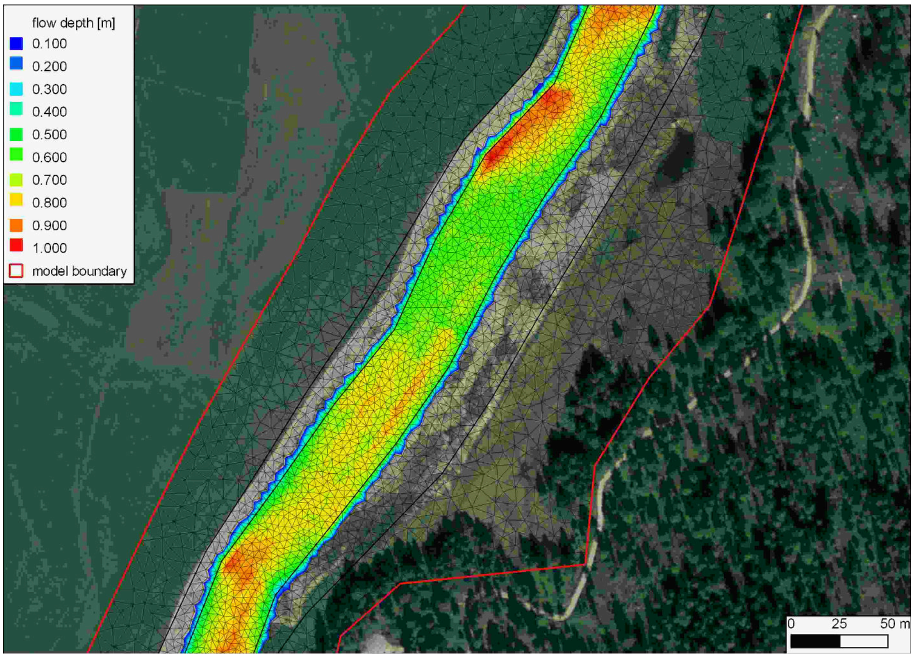


Figure 4.8 *Flow depth at the steady state of the model.*

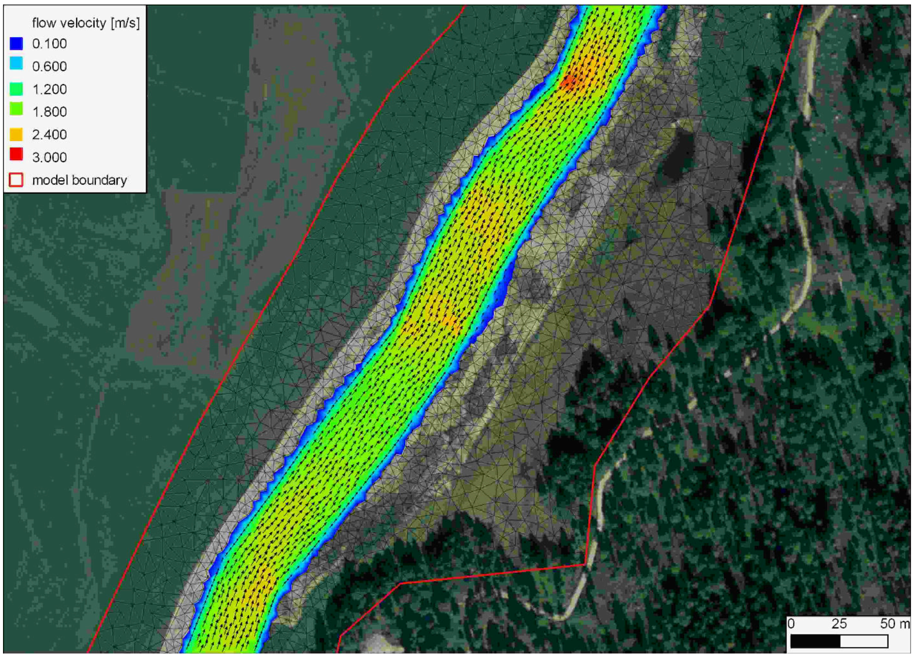


Figure 4.9 *Flow velocity and velocity vectors at the steady state of the model.*

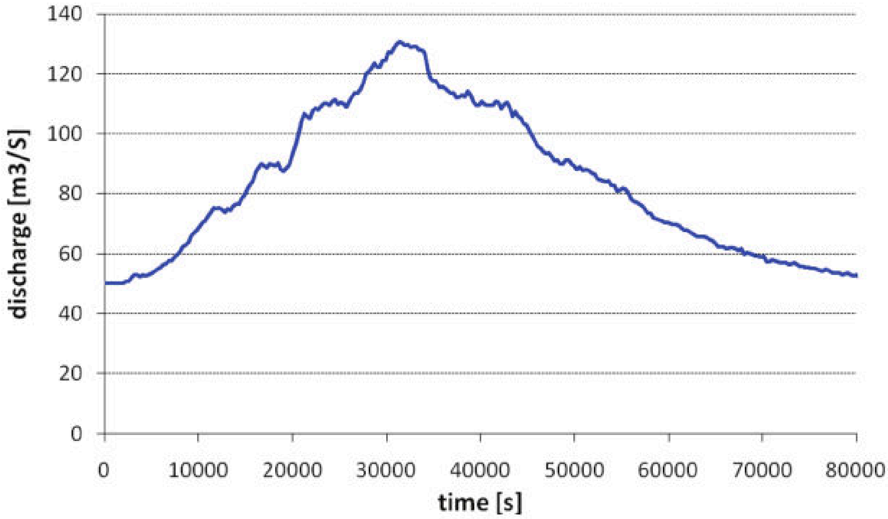


Figure 4.10 *Hydrograph of the flood event of July 2004.*

```
}

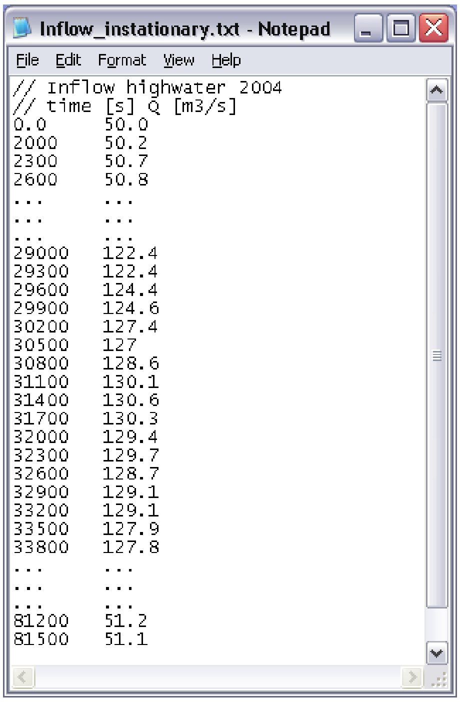
TIMESTEP
{
    start_time = 0.0
    total_run_time = 3000
    CFL = 0.95
    minimum_time_step = 0.0001
}
```

Furthermore the inflow hydrograph of the flood has to be defined and assigned to the upper boundary condition. The hydrograph of the flood shown in Figure 4.10 is saved in the text file *Inflow_transient.txt* with contents as depicted in Figure 4.11. Be aware that the final time defined in this file has to be the same or larger than the computation time. The upper BOUNDARY-block changes to:

```
BOUNDARY
{
    type = hydrograph
    string_name = Inflow
    file = Inflow_transient.txt
    slope = 10.0    // [per mill]
}
```

In the TIMESTEP-block the total run time of the simulation is increased to 84'000 seconds in order to capture the whole flood event:

```
TIMESTEP
{
...
    total_run_time = 84000
```



Inflow_instationary.txt - Notepad

File Edit Format View Help

```
// Inflow highwater 2004
// time [s] Q [m3/s]
0.0     50.0
2000    50.2
2300    50.7
2600    50.8
...     ...
...     ...
...     ...
29000   122.4
29300   122.4
29600   124.4
29900   124.6
30200   127.4
30500   127
30800   128.6
31100   130.1
31400   130.6
31700   130.3
32000   129.4
32300   129.7
32600   128.7
32900   129.1
33200   129.1
33500   127.9
33800   127.8
...     ...
...     ...
...     ...
81200   51.2
81500   51.1
```

Figure 4.11 *Inflow hydrograph stored in the file Inflow_transient.txt. Note that the points (...) are just illustrative in order to show the first and last line of the file.*

```
...
}
```

Last but not least, the OUPUT-block has to be adjusted to the needs of the simulation. For the unsteady simulation, the output time step for the SPECIAL_OUTPUT format sms might be reduced in order to capture the maximum values of the output variables .

```
OUTPUT
{
    output_time_step = 2000
    console_time_step = 500
    SPECIAL_OUTPUT
    {
        format = sms
        type = node_centered
        values = ( depth velocity wse)
        output_time_step = 500
    }
    SPECIAL_OUTPUT
    {
        type = balance
        balance_values = ( timestep )
        output_time_step = 1000
    }
    SPECIAL_OUTPUT
    {
```

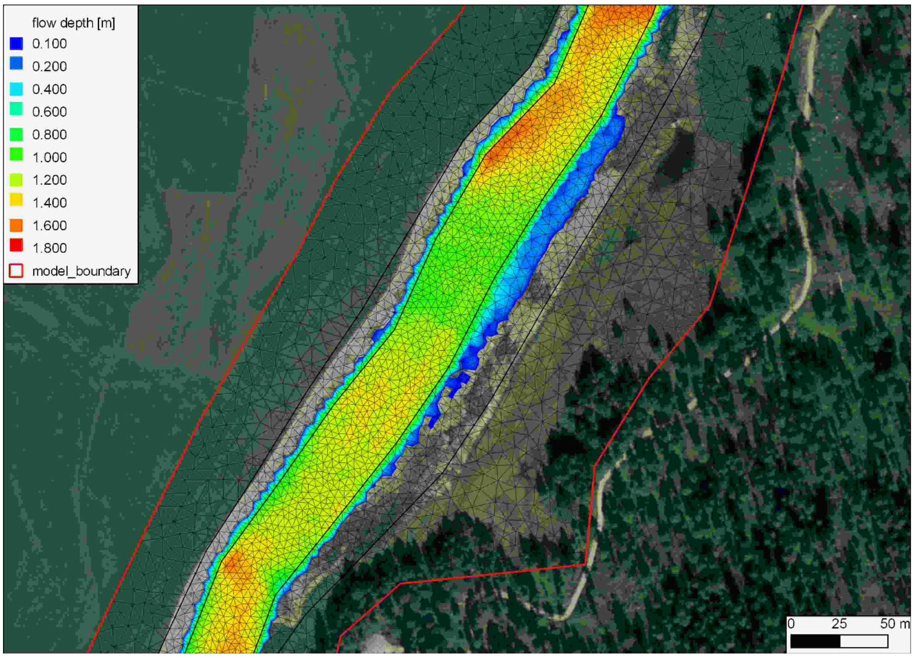


Figure 4.12 *Maximal flow depth of the unsteady flow simulation oberserved at the flood peak after a run time of about 9 hours.*

```
        type = boundary_history
        boundary_values = ( Q )
        history_one_file = yes
        output_time_step = 400
    }
}
```

Open the model file from the BASEMENT GUI (File → Open Scenario Directory → select the folder that contains the configuration files). Run the simulation with the *Run* button of the BASEMENT window. The maxima values of the flow depths and flow velocity vectors can be visualized using QGIS as shown in Figure 4.12 and Figure 4.13.

4.1.3.7.4 Calibration of the hydraulic model

The hydraulic model can be calibrated for example based on flood level marks by comparing the modelled water surface elevations with the flood level marks. Usually the calibration parameter is the bed roughness introduced with the Strickler value. The calibration procedure may need several adjustments and is an iterative process. The demonstration of the calibration is not part of this tutorial. It should be mentioned that it is important to have a calibrated hydraulic model either for further hydraulic modelling or for morphological modelling in a further step.

4.1.4 Morphological simulation with single-grain bed load transport

The MORPHOLOGY-block is not compulsory. If this block is not defined the simulation is purely hydraulic. The command file of the unsteady hydraulic simulation has to be completed for the single-grain bed load transport as shown in this section.

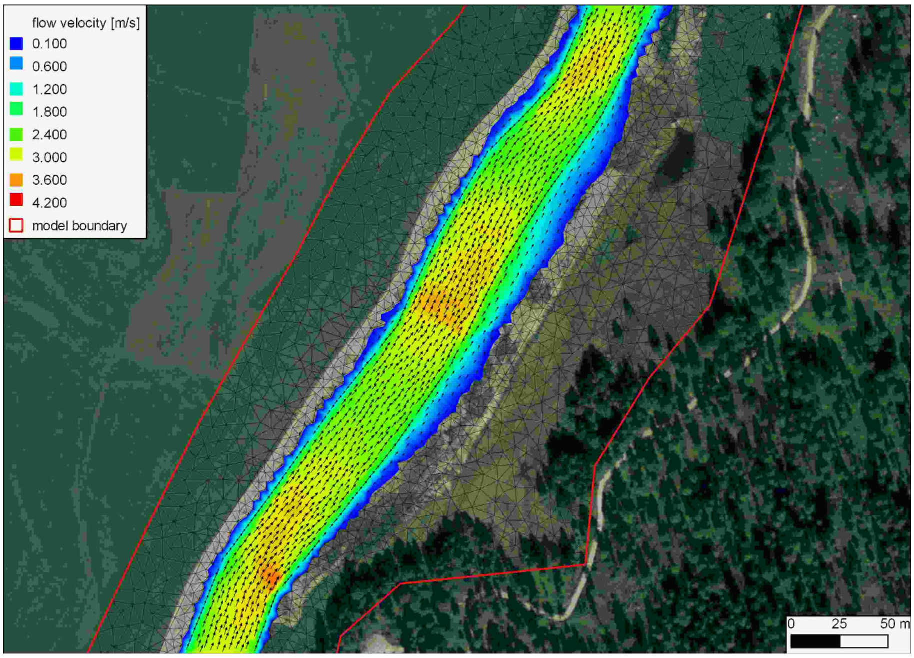


Figure 4.13 *Maximal flow velocity and velocity vectors of the unsteady flow simulation oberserved at the flood peak after a run time of about 9 hours.*

The morphological simulation is based on the flood event in July 2004. Therefore a single-grain bed load transport is added to the unsteady hydraulic simulation in Section 4.1.3.7.3. In the HYDRAULIC-block a small change has to be done in order to define the boundary string *Inflow_sed* for the bed load inflow. Thus a new STRINGDEF-block is added within the GEOMETRY-block as follows:

```
GEOMETRY
{
    ...
    STRINGDEF
    {
        name = Inflow_sed
        node_ids = (3 194 192 210 4)
        upstream_direction = left
    }
    ...
}
```

4.1.4.1 Define the morphological information

The necessary information for the morphological part of the simulation is defined in the *MORPHOLOGY*-block.

```
MORPHOLOGY
{
    PARAMETER
    {...}
```

```
    INITIAL
    {...}
    BEDMATERIAL
    {...}
    BEDLOAD
    {...}
    GRAVITATIONAL_TRANSPORT
    {...}
}
```

4.1.4.1.1 Morphological parameters

In the PARAMETER-block important parameters for the morphological simulation are defined. The bed load control volume is chosen to be constant with a thickness of 0.1 m.

```
PARAMETER
{
    porosity =  40                    // [%]
    density = 2650                    // [kg/m3]
    control_volume_type = constant
    control_volume_thickness = 0.1  // [m]
}
```

4.1.4.1.2 Initial conditions

The initial bed elevation is defined in most cases as the actual topography.

4.1.4.1.3 Bed material

In the BEDMATERIAL-block the grain classes, the composition, the thickness of the soil layers, the level of the fixed bed and the assignment of the soil to the mesh is defined in several sub-blocks.

```
BEDMATERIAL
{
    GRAIN_CLASS
    {...}
    MIXTURE
    {...}
    SOIL_DEF
    {...}
    FIXED_BED
    {...}
    SOIL_ASSIGNMENT
    {...}
}
```

4.1.4.1.3.1 Grain size distribution

The single-grain simulation is performed with only one grain class of a given diameter, e.g. the mean grain diameter.

```
GRAIN_CLASS
{
    diameters = ( 50 )  // [mm]
}
```

4.1.4.1.3.2 Grain mixture

Since we have only one grain size, the volume fraction is equal to 100%.

```
MIXTURE
{
    name = single_grain
    volume_fraction = ( 100 )   // [%]
}
```

4.1.4.1.3.3 Define the soil composition

The soil layers and the according sediment mixture are defined in the SOIL_DEF-block. For a single-grain simulation it is not important how many layers are defined. The negative bottom elevation defines the thickness of the layer. Below the last layer a fixed bed is assumed. If no LAYER-block is defined, then automatically a fixed bed on the surface is assumed. We use this especially for the river bed near the upper boundary condition to avoid uncontrolled erosion. Furthermore the embankments are kept fixed because the main focus is on the river bed morphology. The two soils *soil_fix_20* and *soil_fix_40* are defined to have a gradual transition from the fixed bed to the movable bed. Anyway, the river section with the roughness elements cannot be modelled accurately, because single roughness elements which are more or less fixed stones cannot be discretized within the computational mesh. They have to be modelled with an increased bed roughness instead.

```
SOIL_DEF
{
    name = soil_element_roughness
    LAYER
    {
    bottom_elevation = -0.8     // fixed bed 0.8 m below the surface
    mixture = single_grain
    }
}
SOIL_DEF
{
    name = soil_widening
    LAYER
    {
    bottom_elevation = -2.0     // fixed bed 2.0 m below the surface
```

```
    mixture = single_grain
    }
}

SOIL_DEF
{
    name = soil_alt_bars
    LAYER
    {
    bottom_elevation = -2.0     // fixed bed 2.0 m below the surface
    mixture = single_grain
    }
}
SOIL_DEF
{
    name = soil_fix_20
    LAYER
    {
    bottom_elevation = -0.2     // fixed bed 0.2 m below the surface
    mixture = single_grain
    }
}
SOIL_DEF
{
    name = soil_fix_40
    LAYER
    {
    bottom_elevation = -0.4     // fixed bed 0.4 m below the surface
    mixture = single_grain
    }
}
SOIL_DEF
{
    name = soil_fix             // fixed bed
}
```

4.1.4.1.3.4 Fixed bed elevation

There are several possibilities to define a fixed bed. In the FIXED_BED-block, the elevations of areas with fixed bed can be defined either with a separate mesh file containing the fixed bed elevations or with specific fixed bed elevations for some selected nodes. Furthermore a fixed bed can be implemented in the SOIL_DEF-block (Section 4.1.4.1.3.3). If there is no layer defined, a fixed bed will be assumed. In any case, a fixed bed is assumed below the last layer. In this tutorial the FIXED_BED-block is used as an example to define a fixed bed for a single node. This can be used to consider a big stone for example. A fixed node (node id 8956) is implemented by giving *zb_fix* a value smaller or equal to -100.

```
FIXED_BED
```

```
{
    type = nodes
    node_ids = ( 5486 )
    zb_fix = ( -100 )
}
```

4.1.4.1.4 Assignment of the defined soil types

The soil types defined in the SOIL_DEF-blocks (Section 4.1.4.1.3.3) are assigned to the elements of the mesh by the material index.

```
SOIL_ASSIGNMENT
{
    type = index_table
    index = ( 1  2  3  4  5  6  7  8  9  10  11  12 )
    soil = ( soil_element_roughness soil_fix soil_fix soil_widening
    soil_fix soil_widening soil_alt_bars soil_fix soil_fix soil_fix
    soil_fix_20 soil_fix_40 )
}
```

4.1.4.2 Bedload

In the BEDLOAD-block all needed data for bedload transport as well as boundary conditions are defined in several sub-blocks.

```
BEDLOAD
{
    PARAMETER
    {...}
    FORMULA
    {...}
    BOUNDARY
    {...}
    DIRECTION
    {...}
}
```

4.1.4.2.1 Bed load parameter

The control parameters for the bed load simulation are defined in the PARAMETER-block. Since the *limit_bedload_wetted* tag is turned off, the bed load is computed not only in completely wetted cells but in partially wetted cells as well. Averaging the bedload fluxes over the sediment cells is turned off. This option is computational less expensive and less diffusive.

```
PARAMETER
{
    limit_bedload_wetted = off
    use_cell_averaged_bedload_flux = off
}
```

4.1.4.2.2 Bed load formula

The bed load transport is computed with the Meyer-Peter and Mueller's (mpm) formula.

```
FORMULA
{
    bedload_formula = mpm
    bedload_factor = 0.4
    theta_critic_index = ( 1 2 3 4 5 6 7 8 9 10 11 12 )
    theta_critic = ( 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04
    0.04 0.04)
}
```

4.1.4.2.3 Bed load boundary condition

The bed load input is handled with a boundary condition which determines the transport capacity at the inflow cross section. The *IODown* is the only downstream boundary condition available for sediment transport at the moment. All sediment entering the last computational cell will leave the cell over the downstream boundary.

```
BOUNDARY
{
    type = transport_capacity
    string_name = Inflow_sed
    mixture = single_grain
    factor = 0.7
}
```

```
BOUNDARY
{
    type = IODown
    string_name = Outflow
}
```

4.1.4.2.4 Bedload direction

This block contains general settings dealing with the adaption of the bedload transport direction. The lateral transport caused by a *lateral_bed_slope* with respect to the main flow direction is taken into account. The *lateral_index* defines the regions of the computational mesh, where lateral transport should be considered.

```
DIRECTION
{
    lateral_transport_type = lateral_bed_slope
    lateral_transport_factor = 1.5
    lateral_index = ( 1 2 3 4 5 6 7 8 9 10 11 12 )
}
```

4.1.4.3 Gravitational transport

In the GRAVITATIONAL_TRANSPORT-block the parameters for gravitation induced transport are defined. The gravitational transport can be limited to elements which are fully wetted or can be considered for all elements. Over the material index the scope and the applied angles for the gravitational transport can be defined. Note that for soils with a fixed bed the gravitational transport is not active. In this model gravitational transport is applied only for the mesh elements with index 6. This enables river bed widening due to bank collaps on parts of the right embankment of the widening zone.

```
GRAVITATIONAL_TRANSPORT
{
    index = (6)
    angle_failure_dry = (30)
    angle_failure_wetted = (15)
    angle_failure_deposited = (10)
    gravity_transport_on_cells = partially wetted
    angle_wetted_criterion = partially_wetted
}
```

4.1.4.4 Define the output

The desired output of the simulation has to be defined explicitly in the OUTPUT-block. The *output_time_step* defines the time steps of the results. The *console_time_step* defines the time step to appear in the BASEMENT window during simulation. Specific output modes have to be defined in the repeatable SPECIAL_OUTPUT-blocks. Inside this block the *output_time_step* defines the output time step for this particular output. A detailed overview of all possible output types, values, format types and more can be found in the Input block structure.

```
OUTPUT
{
    console_time_step = 1000
    SPECIAL_OUTPUT
    {
        type = BASEviz
        output_time_step = 5
    }
    SPECIAL_OUTPUT
    {
        format = sms
        type = node_centered
        values = ( depth wse velocity deltaz z_node )
        output_time_step = 1000
    }
    SPECIAL_OUTPUT
    {
        type = balance
        balance_values = (sediment timestep)
```

```
        output_time_step = 1000
    }
    SPECIAL_OUTPUT
    {
        type = element_history
        element_ids = (3517 10729)
        output_time_step = 1000
        element_values   = (depth velocity z_element)
    }
    SPECIAL_OUTPUT
    {
        type = boundary_history
        boundary_values = ( Q Qsed )
        history_one_file = yes
        output_time_step = 1000
    }
}
```

4.1.4.5 Perform morphological simulation with single-grain bed load transport

Open the *model.json* file via the menu of the BASEMENT GUI (File → Open Scenario Directory → select the folder that contains the configuration files). Run the simulation with the Run button of the BASEMENT window.

The output files with the ending *.sol* can be visualized using QGIS . The bed elevation after the flood event is shown in Figure 4.14. Two cross sections are defined and the bed elevation along these cross sections before and after the flood event is compared using the QGIS plugin *Profile tool* (Figure 4.15). The morphological changes *(deltaz)* due to the flood event are shown in Figure 4.16 .The position of the simulated depositions matches quite well with the position of the banks observed in the aerial image.

4.1.5 Morphological simulation with multi-grain bed load transport

In order to avoid duplication, only the modifications of the *model.json* file, compared to the single-grain simulation, are detailed here. A modification that is not considered here is the possibility to use the grain size distribution to determine the bed friction in the FRICTION-Block. To simplify this tutorial, the friction is defined with the Strickler value. Generally it is suggested to try both options and to choose the most suitable for your model purpose.

4.1.5.1 Morphological parameters

In the PARAMETER-block important parameters for the morphological simulation are defined. In multi-grain simulations the thickness of the bed load control volume is an important calibration parameter. This parameter influences significantly the grain sorting process.

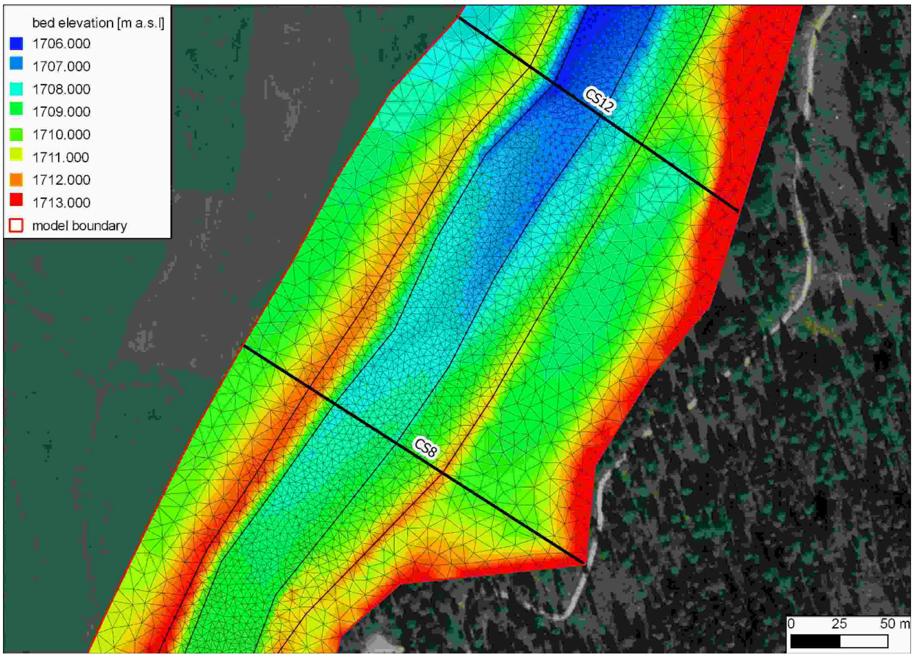


Figure 4.14 *Modeled bed elevation (z_bed) and two cross sections defined in the widening part.*

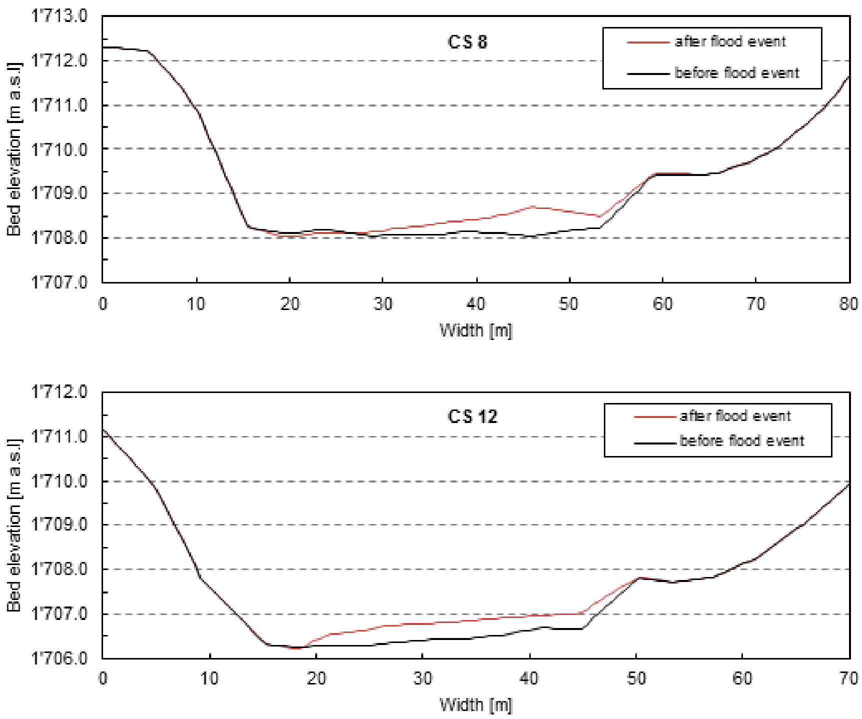


Figure 4.15 *Comparison of the river bed before and after the flood event in cross-section CS 8 and CS 12.*

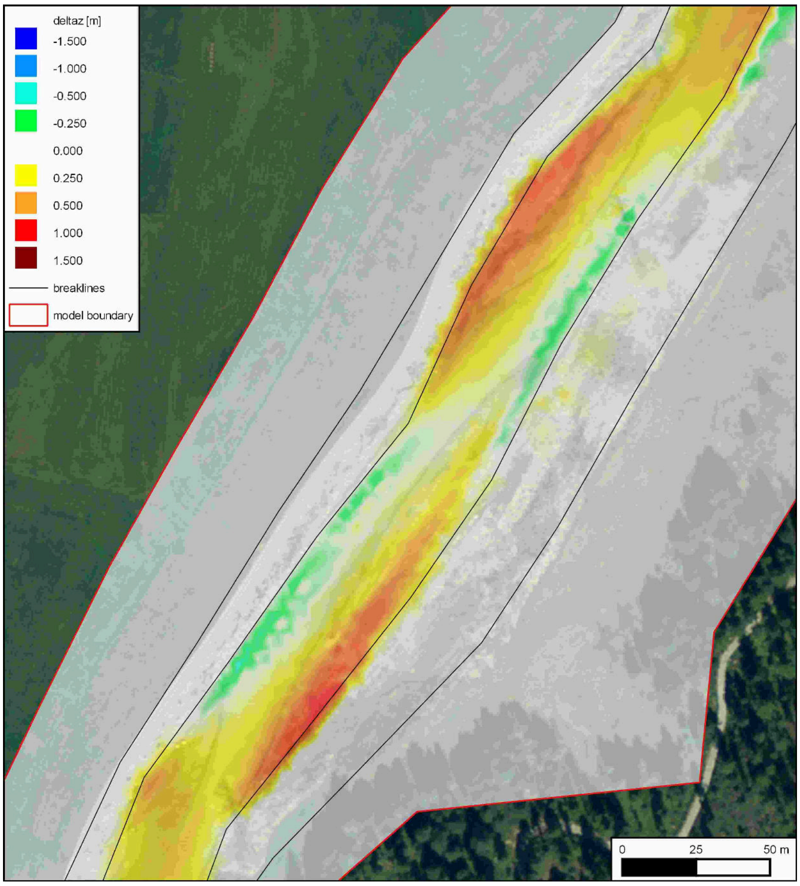


Figure 4.16 *Changes of the morphology (deltaz) due to the flood event with the single-grain model. The red colour range represents deposition and the green/blue colour range shows erosion.*

```
PARAMETER
{
    ...
    control_volume_type = constant
    control_volume_thickness = ( 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 )  // [m]
    control_volume_thickness_index = (1 2 3 4 5 6 7 8 9 10 11 12)
}
```

4.1.5.2 Grain size distribution

The grain size distribution is discretized with six grain classes. They have to be defined in ascending order from the smallest to the largest grain.

```
GRAIN_CLASS
{
    diameters = ( 1 5 15 44 82 150 )    // [mm]
}
```

4.1.5.3 Grain mixture

In the MIXTURE-block the volume fraction of the different mixtures are defined. The three river sections are considered with different sediment mixtures. Furthermore a mixture for the inflow is defined.

```
MIXTURE
{
    name = mixture_inflow
    volume_fraction = ( 15 15 23 27 10 10 )
}
MIXTURE
{
    name = mixture_element_roughness
    volume_fraction = ( 17 11 14 27 14 17 )
}
MIXTURE
{
    name = mixture_widening
    volume_fraction = ( 21 13 16 25 11 14 )
}
MIXTURE
{
    name = mixture_alt_bars
    volume_fraction = ( 27 14 14 20 14 11 )
}
```

4.1.5.4 Define the soil composition

The soil layers with the corresponding sediment mixture are defined in the SOIL_DEF-block. The soil can be defined with several layers of different material, but to keep it simple we assume a single layer. The negative bottom elevation defines the thickness of the layer. Below the last layer a fixed bed is assumed. If no LAYER-block is defined then automatically a fixed bed on the surface is assumed. We use this especially for the river bed near the upper boundary condition to avoid uncontrolled erosion. Furthermore the embankments are kept fix because the main focus is on set on the river bed morphology. The two soils *soil_fix_20* and *soil_fix_40* are defined to have a gradual transition from the fixed bed to the movable bed.

```
SOIL_DEF
{
    name = soil_element_roughness
    LAYER
    {
    bottom_elevation = -0.8     // fixed bed 0.8 m below the surface
    mixture = mixture_element_roughness
    }
}
SOIL_DEF
{
    name = soil_widening
    LAYER
    {
    bottom_elevation = -2.0     // fixed bed 2.0 m below the surface
    mixture = mixture_widening
    }
}
SOIL_DEF
{
    name = soil_alt_bars
    LAYER
    {
    bottom_elevation = -2.0     // fixed bed 2.0 m below the surface
    mixture = mixture_alt_bars
    }
}
SOIL_DEF
{
    name = soil_fix     // fixed bed
}
SOIL_DEF
{
    name = soil_fix_20
    LAYER
    {
    bottom_elevation = -0.2     // fixed bed 0.2 m below the surface
```

```
    mixture = mixture_element_roughness
    }
}


SOIL_DEF
{
    name = soil_fix_40
    LAYER
    {
    bottom_elevation = -0.4     // fixed bed 0.4 m below the surface
    mixture = mixture_element_roughness
    }
}
```

4.1.5.5 Bed load boundary condition

The bed load input is regulated with a boundary condition which determines the transport capacity at the cross section defined. The factor for the bed load at the boundary is an important calibration parameter and depends on the transport formula. Therefore this factor is different for single-grain and multi-grain simulations. The outflow boundary is handled as in the single-grain simulation.

```
BOUNDARY
{
    type = transport_capacity
    string_name = Inflow_sed
    mixture = mixture_inflow
    factor = 0.7
}
BOUNDARY
{
    type = IODown
    string_name = Outflow
}
```

4.1.5.6 Bed load formula

For the sediment transport computation different bed load transport formulas are available. In this tutorial the formula of Meyer-Peter and Mueller for multiple grain classes is chosen. It is suggested to try different sediment transport formulas.

```
FORMULA
{
    bedload_formula = mpm_multi
    bedload_factor = 0.5

}
```

4.1.5.7 Define the output

The desired output of the simulation has to be defined explicitly in the OUTPUT-block. The specific output is defined in the repeatable SPECIAL_OUTPUT-blocks. For the multi-grain simulation some additional output may be interesting such as for example the grain size distribution in selected nodes. This way grain sorting effects can be observed. A detailed overview of all possible output types, values, format types and more is given in help buttons in the Command File Editor of BASEMENT.

```
OUTPUT
{
    console_time_step = 1000
    SPECIAL_OUTPUT
    {
        format = sms
        type = node_centered
        values = ( depth deltaz z_node )
        output_time_step = 1000
    }
    SPECIAL_OUTPUT
    {
        type = node_history
        node_values = ( grain_size )
        node_ids = (1138 3235)
        history_one_file = yes
        output_time_step = 4000
    }
    SPECIAL_OUTPUT
    {
        type = boundary_history
        boundary_values = ( Q Qsed )
        history_one_file = yes
        output_time_step = 1000
    }
}
```

4.1.6 Perform morphological simulation with multi-grain bed load transport

Open the *model.json* file via the menu of the BASEMENT GUI (File → Open Scenario Directory → select the folder that contains the configuration files). Run the simulation with the Run button of the BASEMENT window.

The morphological changes *deltaz* are shown in Figure 4.17. Here the multi-grain model is not compared quantitatively with the single-grain model. Nevertheless the qualitative comparison is indicating a quite similar behaviour (Figure 4.16 and Figure 4.17). At this state much more details could be investigated such as the grain class fractions, the hiding-and-exposure function *(hiding_exponent)*, the amount of grain classes etc. Further important calibration parameters are the critical dimensional shear stress, the bed load factor and the bed load inflow controlled with the bed load factor at the boundary.

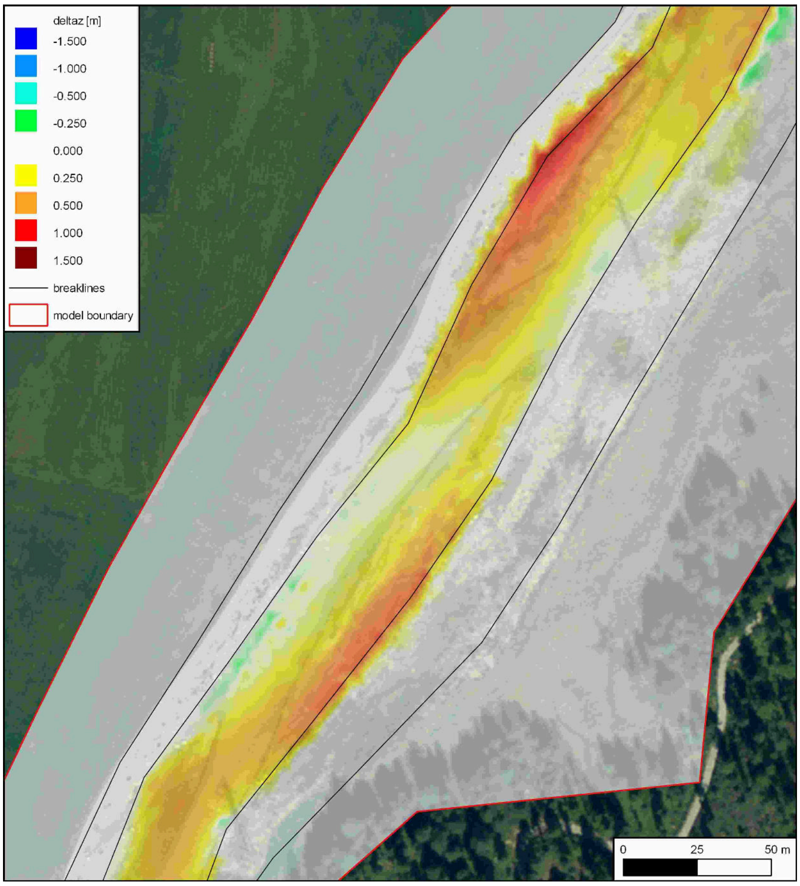


Figure 4.17 *Changes of the morphology (deltaz) due to the flood event with the multi-grain model. The red colour range represents deposition and the green/blue colour range shows erosion*

5

Hydrodynamics and sediment transport at the river Thur

5.1 Hydrodynamics and sediment transport at the river Thur (1D)

5.1.1 Introduction

This tutorial gives an introduction to the capabilities of the 1D modelling module BASEchain of BASEMENT. It provides a step-by-step guidance on how build up a model for BASEchain.

5.1.1.1 General description

This Tutorial describes the necessary steps for the simulation of hydrodynamics and bed load in a specific section of the river Thur. In the considered section a river widening has been realized during the last years. It's located in Altikon and illustrated in the figure below. The flow direction is from right to left. The bed modification over a year including an important flood will be simulated.

5.1.1.2 Used features

In this tutorial the following points will be treated:

- Preparation of the needed input files;
- Simulation of a steady flow to use for the following simulations;
- Use of composite cross sections;
- Simulation of bed load with formula of Meyer-Peter Müller;

Figure 5.1 *View of the simulated river section*

- Use of dry initial condition;
- Use of a file to define the initial conditions;
- Use of the following boundary conditions:
  - Inflow hydrograph
  - Inflow of sediment in/out
  - Outflow h-q relation
  - Outflow of sediment in/out
- Representation of the results.

5.1.1.3 Purpose

In the year 2005, intensive rainfall led to a large flood event. The aim of the simulations in this tutorial is to study, which influence this flood had on the channel geometry of the river Thur.

5.1.2 Setting up the topography file

5.1.2.1 Cross sections

The data of the topography are available in the form of cross section measurements, where each measured point is given by its x, y and z coordinates. This is an extract from the raw data:

x	y	z
698578.504	272450.223	376.841
698578.494	272446.999	374.991
698578.32	272444.286	373.748
698577.929	272441.889	373.229
698578.081	272439.244	372.207
698578.533	272437.229	371.544
698578.56	272434.366	370.869
698578.612	272431.522	370.766

x	y	z
698578.86	272429.064	370.401
698579.201	272426.526	370.388
698579.323	272424.56	370.617
698578.937	272422.91	370.341
698579.208	272421.645	370.436
...		

These data have to be separated into groups belonging to one cross section and then transformed in a way to have a z(y) relation, where the smallest y is the extreme point on the left river side.

Example:

y	z
0	376.264
1.455081097	376.327
4.349044033	377.804
5.134094857	378.133
6.803278107	378.238
8.241452785	378.227
9.123103693	377.965
10.23346129	377.395
11.41786604	376.664
12.57016281	376.221
14.53240603	376.21
16.34176138	376.215
17.09961488	375.99
18.74552432	375.296
...	

Additionally the distance from the upstream end of the channel (first cross section) has to be determined for each cross section.

The obtained geometry points can be introduced in the topography by copy pasting it directly into the node coordinates field in the grid file editor (Figure 5.2). The editor will translate the column wise data into the proper syntax. Another, more efficient way is to use the python scripts available on http://www.basement.ethz.ch to transform topography data in excel format into the BASEMENT format in a first step.

The minimum information we have to provide for each cross section besides the node coordinates are the cross section name and the distance coordinate measured from upstream to downstream in km.

5.1.2.2 Definition of different cross section zones

To reduce some drawbacks of the 1-D simulation, in the present case it is useful to define a main channel and flood plains, as well as the bed bottom which is limiting the bed load

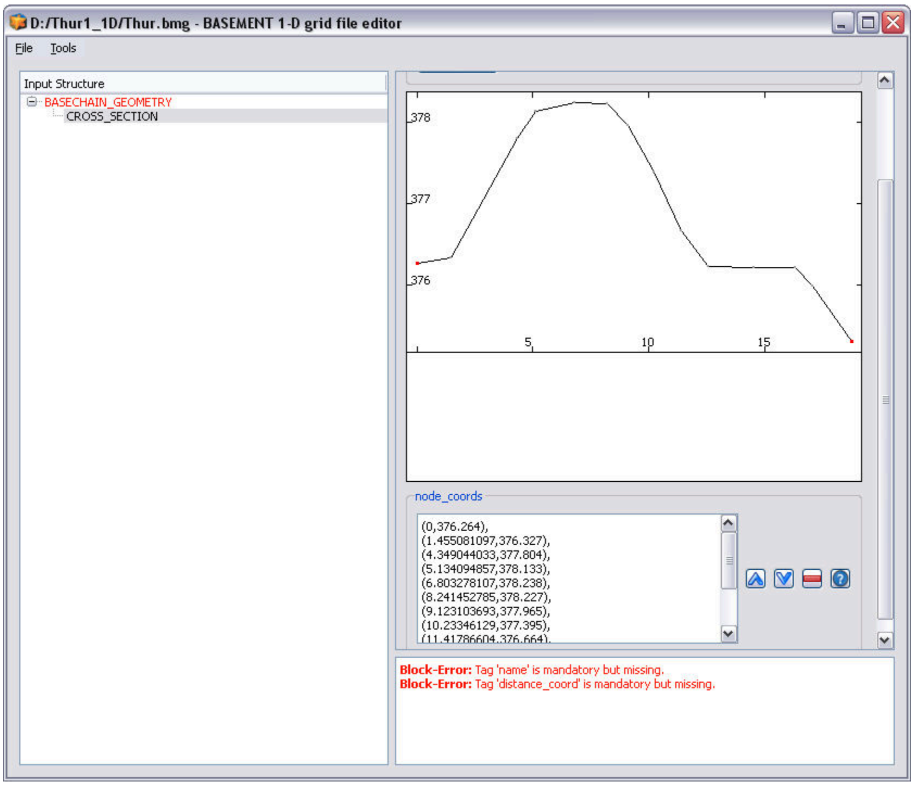


Figure 5.2 *Cross section points inserted in the topography editor*

transport.

In Figure 5.3 , the flood plains are given by the part of the cross section not defined as the main channel. The soils by their indexes. The keys 2 or 1 refer to the type of soil which is defined later in the command file. Here we use only one soil for the whole bottom, but it is also possible to add several soils of the same type or of different types as shown in Figure 5.3. Further, different friction values can be defined for different parts of the cross section. The active range should span from the left to the right dike. Points outside the active range are simply ignored (Figure 5.4).

The graphical view of the cross section data helps to identify the correct point and set the ranges to the correct lateral node coordinates. For convenience, one can switch into the text editor mode of the input file by choosing from the *Tools* Menu the option *Edit Raw*.

5.1.2.3 Friction values

For the friction determination the Strickler approach is used. This is declared in the command file by setting the *type* in the FRICTION block within the HYDRAULICS section to *strickler*. In this case, Strickler k-values have to be defined for the different regions. The banks of the main channel are partially covered with small bushes. The flood plains are covered with grass, stones and sand, but there are also zones with trees.

The following k_{Str} values are used:

- Banks of main channel: $k_{Str} = 35$ $[m^{1/3}/s]$
- Flood plains: $k_{Str} = 33$ $[m^{1/3}/s]$.

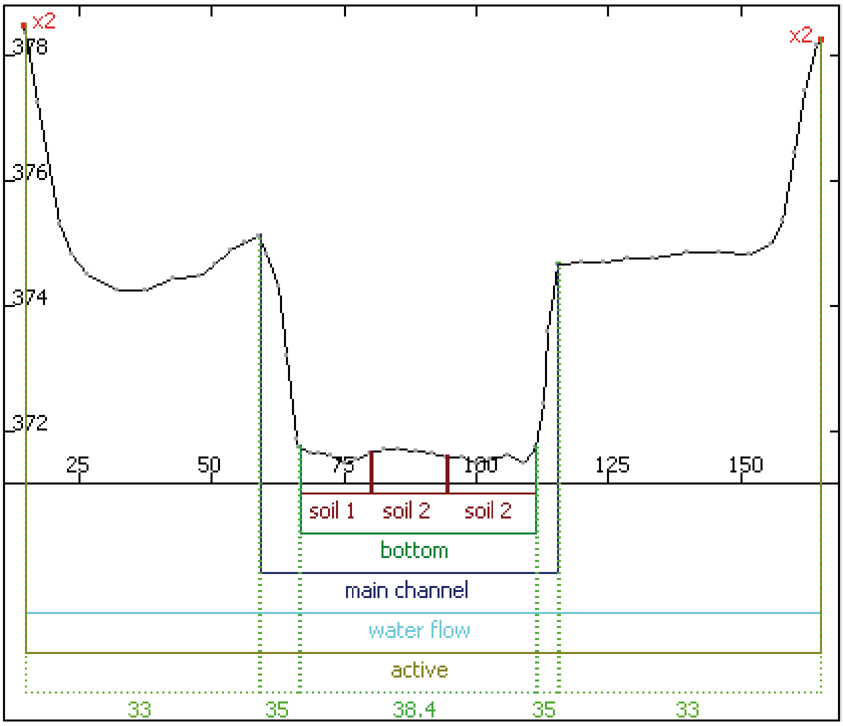


Figure 5.3 *Delimitation of cross section zones*

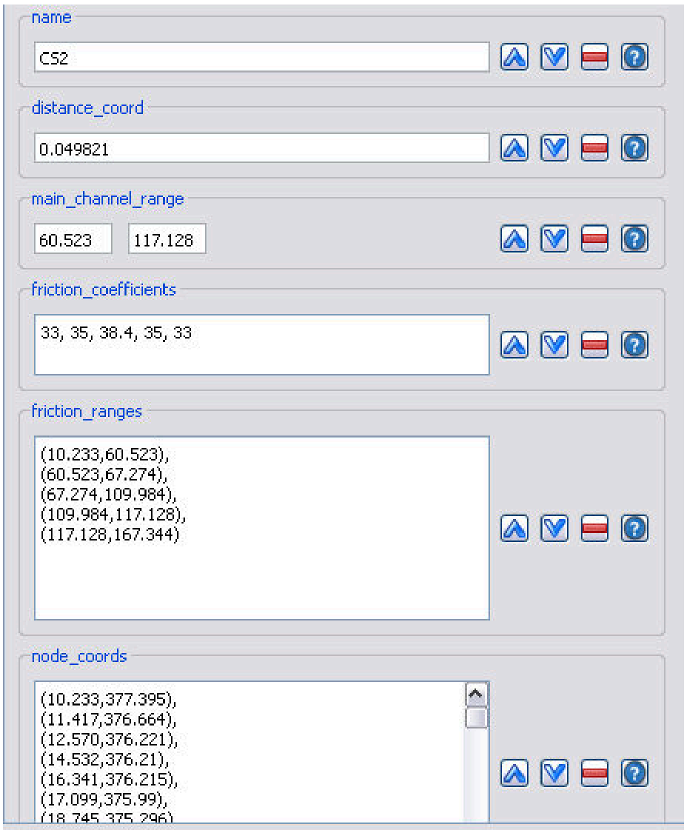


Figure 5.4 *Definition of cross section properties*

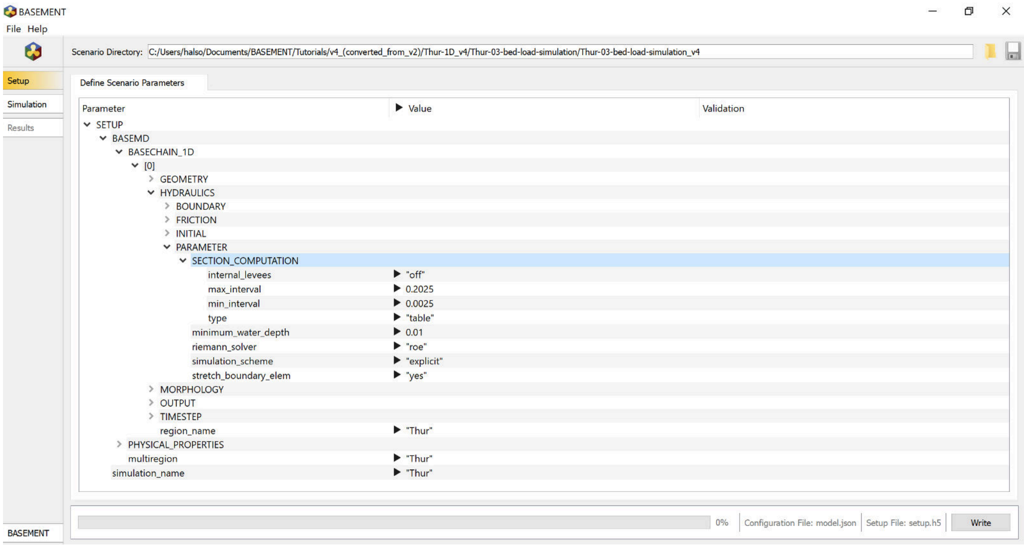


Figure 5.5 *Definition of table values*

For the bed bottom the following transformation, based on the grain characteristics of the sediment is used (d_{90} = 5 cm):

Bottom: $k_{Str} = \frac{23}{\sqrt[6]{d_{90}}} = 38$ [m$^{1/3}$/s].

In BASEMENT internally, the cross section is represented by slices, defined by the segment between two nodes. Each slice has its own properties. Therefore we have to provide so called ranges to assign the friction values to the respective slices. The ranges can be defined either referring to node coordinates (note that you have to match the coordinates exactly) or by referring to slice indexes, starting at index 1 from left to right.

5.1.2.4 Computation of water surface elevation

As it is much quicker, the use of tables for the computation of the water surface elevation and other hydraulic variables is chosen for this example. In the case of tables, all properties are pre-computed for a given set of points and only updated in case of a non-negligible change of the soil. This is accomplished using the block SECTION_COMPUTATION in PARAMETER. As all variables are calculated for several water surface elevations, the maximum and minimum intervals between the different levels have to be set accordingly. The default spacing is given by max_interval – min_interval. Whenever the bed changes, the table is updated accordingly.

5.1.2.5 Characterization of the sediments

Two types of ground will be defined:

1. the ground is not erodible;
2. the ground is composed by sediments with a mean diameter of 2.5 cm.

In the topography file the codes of the different types are assigned to different cross sections. A code can be set in the cross sections by creating a new sub block SOIL_DEF, where the

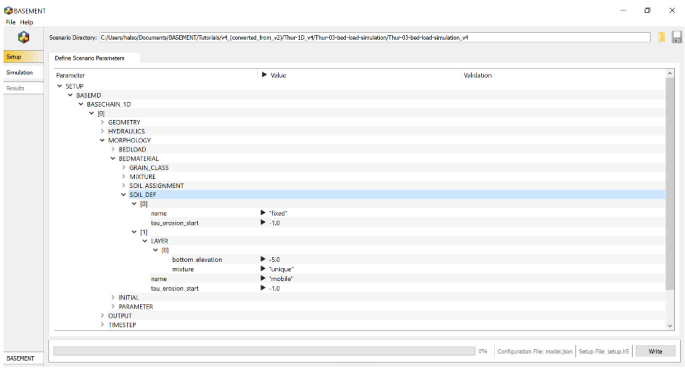


Figure 5.6 *Declaration of soil types*

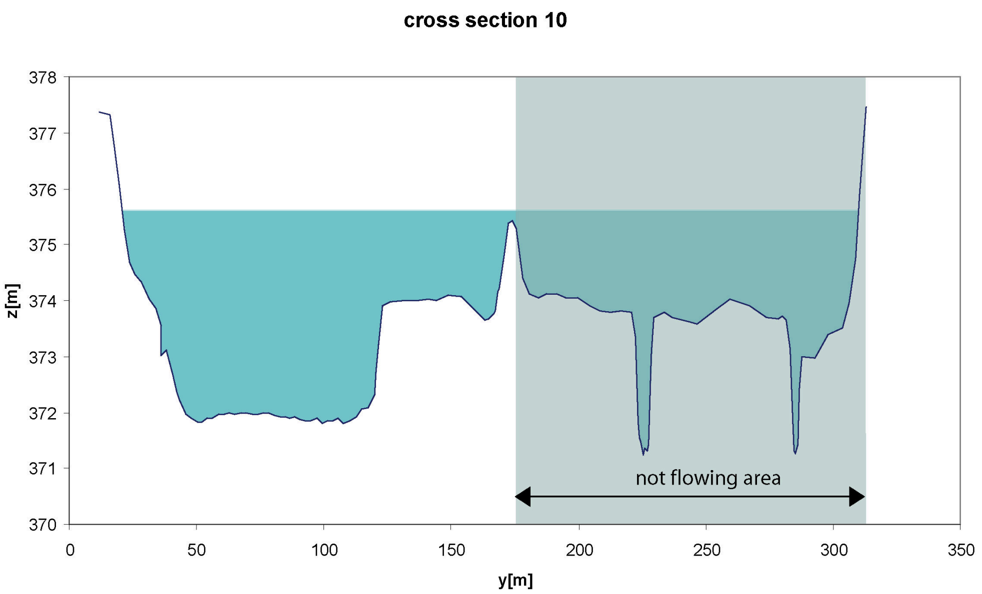


Figure 5.7 *Definition of non flowing areas*

index is assigned to the respective soil index in the command file and the span of the soil is defined via the range it extends.

5.1.2.6 Define flowing zones

The 1-D model considers the flow velocity to be the same over the whole width of the cross section: This is obviously not true, especially for cross sections where important zones are behind a sort of dike, like it occurs very often at the Thur. This effect has an important influence on the bed load transport. For this reason, regions where the water does not flow are declared using the water_flow_range tag. The next figure shows an example of a cross section with the different zones. Of course, we only mention this here. The tutorial topology already contains the required ranges.

5.1.3 Setting up the model file

5.1.3.1 Setup

The first configuration file is called “model.json”. Open the model file from the BASEMENT GUI (File → Open Scenario Directory → select the folder that contains the configuration files).

The first step is to define a project by its name:

```
SETUP
{
    "simulation_name": "Thur"
}
```

5.1.3.2 Domain

A domain is defined by including all relevant parameters for this computation. The first parameter is the name of the computation region.

```
BASEMD
{
    multiregion = Thur
    [...]
}
```

5.1.3.3 Define the physical properties

The Physical properties normally do not change from one project to another.

```
PHYSICAL_PROPERTIES
{
    gravity = 9.81
    viscosity = 0.000001004
    rho_fluid = 1000
}
```

5.1.3.4 One dimensional simulation

The next step is to declare a *BASECHAIN_1D* block. This will make the program execute a 1-D simulation. The name of the computational region is given here.

```
BASECHAIN_1D
{
    region_name = Thur
}
```

5.1.3.4.1 Define the geometry

The next block defines in which file the topography is stored and the type of geometry file used. The cross section names are listed from upstream to downstream.

```
GEOMETRY
{
    type = basement
    file = ThurTopo.bmg
    cross_section_order = ( CS1 CS2 CS3...CS54 CS55 )
}
```

5.1.3.4.2 Define hydraulic information

All information concerning the hydraulic simulation is declared in the block *HYDRAULICS*.

```
HYDRAULICS
{
    [...]
}
```

5.1.3.4.2.1 Define the upper boundary condition

The upper boundary condition is defined by a hydrograph, which is stored in a separate file. Indications are given about the precision required between the discharge corresponding to the iteratively determined area and the given discharge, as well as the maximum number of iterations allowed to reach this precision. The slope of the first cross section must be given in per mil (the last 3 values are used only in case of supercritical flow).

Create a hydrograph file named ThurSteadyHydrograph.txt:

```
// T     Q
0       30
100000  30
```

Then, add the upper boundary block:

```
BOUNDARY
{
    type = hydrograph
    string = upstream
    file = ThurSteadyHydrograph.txt
    precision = 0.001
    number_of_iterations =100
    slope = 0.93
}
```

5.1.3.4.2.2 Define the lower boundary condition

The lower boundary is an h-q-relation which is calculated internally. Again, we have to define the boundary condition with a specific slope.

```
BOUNDARY
{
    type = hqrelation
    string = downstream
    slope = 1.5
}
```

5.1.3.4.2.3 Define initial condition

The channel is considered to be initially dry. Note that starting with a dry channel is for the depth-average equations a numerically delicate problem. So this option will require some care when we set the numerical parameters.

```
INITIAL
{
    type = dry
}
```

5.1.3.4.2.4 Define default friction values

The declaration of a default friction type and a default friction value are mandatory. The friction values are overwritten by the values declared in the topography file.

```
FRICTION
{
    type = strickler
    default_friction = 35
}
```

5.1.3.4.2.5 Declare parameters for hydraulic computation

In the *PARAMETER* block the relevant parameters for the hydraulic simulation are defined. With the flag *minimum_water_depth*, the water depth is defined for the case where the channel is considered to be dry. The simulation is using an explicit Euler scheme using a Roe solver for the Riemann problem at the edges of the control volumes.

```
PARAMETER
{
    minimum_water_depth = 0.01
    simulation_scheme = explicit
    riemann_solver = roe
}
```

5.1.3.4.3 Define time step information

For the first computation the simulation time is set to 150000 s. For a computation on a dry bed, a small initial time step should be chosen. It is used only at the very beginning, as there is no flow in the channel from which the time step could be deduced. The maximum time step should be bigger than all time steps computed during the simulation.

```
TIMESTEP
{
    total_run_time = 150000
    initial_time_step = 1.0
    maximum_time_step = 60.0
    CFL = 0.95
}
```

5.1.3.4.4 Define output

If only standard output is needed, only the time step for file printing and for console printing have to be defined. If Tecplot software is available, it is also very useful to generate a tecplot file.

```
OUTPUT
{
    output_time_step = 100
    console_time_step = 100
    SPECIAL_OUTPUT
    {
        type = tecplot_all
        output_time_step = 100
    }
}
```

5.1.4 Perform hydraulic simulations

5.1.4.1 Write the setup file

Once all the inputs have been set in the in the *model.json* file, a setup file must be written. Click *write* in the bottom right corner of the GUI. This will combine the model file with the computational mesh and external data, and store it in a binary file named *setup.h5*.

5.1.4.2 Setting up the simulation file

To set up the simulation file, switch to the *simulation* tab on the left. Select whether the simulation should be run on a single core (select *Single-threaded on CPU*) or on multiple cores (selected *Multi-threaded on CPU*). If multiple cores are selected, you must enter the *number of CPU cores*. This selection should depend on the number of threads your computer has available.

5.1.4.3 Perform steady flow simulation

Run the simulation with the *Run* button of the BASEMENT window. If the SPECIAL_OUTPUT of the type *BASEviz* is chosen press the keyboard button p to start the simulation.

5.1.4.4 Results of the steady flow simulation

When the simulation has finished, several results files will be produced in ".dat" form. *In the Basement window, you may ignore the "Results" tab on the left side. This tab is only active for 2D simulations.* remains open the main output file named "Thur_out.dat" using a text-editor such as notepad++ or gedit. Scroll to the end of the file, where the output data of the last time step is listed. Check the discharges Q which are given in the column labeled "Mass_Flux_[m^3/s]". If the discharges correspond to the steady inflow discharge of 30 m^3/s at all edges between the cross sections, then the steady-state has been reached. You should also have a look at the other output values to see if there are suspicious values, which indicate an error somewhere in your model setup.

Edge_number	Mass_Flux_[m^3/s]	Momentum_Flux_[m^4/s^2]	...
0	30	21.0328	...
1	30	20.7677	...
2	30	20.8081	...
3	30	18.4419	...
4	30	16.5479	...
5	30	18.1862	...
6	30	19.3961	...
7	30	21.1823	...
8	30	21.8026	...
...			

If the steady-state has been reached, then we use this result for subsequent simulations (hot start). For this purpose you can use the file "Thur_restart_150000.dat", which contains the results of the last time step. It is recommended to rename the restart file (e.g. "ThurInitial.dat") in order to use it as an initial condition in further simulations.

You should also have a look at the file named "ThurTopo_tables.txt" and verify whether there have been any errors or strange values resulting from your topography file. (Of course, the grid file you have here in the tutorial should not have any errors. It's just a good exercise to check your geometry if the program does not work as expected).

Now, take from the main output file "Thur_out.dat" the columns named "distance_[m]", "z_talweg_[m_asl]", "wse_[m_asl]" and "energy_head_[m_asl]" for the last time step and use them to plot a longitudinal profile (e.g. with Excel).

As it seems that there is no problem, we can proceed to the next step.

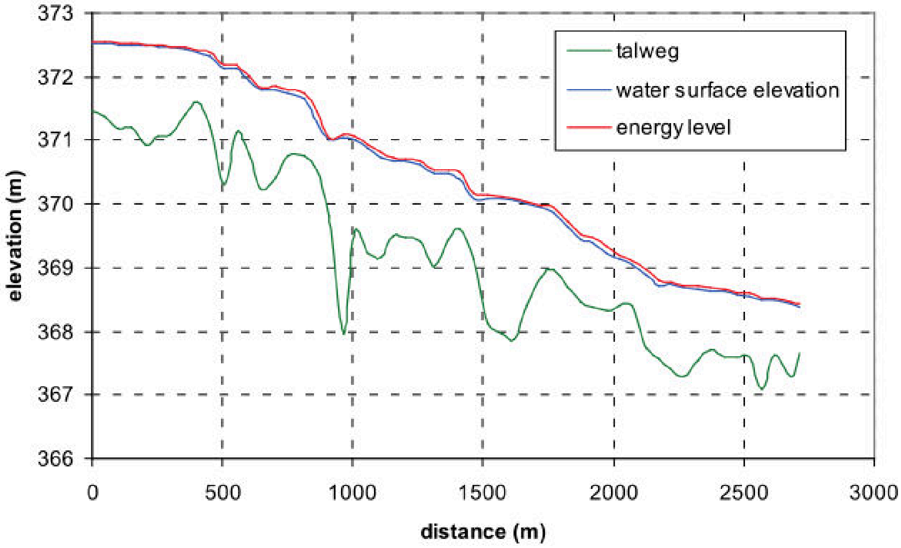


Figure 5.8 *Longitudinal profile*

5.1.4.5 Perform simulation of the floods (Thur2)

The zip file "Thur-02-flood-simulation.zip" contains the files for simulation of the flood. The "ThurInitial.dat" file contains the results of the last time step of the steady flow simulation, for use as a restart for this unsteady flow simulation.

The "ThurHydrograph.txt" contains the hydrograph of the flood event in 2005.

T	Q
0	30.648
3600	34.05
7200	37.305
10800	39.707
14400	41.18
18000	41.916
21600	42.275
25200	42.654
28800	43.646
32400	45.444
...	

For the upstream boundary condition, change the data file into "ThurHydrograph.txt".

```
BOUNDARY
{
    type = hydrograph
    area = upstream
    file = ThurHydrograph.txt
    precision = 0.001
    number_of_iterations =100
    slope = 0.93
}
```

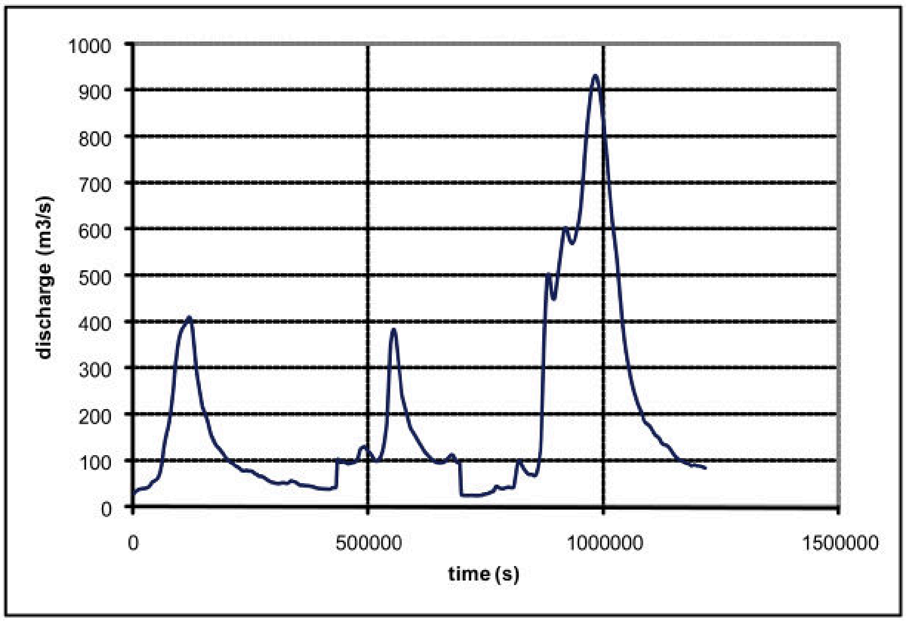


Figure 5.9 *Hydrograph of the flood event of 2005*

The renamed restart file "ThurInitial.dat" shall be input as an initial condition for the new simulation. Therefore we have to consider two things:

1. Choose the restart file
2. Define the start time of the new simulation.

```
INITIAL
{
    type = continue
    file = ThurInitial.dat
}
```

Because we want to restart from time zero we set the flag *start_time* in the TIMESTEP block to zero. Be aware that if the *tag start_time* is not defined, the time in the restart-file is used (i.e. # time: 150000 sec).

The total running time of the simulation is increased to 338 hours (1216800 sec.). So we change the settings in the *TIMESTEP* block accordingly.

```
TIMESTEP
{
    start_time = 0.0
    total_run_time = 1216800
    CFL = 0.95
    maximum_time_step = 60.0
}
```

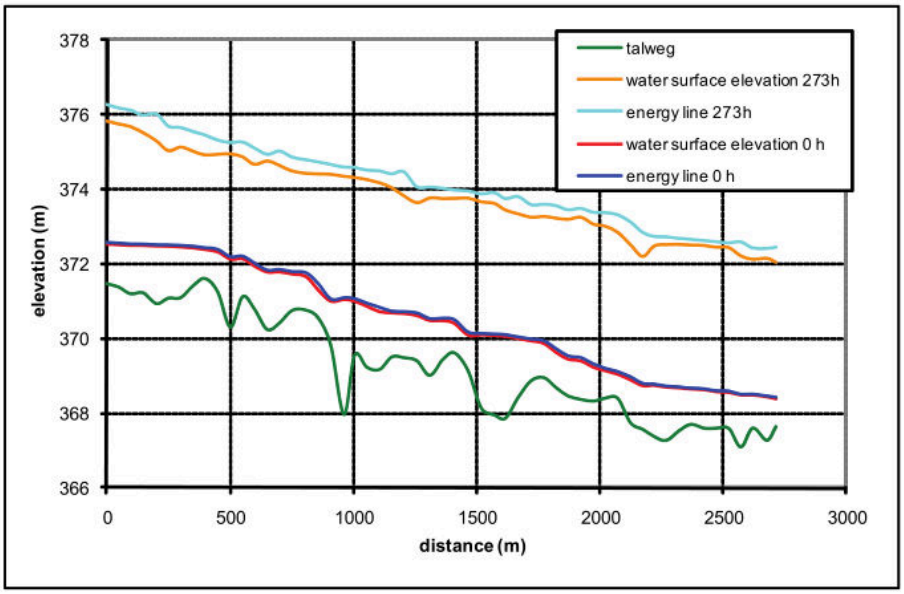


Figure 5.10 *Longitudinal profile for maximum discharge*

The output should be plotted less often. Therefore, we change the console and output time.

```
OUTPUT
{
    output_time_step = 1000
    console_time_step = 1000
}
```

Now we can run the simulation by writing the *setup.h5* file, and then clicking on the Run button in the simulation tab. When the simulation is finished, have a look at the main output file "Thur_out.dat". Take the columns of "z_talweg_[m_asl]", "wse_[m_asl]" and "energy_head_[m_asl]" for the time of maximal discharge (ca. 933 m^3/s) at ca. 982.000 s (= 273 hours) and plot them over the "distance_[m]" (see Figure 5.10).

Then we plot some interesting cross sections with their water surface elevation, for the same time (see Figure 5.11). This can help to see what happens, and which parts of the cross sections are touched by the flood. For this purpose the cross section geometry and can be taken from the topography file and the water surface elevation from the main output file. Alternatively a monitoring point of type "geometry" could be used.

5.1.5 Edit the model file for bed load transport

The zip file "Thur-03-bed-load-simulation.zip" contains the files for simulation of the flood with bed load transport. Information about bed load is grouped in the block MORPHOLOGY. In the block BASECHAIN-1D, chose MORPHOLOGY and press Add Block. Go in the block MORPHOLOGY.

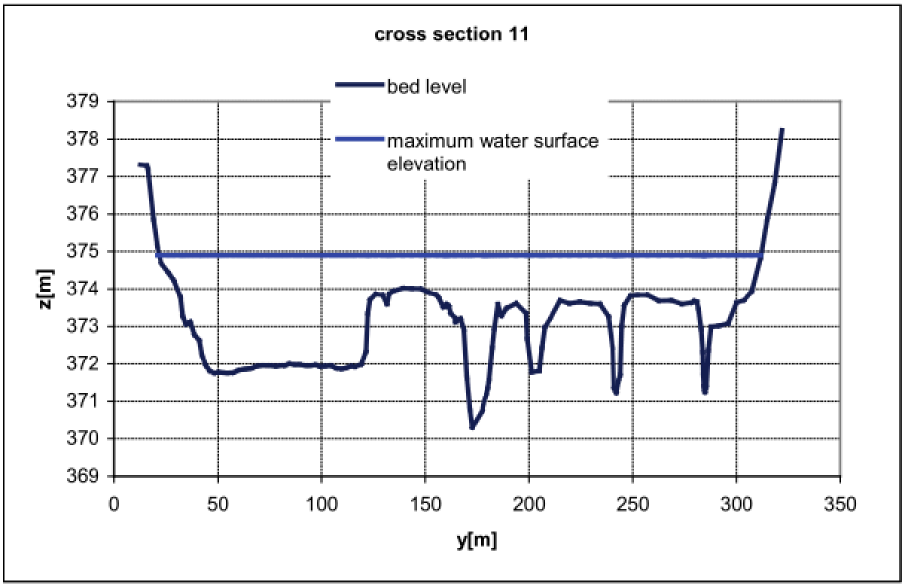


Figure 5.11 *Example of resulting water surface elevation*

5.1.5.1 Define the bed material

The simulation is executed with a single grain class with mean diameter = 2.5 cm. This means that you have to define one grain class and one mixture. Add a block of type GRAIN_CLASS and one of type MIXTURE. In the GRAIN_CLASS block add the diameter.

In the MIXTURE block add the name and the volume fraction.

```
BEDMATERIAL
{
    GRAIN_CLASS
    {
        diameters = ( 25 )
    }
    MIXTURE
    {
        name = unique
        volume_fraction = ( 100 )
    }
    [...]
}
```

Two types of soils are defined: one which is fixed (code 1) and one with a sub layer of 5 m thickness which is attributed to the bed bottom where bed load takes place (code 2). Add twice a block of type SOIL_DEF. The first one needs only a name as it has no layers of material. In the second one add a LAYER block. Then give the layer a bottom elevation and a mixture.

```
SOIL_DEF
```

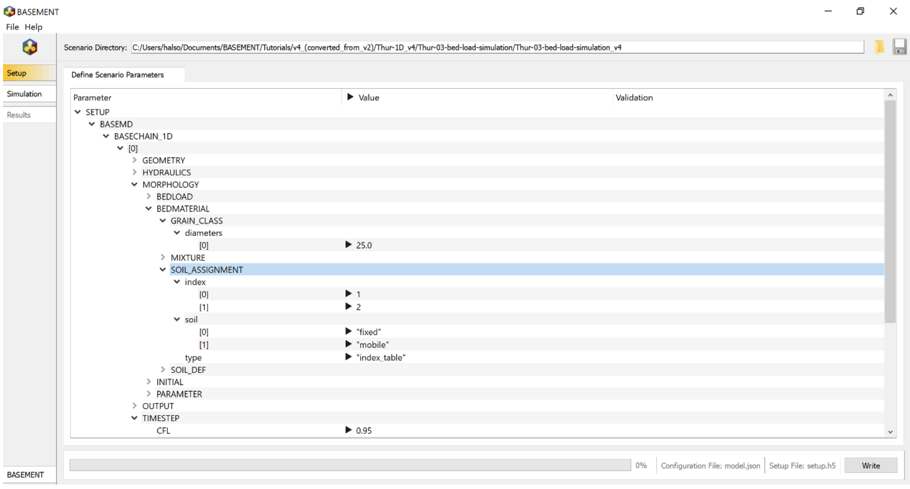


Figure 5.12 *Soil assignment in the user interface*

```
{
    name = fixed
}
SOIL_DEF
{
    name = mobile
    LAYER
    {
        bottom_elevation = -5.0
        mixture = unique
    }
}
```

5.1.5.2 Soil assignment

The names of the described soils have now to be assigned to the soil codes used in the topography file. Add a SOIL_ASSIGNMENT block and there the attributes type, index and soil. The first value in the index window has to correspond to the first name in the soil window etc.

5.1.5.3 Define general parameters for sediment transport

The porosity and the density of the material are standard values.

The control volume is set to a constant thickness of 20 cm (varying this parameter influences the grain sorting processes in the simulation). The tables for the hydraulic computation will be updated each time when the bed level has changed more than 5 cm.

```
PARAMETER
{
    porosity = 37
    control_volume_type = constant
    control_volume_thickness = 0.2
```

```
    density = 2650
    max_dz_table = 0.05
}
```

5.1.5.4 Define specific parameters for bed load transport

The parameter for upwind scheme is set to 1.0 and the ‘velocity_area’ which defines wich part of the cross section area is taken for the velocity computation for bedload transport, is changed to ‘main’.

```
PARAMETER
{
    upwind = 1
    velocity_area = main
}
```

5.1.5.5 Define bed load transport formula

The Meyer-Peter and Müller bed load approach will be applied without adjusting the calculated transport capacity (bedload_factor = 1.0). For the critical angle a standard value has been choosen.

```
PARAMETER
{
    bedload_formula = mpm
    bedload_factor = 1
    angle_of_repose = 30
}
```

5.1.5.6 Define boundary conditions for bed load

At the downstream boundary it is considered that the quantity of sediment which enters the last element leaves it by the boundary.

```
BOUNDARY
{
    type = IODown
    string = downstream
}
```

At the upper boundary, the observed modification of the bed level before and after the floods is very small. For this reason it can be assumed that at the upstream boundary there is as much sediment coming in, as is transported out of the first element.

```
BOUNDARY
{
    type = IOUp
    string = upstream
}
```

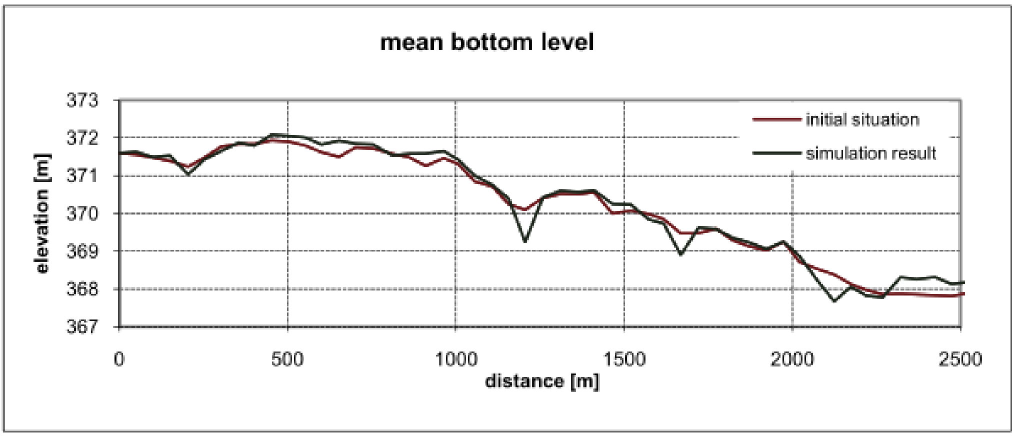


Figure 5.13 *Longitudinal profile of mean bottom level*

5.1.5.7 Generate a "geometry" file

To see how the geometry of cross section 14 changes during the flood add a SPECIAL_OUTPUT block to the *OUTPUT* block. Set the type of the SPECIAL_OUTPUT to monitor.

```
OUTPUT
{
    output_time_step = 1000
    console_time_step = 1000
    SPECIAL_OUTPUT
    {
        type = monitor
        output_time_step = 1000
        cross_sections = ( CS14 )
        geometry = ( time )
    }
```

5.1.6 Perform bed load simulation (Thur 3)

Run the simulation of the flood with bedload transport. When the simulation has finished, look at the "Thur_out.dat" file, take the columns of distance and mean bottom level of the start and end situation and make a longitudinal profile of it (Figure 5.13).

Additionally open the topology file of cross section 14 "ThurCS14_tec.dat" and plot the old and new geometry of this cross section to see the morphodynamical changes (Figure 5.14).

Obviously this is only a first run for exercise. This computation now needs calibration and validation before it can be used to make prediction of future bed evolution.

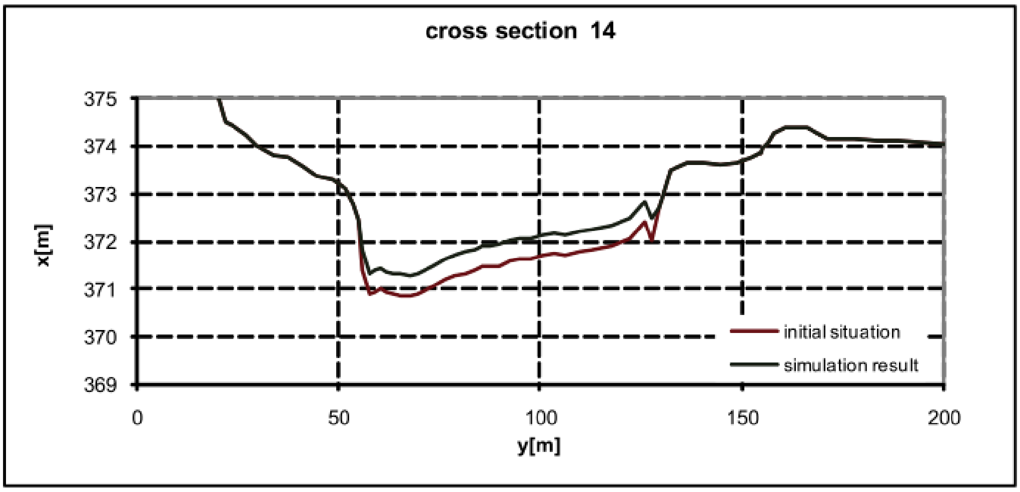


Figure 5.14 *Transversal cross section profile*

6

Dynamics of longitudinal bed profile due to local river widening

6.1 Dynamics of longitudinal bed profile due to local river widening (1D)

6.1.1 Introduction

In this tutorial the capabilities of *BASEchain* in modelling the evolution of the longitudinal bed profile due to a local symmetric widening is shown and discussed. The general concepts of the 1D simulation with *BASEMENT* and how to set up the configuration files are demonstrated in the previous tutorial 'Hydrodynamics and sediment transport at the river Thur' (Section 5.1).

6.1.1.1 General description

In the context of river engineering, local river widenings are a measure for river bed stabilisation and ecological restoration. The example river widening can be divided into three main parts (Figure 6.1): Upstream channel (L_{US}) with a certain channel width (W_C), transition zone between channel and widening (L_T), widening with length (L_W) and width (W_W) and the downstream channel (L_{DS}).

The new channel geometry due to the widening affects the hydraulic conditions in the particular river reach. This causes morphological processes that lead to a new equilibrium state of the system (Figure 6.2). Starting from an initially plane bed, erosion occurs upstream of the widening due to a temporary flow acceleration towards the widening (Scour_US). A significantly larger erosion can be observed at the downstream end of the widening (Scour_DS) as a result of the bed load deficit caused by the deposition inside the widening. This deposition (ΔH) increases and migrates in downstream direction until the end of the widening is reached. The material slowly fills up the scour whereby the downstream bed tends towards its initial state again. The longitudinal slope within the

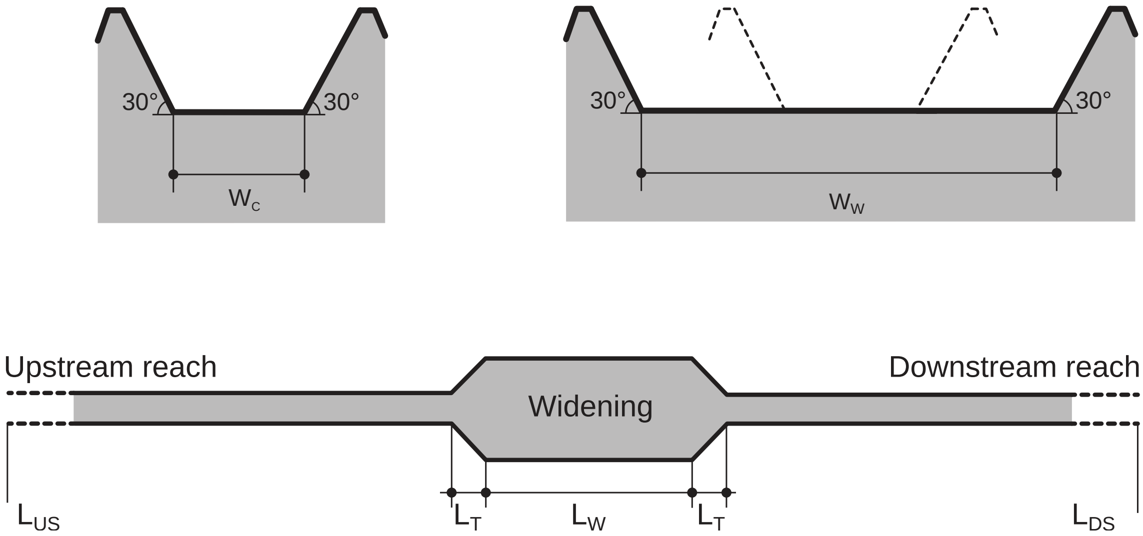


Figure 6.1 *Sketch of symmetric widening used for the numerical simulations in this tutorial.*

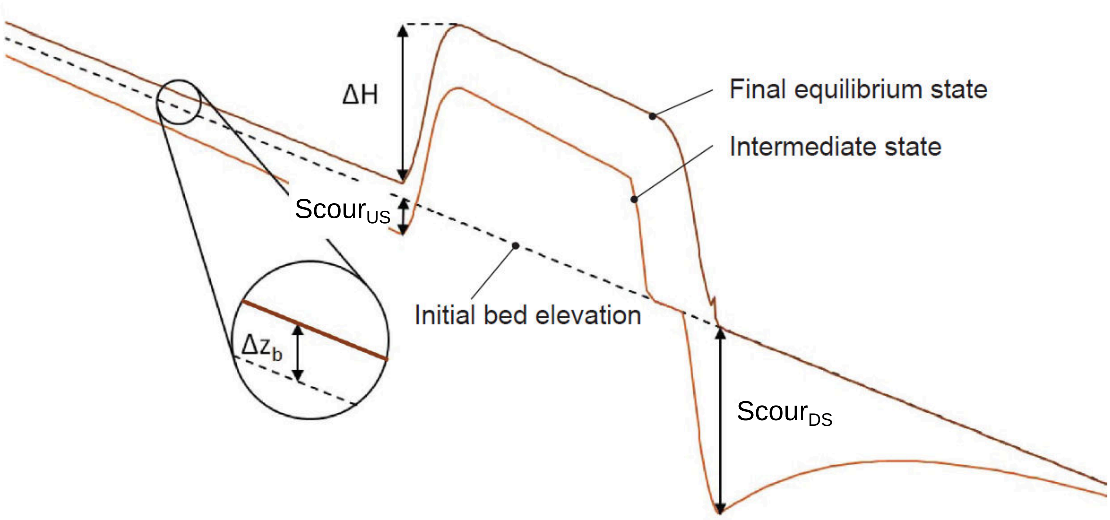


Figure 6.2 *Temporal evolution of the longitudinal bed profile due to a local river widening.*

widening increases until a new equilibrium slope is reached, providing enough transport capacity to convey the entire bedload discharge downstream. The widening may induce an uplift (Δz_b) of the river bed in the upstream reach. However, before the depositions in the widening, reach equilibrium state, erosion may be observed in the upstream channel.

6.1.1.2 Purpose

Based on the general conditions of the river widening at the River Thur near Altikon (ZH, Figure 6.3), numerical 1D simulations with simplified geometry are performed in order to analyse the effects of an artificial river widening on the evolution of the longitudinal bed profile (mean bottom elevation). Besides the temporal evolution, the final equilibrium state of the longitudinal bed profile shall be determined by means of a parameter variation for different length of the widening, width of the widening, discharge and mean grain size diameter.

Figure 6.3 *River widening at the River Thur near Altikon (ZH) in 2014, source: C. Herrmann, BHAteam Ingenieure AG, Frauenfeld*

6.1.1.3 Used features

BASEMENT version 4.0 is used for the simulations in this tutorial. All relevant files to run the simulations including the topographies for the different scenarios are provided. Bedload transport is calculated using the Meyer-Peter and Müller (MPM) formula for a single grain configuration. In general default values of the program are used. Two important parameters, which have been modified, are described in Table 6.1.

Table 6.1 *BASEMENT parameters used for this tutorial*

Parameter	Description	Default value	Used value
max dz table	Change in bottom elevation to trigger recomputation of tables [tables1D]	0.1 [m]	0.01 [m]
upwind	Weighting for sediment flux calculation on edge		0.7 [-]

6.1.1.4 Parameter variation

Starting from the default configuration of the reference geometry, the parameters are altered according to Table 6.2 . The input files and *BASEMENT* command files (*.bmc) for each run are provided and can be identified by their run-number.

Table 6.2 *Summary of the simulation runs for different parameter combinations*

Parameter	run	W_W [m]	L_W [m^2]	Q [m^3/s]	d [mm]
	default	100	500	800	20
Width variation	1	150	500	800	20
	2	200	500	800	20
Lenght variation	3	100	250	800	20
	4	100	750	800	20
	5	100	1000	800	20
Discharge variation	6	100	500	200	20
	7	100	500	400	20
	8	100	500	1600	20
Diameter variation	9	100	500	800	5
	10	100	500	800	10
	11	100	500	800	40

6.1.2 Model setup

6.1.2.1 Definition of 1D topography

All the topography files (*.bmg*) used in this tutorial are provided to the user. A uniform value for the Strickler roughness is chosen for all cross sections. The *bottom_range*, which defines the part of the cross section considered for the sediment transport calculations, spans from the left to the right embankment toe (Figure 6.4). This means that deposition and erosion only occur at the bottom, the embankments are fixed. A mobile bed (layer soil 1) with a thickness of 2 m is defined at the bottom.

The parameter variation is performed based on the reference geometry as specified in Table 6.3:

Table 6.3 *Default configuration and variation of the investigated parameters.*

Type	Symbol	Units	Description	Default value	Variation
Reference geometry	L_{US}	m	Length upstream channel	3000	
	L_T	m	Length transition zones (US/DS)	150	
	L_W	m	Length widening	5000	250-1000

Type	Symbol	Units	Description	Default value	Variation
	L_{DS}	m	Length downstream channel	3000	
	W_C	m	Width cannel	50	
	W_W	m	Width widening	100	100-200
	S_C	%	Channel slope	0.15	
	S_W	%	Initial slope widening	0.15	
Additional variables	Q	m^3/s	Steady discharge	800	200-1600
	Q_S	m^3/s	Steady sediment discharge	0.178	$f(Q,d)$
	d	mm	Grain diameter (single grain)	20	5-40
	$k_{St,C}$	$m^{1/3}/s$	Strickler roughness channel	34	
	$k_{St,W}$	$m^{1/3}/s$	Strickler roughness widening	34	

6.1.2.2 Determination of the upstream sediment boundary conditions

The equilibrium sediment discharge at the inflow model boundary is determined for each discharge Q using a topography with a slope equal to the reference geometry but without river widening. The sediment discharge is calculated for different discharge and grain diameters (see Table 6.4) by *BASEMENT* using the boundary condition of type *transport_capacity*. The resulting sediment discharges are used for the parameter variation simulations afterwards. This approach was chosen to assure a constant sediment inflow independent of local erosions or depositions when running the final simulations including the local widening.

Table 6.4 *Upstream sediment boundary inflow Q_S defined for different stationary discharges Q and mean grain size diameters d.*

	Q [m^3/s]	d [mm]	Q_S [m^3/s]
Discharge variation	800	20	$Q_{S,Q800} = 0.178$
	200	20	$Q_{S,Q200} = 0.020$
	400	20	$Q_{S,Q400} = 0.043$
	1600	20	$Q_{S,Q1600} = 0.363$
Diameter variation	800	5	$Q_{S,Q800,d5} = 0.282$
	800	10	$Q_{S,Q800,d10} = 0.245$
	800	40	$Q_{S,Q800,d40} = 0.067$

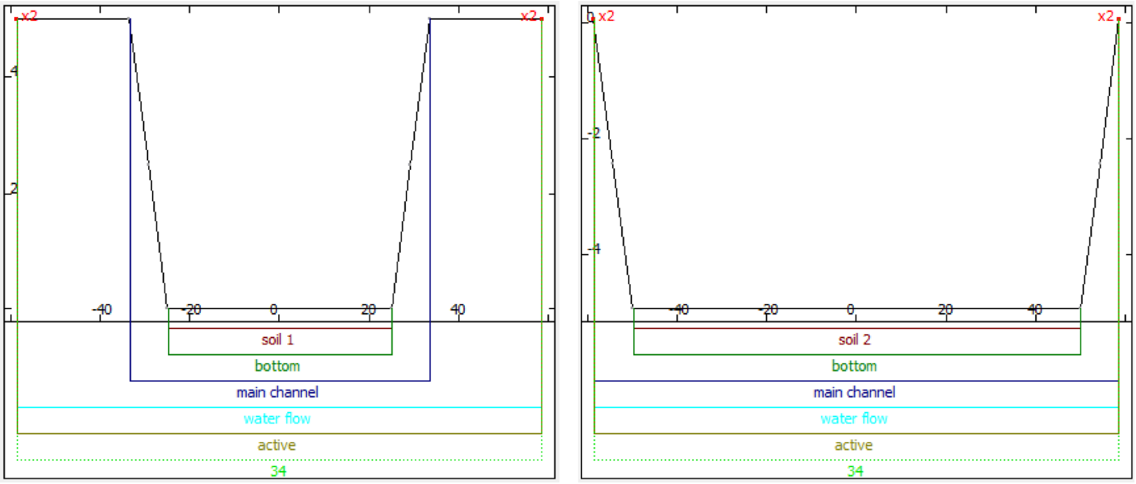


Figure 6.4 *Cross sections of the BASEMENT topography representing the channel (left) and the widening (right) to illustrate the geometry and the bottom/soil definition.*

6.1.3 Results of numerical simulations

6.1.3.1 Temporal evolution of longitudinal bed profile

The basic morphological processes described in the introduction can be reproduced generally well with *BASEMENT*. The results with default configuration are shown in Figure 6.5. Steady state river bed conditions are reached after a total simulation runtime of about one year.

6.1.3.2 Width and length of the widening

The effect of the width and the length of the widening (geometric parameters W_W and L_W) on the longitudinal bed profile and equilibrium slope is shown in Figure 6.6 and Figure 6.7. The corresponding bottom offset ΔH and upstream bed level change Δz_b is shown in Figure 6.8. For increasing width, ΔH rises significantly and reaches about 2.7 m for $W_W = 200$ m. The new equilibrium slope inside the widening is steeper than the initial slope (Figure 6.6). This causes a bed level change (aggradation) of 0.3 m upstream of the widening. The effect of the river widening length on ΔH and Δz_b is rather small as the slope in the widening remains almost constant. Δz_b increases slightly upstream with increasing length of the widening.

6.1.3.3 Discharge and grain diameter

The effect of the discharge and the grain diameter (parameters Q and d) on the longitudinal bed profile and the equilibrium slope is shown in Figure 6.9 and Figure 6.10. The corresponding bottom offset ΔH and upstream bed level change Δz_b are shown in Figure 6.11. For one geometry but varying discharge, big differences regarding the final topography are observed. For small discharges (200 and 400 m^3/s), ΔH reaches only about 1 m but the slope in the widening is much steeper than the initial one. Therefore the bed level change upstream of the widening is quite large. For very high values of Q however, the slope in the widening is smaller than in the channel and Δz_b becomes negative. The

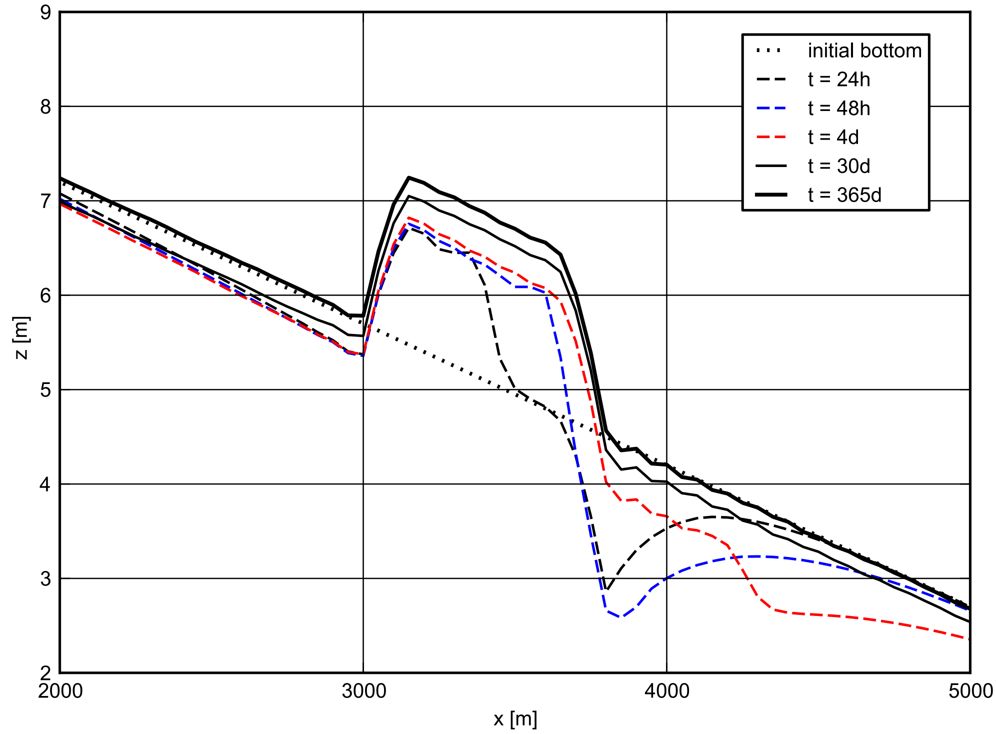


Figure 6.5 *Temporal evolution of the mean bottom elevation of the reference geometry with default configuration.*

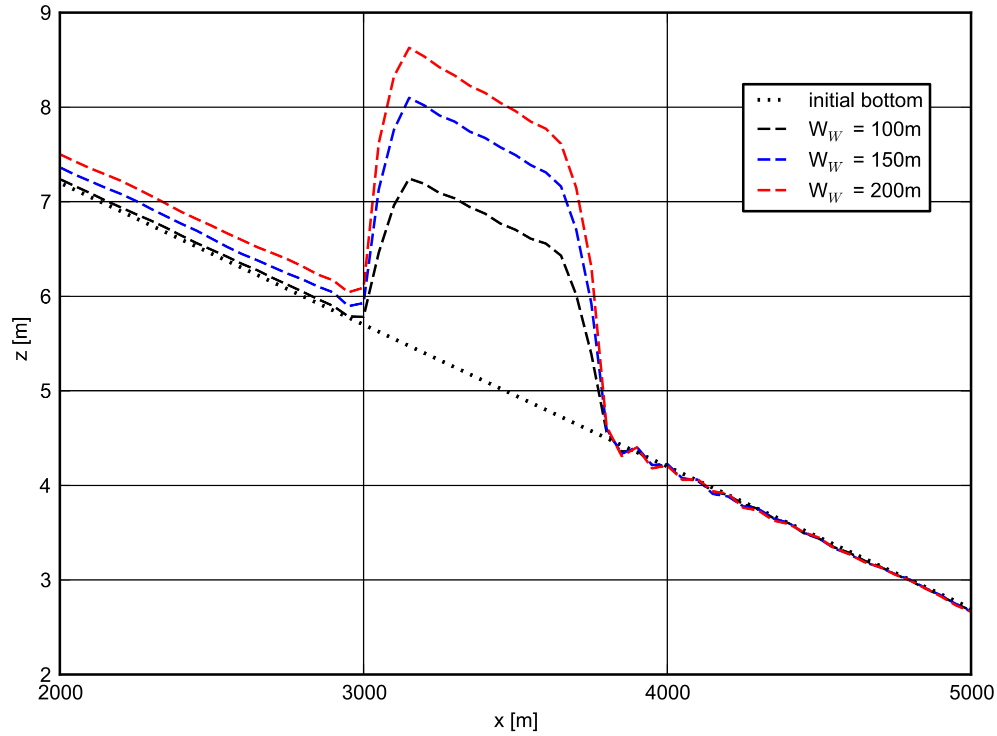


Figure 6.6 *Longitudinal bed profile of the initial and resulting steady state for different widening width W_W.*

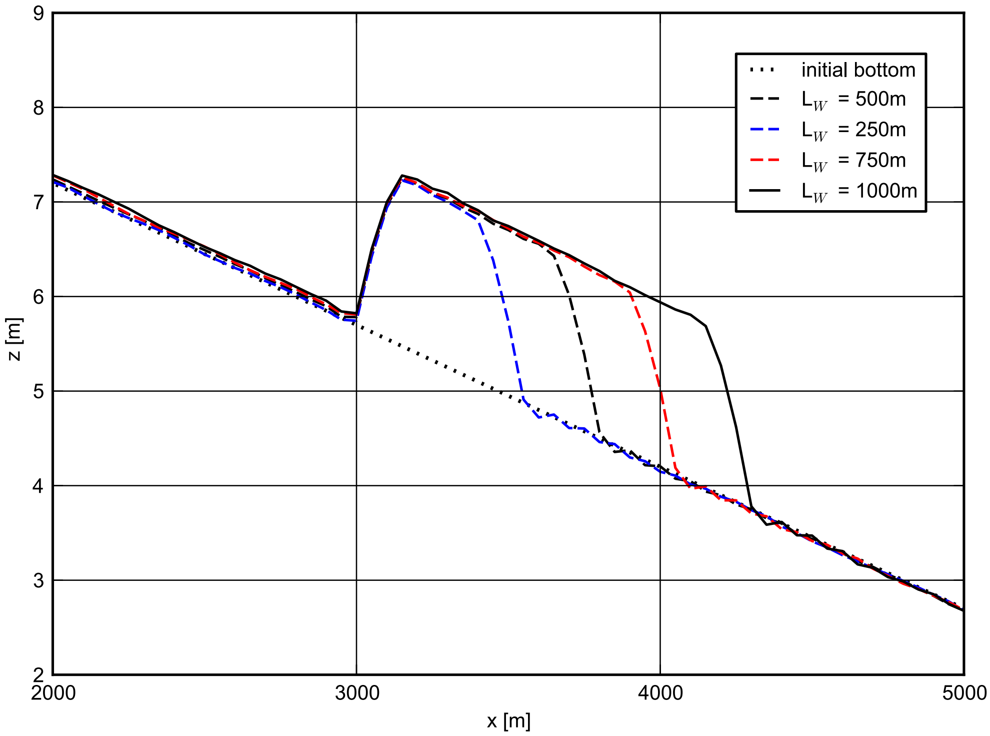


Figure 6.7 *Longitudinal bed profile of the initial and resulting steady state for different widening length L_W.*

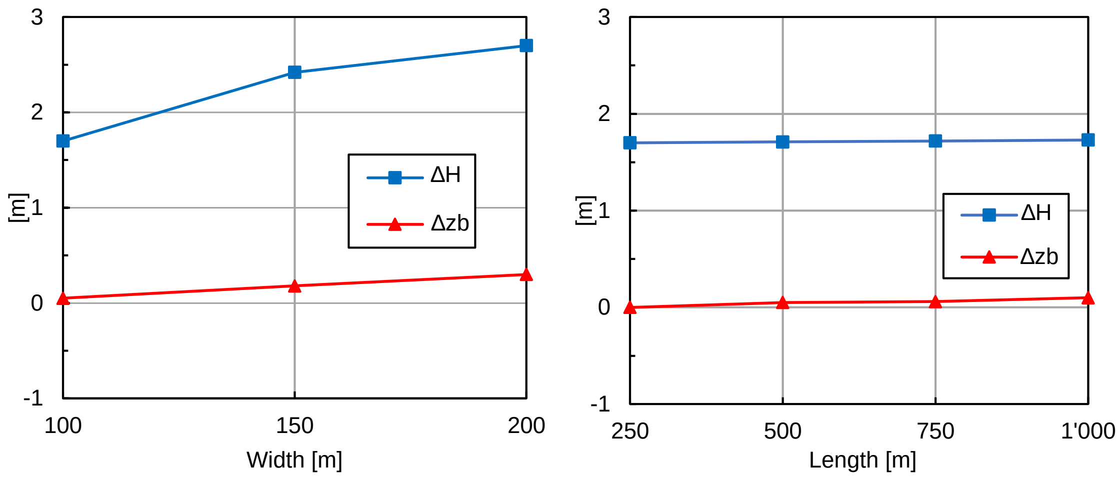


Figure 6.8 *Bottom offset ΔH and upstream displacement Δz_b for different W_W (left) and L_W (right), parameter variation according to table 6.2.*

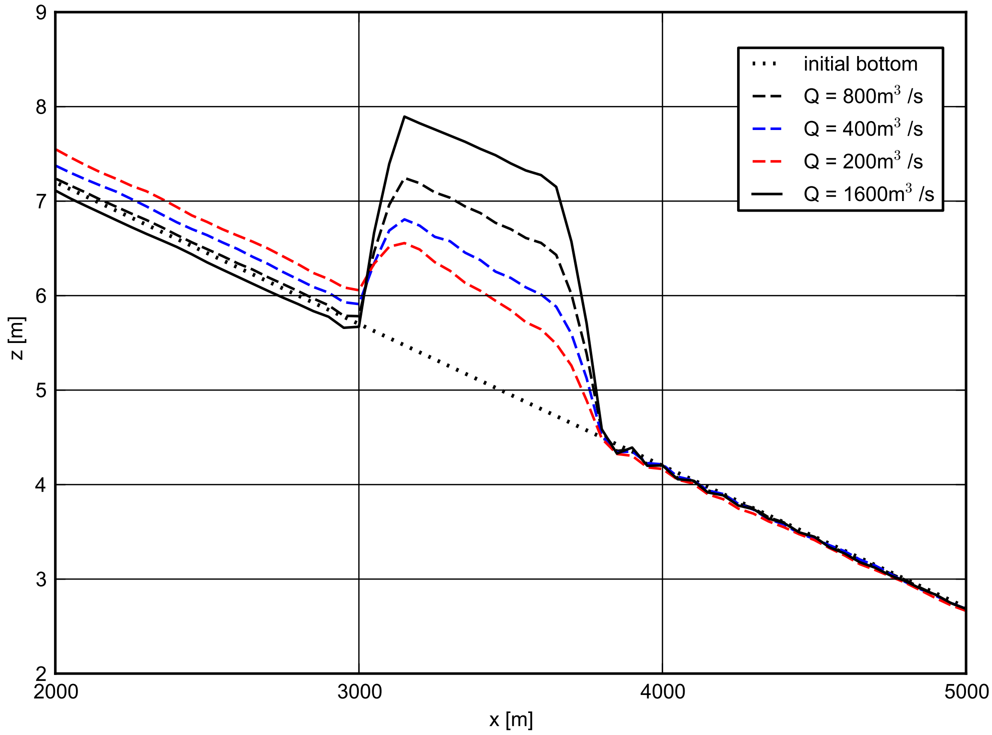


Figure 6.9 *Longitudinal bed profile of the initial and resulting steady state for different discharges Q.*

same effect can be observed for small grain diameters ($d = 5$ mm). Note that these extreme values for discharge and grain diameters do not correspond to the real conditions at the river Thur and can therefore be considered as hypothetical configurations. In the case of a coarser grain diameter of 40 mm, the bed slope in the widening get larger than for the default configuration and again depositions in the upstream reach are observed.

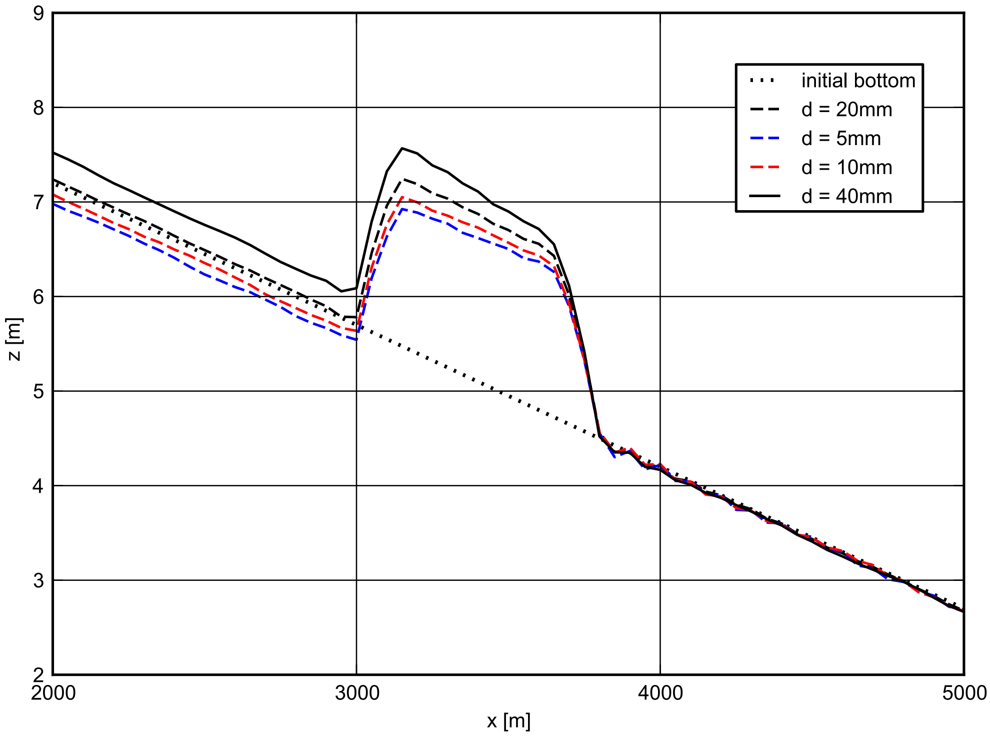


Figure 6.10 *Longitudinal bed profile of the initial and resulting steady state for different mean grain size diameters d.*

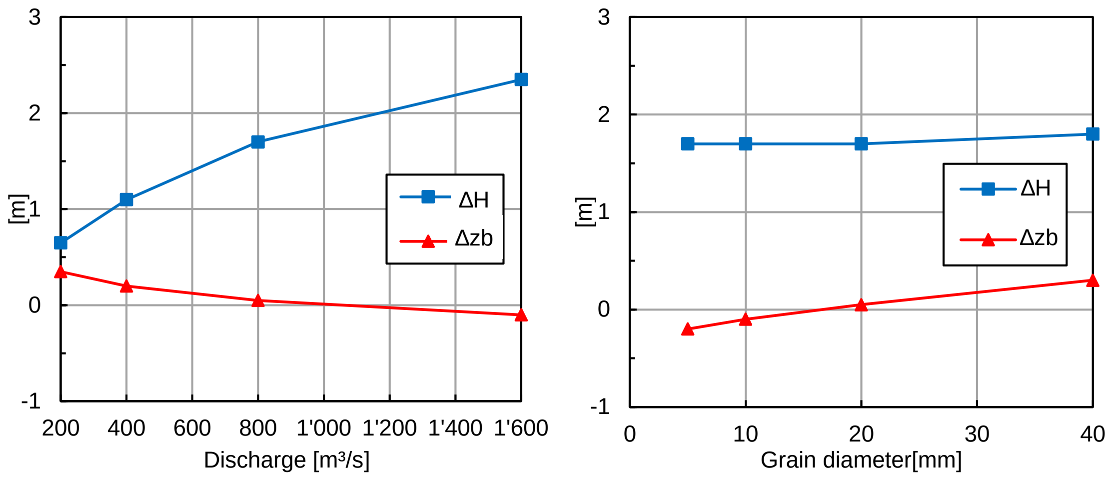


Figure 6.11 *Bottom offset ΔH and upstream displacement Δz_b for different discharges Q (left) and mean grain size diameter d (right) parameter variation according to table 6.2.*

7

Laterally coupled 1D-2D hydrodynamic simulation

7.1 Laterally coupled 1D-2D hydrodynamic simulation

7.1.1 Introduction

BASEMENT offers the possibility to combine BASEchain (1D) and BASEplane (2D) domains in coupled simulations. So-called "laterally coupled" simulations simulate the channelized river flow with a 1D approach, while the overland flow in the floodplains, in contrast, is simulated with a 2D approach. Using this coupling concept, the advantages of 1D models (like efficiency, simplicity, representation of 1D flow structures (weirs, gates)) and the advantages of 2D models (like differing flow directions and flow paths, complex topographies) shall be combined.

Coupled 1D / 2D simulations are an interesting modelling approach, especially in case of spatially extended scenarios with a clearly defined main channel and overflow into 2D floodplains with complex flow paths or topographies (like urban areas). However, be aware that this concept also suffers from the limitations of both model types (like the 1D flow assumptions, neglect of momentum exchange, etc.) and should be applied with caution.

The model coupling takes place laterally along the 1D river. If the water level exceeds the left or right river dyke crest, the water overtops the dyke and flows into the 2D floodplain. The water exchange is internally modelled as external sources, i.e. the water is removed from the 1D model and added to the 2D model as external sources, thereby neglecting the momentum exchange. In a similar way, water from the 2D floodplain flows back, if its water level exceeds the dyke crest and the water level of the 1D domain.

Water exchange takes place at defined connections between 2D boundary edges and 1D cross sections. The overtopping flow is determined using simple 1D weir formulas. To apply these weir formulas, water levels are needed from both models. The 1D water level is hereby interpolated between two cross-sections and the 2D water level is taken from the corresponding 2D cell.

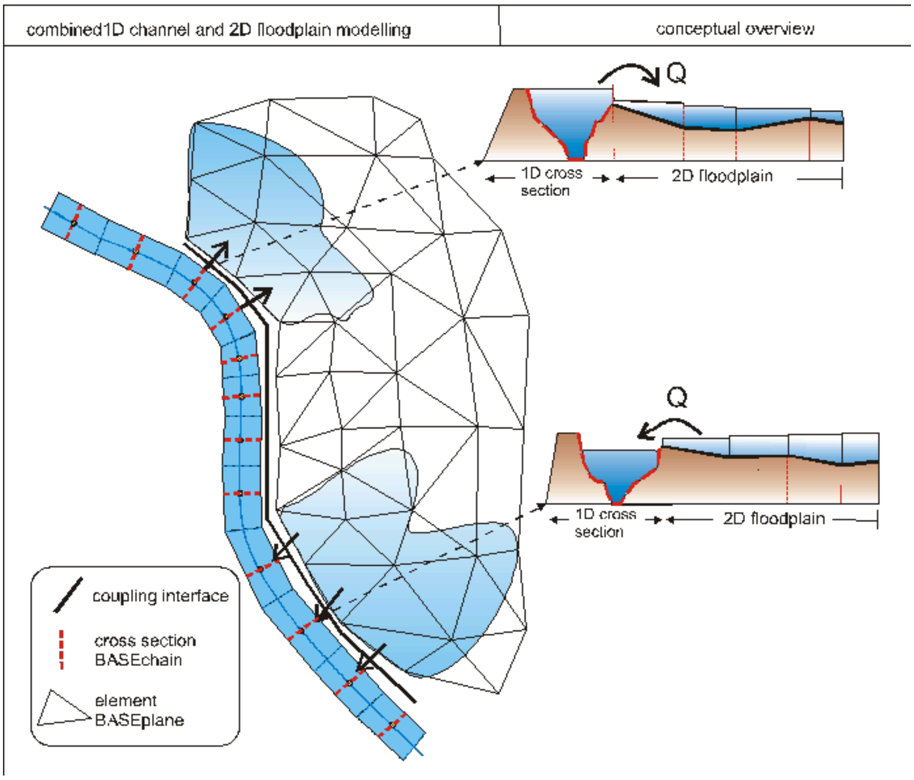


Figure 7.1 *Conceptual sketch of lateral coupling of 1D BASEchain (river channel) and 2D BASEplane (overland flow) sub-domains. Water is exchanged as weir overflow over the river dykes.*

This tutorial briefly introduces the use of this lateral coupling approach based on a simple scenario. Only hydraulic computations are performed, since the lateral coupling supports no morphological computations up-to-now. The tutorial makes use of the QGIS-plugin BASEmesh (see BASEmesh tuturial Section 1.1) for visual checks, which is recommended for setting-up lateral coupling simulations.

7.1.2 Set-up of model file

7.1.2.1 General remarks on mesh creation

Using the 1D / 2D coupling, parts of the domain are represented with the 1D model and other parts with the 2D model. It is important hereby, that both meshes do not overlap, since this would create artificial and unphysical storage volumes and flow paths. In a similar way, there should be no gaps between the model meshes. In this tutorial, both model meshes are adapted to fit to each other along the right river dyke as illustrated in Figure 7.2.

7.1.2.2 BASEchain (1D) river model

First, the 1D model of the river is set-up, analogous to the steps of the Thur tutorial (see Section 5.1) outlined above.

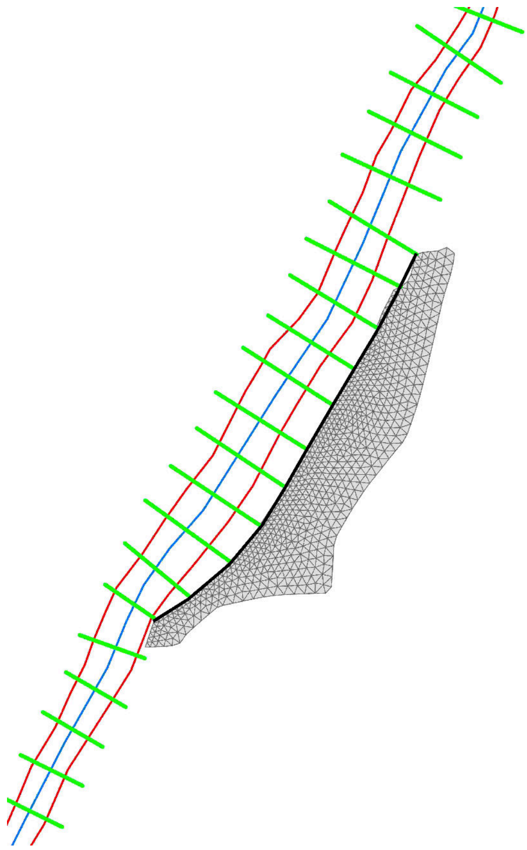


Figure 7.2 *1D cross-sections (green lines), 2D mesh (gray) and dyke break-line (black). Cross-sections and 2D mesh are connected along the river dyke, without gaps or overlapping areas. Flow direction is from bottom left to top right.*

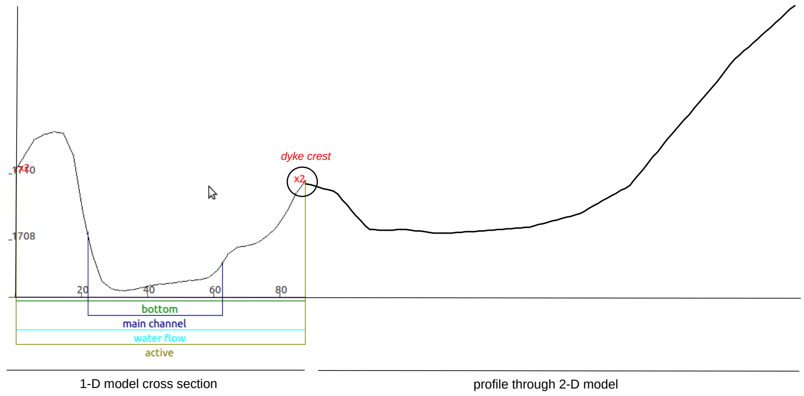


Figure 7.3 *Connection of 1D cross section (left) with 2D model (transversal profile, right) at the dyke location. Water overtopping takes place via the coupling connection.*

```
BASECHAIN_1D {
        region_name = river_flaz_1D
        GEOMETRY {
                ...
        }
        TIMESTEP {
                ...
        }
        HYDRAULICS {
                ...
        }
    }
```

The topography file (*.bmg) contains the cross section points, the main channel definitions, and the active range definitions. This data was obtained here by cutting profiles through a digital terrain model. Of special importance for the lateral coupling is the accurate definition of the active range (defined by the left and right dykes), because the water exchange into the 2D floodplain takes place along these dykes. Figure 7.3 shows the definition of the right dyke in the 1D cross-section and the connection to the 2D mesh (shown as transversal profile).

The adaptation ("fitting") of the model meshes along the river dyke was achieved by cutting the 1D cross-sections *(active_range)* at the river dyke location and by using the dyke as break-line for the boundary of the 2D model.

In this scenario, a steady-state inflow of 700 m^3/s is defined for the 1D model using a hydrograph inflow boundary. This discharge is large enough to overtop the dyke and to flood the 2D floodplain. The outflow boundary is modelled as a zero-gradient boundary. The simulation is run until steady-state conditions are reached, which are used later on as initial conditions for the coupled simulation.

7.1.2.3 BASEplane (2D) floodplain model

The floodplain outside of the main river channel is modelled with a 2D BASEplane sub-domain. Figure 7.4 illustrates the corresponding 2D mesh.

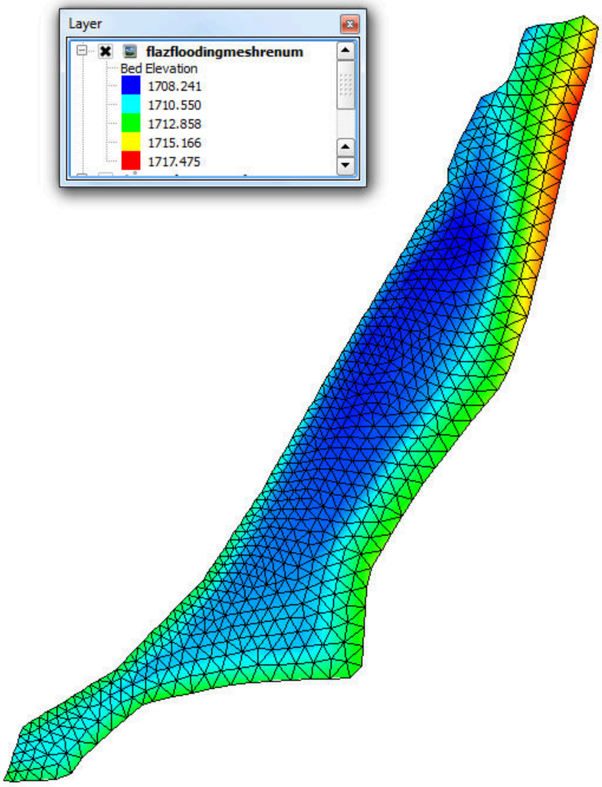


Figure 7.4 *Unstructured 2D mesh of the floodplain located to the right of the 1D river channel.*

The 2D floodplain model is quite simple to set-up – it has neither inflow boundaries nor outflow boundaries, i.e. water cannot enter or leave the domain, except via the lateral coupling. The model domain is dry at simulation start.

```
BASEPLANE_2D {
    region_name = floodplain_flaz_2D
    GEOMETRY {
        ...
    }
    HYDRAULICS {
        ...
    }
    TIMESTEP {
        ...
    }
}
```

7.1.2.4 Lateral coupling set-up

The command file of the coupled simulation must contain both the BASEchain and BASEplane sub-domain definitions. These are coupled with each other by defining an additional COUPLINGS-block:

```
DOMAIN {
    BASECHAIN_1D {
        ...
    }
    BASEPLANE_2D {
        ...
    }
COUPLINGS {
         PARAMETER {
            max_time_level = 1
        }
        COUPLING_LATERAL {
            basechain = flaz_river_1D
            baseplane = flaz_floodplain_2D
            connections_filename = connections.dat
            c_m = 0.6
            weir_from_dyke1D = no
        }
}
}
```

The COUPLINGS-block has just two inner blocks in this scenario. The PARAMETER-block is used to define the time level at which the exchange takes place (for details see {#sec:afmodelcoupling} (Section 8.2) in the User manual). Usually, this parameter is set to 1 for lateral coupling, meaning that both sub-domains are executed with the same (minimum) time step size and water exchange takes place after each time step. This setting is recommended for lateral coupling to prevent or mitigate oscillations.

The second inner block is the COUPLING_LATERAL-block. Its main settings are the names of the coupled BASEchain and the BASEplane sub-domains and the filename of the coupling connections file (see Section 7.1.3). Additional parameters are the empirical coefficients for the weir / side-weir formulas. Furthermore, one must specify whether the weir crest elevation (= the dyke crest) is taken from the 2D mesh elevations (*weir_from_dyke1D = no*, default) or is interpolated in between the 1D cross-sections at the connection location. Determining the weir crest elevation from the 2D mesh topography is often advantageous, especially if the 2D mesh topography is based on high-resolution DEM models. Interpolating between 1D cross-sections, in contrast, may neglect local depressions or dyke openings.

7.1.3 Coupling connections between 1D and 2D subdomains

7.1.3.1 Definition of coupling connections

The dynamic interactions between the 1D and 2D models take place via a list of defined coupling connections. These connections are defined by the name of a 1D cross-section and the corresponding node numbers of the connected 2D boundary edge. Cross-sections thereby may have multiple 2D boundary edges attached to it (1:n-relation), whereas each 2D boundary edge can only be connected to a single cross-section (1:1-relation).

The geometrical connections must be listed in an ASCII-file, which is read at the start of the simulation. The file contains the following information and has the shown data format:

Cross section name	dyke location	nodeID 1	nodeID 2
CS1	1	44	67
CS1	1	67	43
CS2	1	47	46
...			

1. Column = name of cross-section
2. Column = location of the dyke (0 = left, 1 = right; seen in flow direction)
3. Column = node 1 (of 2-D boundary edge)
4. Column = node 2 (of 2-D boundary edge)

In principle, it is possible to define these connections manually by filling out the connections file. In practice, however, this is usually unfeasible, due to the large number of connections along the river reach. To ease the determination of the coupling connections between both meshes, BASEMENT offers an automatic detection mechanism.

7.1.3.2 Automatic generation of coupling connections

The automatic detection and generation of coupling connections is based on a search algorithm. It searches from the left and right dyke of each 1D cross section for the nearest 2D boundary edges within a specified distance.

```
COUPLING_LATERAL {
            ...
connections_automatic = yes
connections_distance = 30
connections_index = ( 6 )
...
}
```

To use the automatic detection, insert the tag *connections_automatic = yes* in the COUPLING_LATERAL block. Furthermore, you need to set a *connection_distance*, which defines the search distance in which it is searched for 2D boundary edges (If you choose the distance too small, some 2D boundary edges may not be connected to a cross-section!). In addition, you can limit the detection of 2D boundary edges to a list of cell material indices. Using this option, you can easily prevent some areas from being automatically connected and from taking part in the lateral coupling by setting corresponding material indices.

The general workflow of the automatic connection detection is as follows:

1. Open the model file in BASEMENT and set the tag: *conections_automatic = yes.*
2. Write the *setup.h5* file. On the simluation tab, Run BASEMENT. The program will automatically search for the connections and write the detected connections to file and then terminates. The simulation will then abort with the error *ERROR -> Please check the created lateral connections in the file 'lateral_connections_created.dat' and*

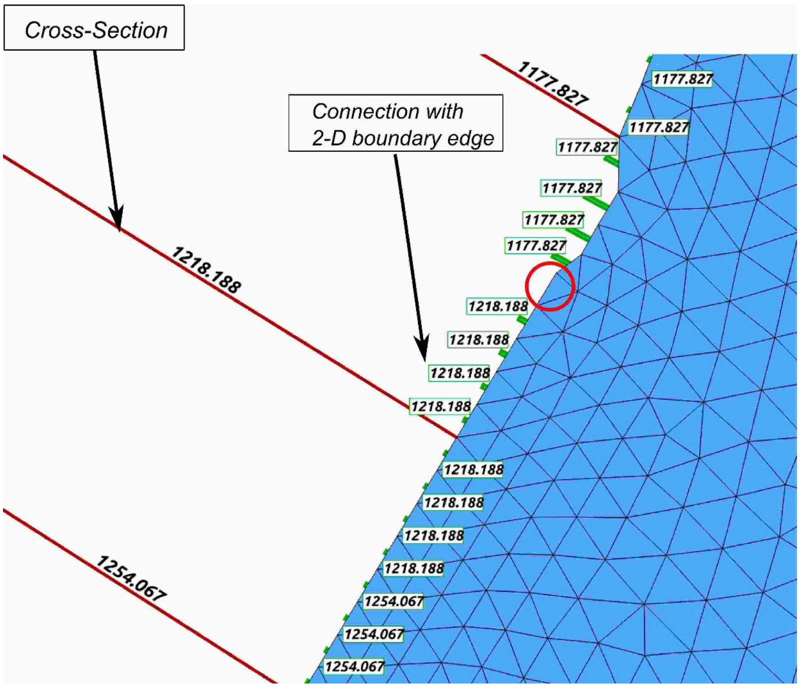


Figure 7.5 *1D cross sections (red) connected to 2D boundary edges (blue mesh) via coupling connections (green). The labels show the cross-section names and indicate the corresponding mapping of the 2D edge -> 1D cross-section. The red circle indicates a 2D boundary edge without a coupling connection, which is not taking part in the lateral coupling.*

restart with 'connectons_automatic = no' using the created file. Note: Automatic creation of lateral connections may have failed. This error is normal. Three files are written related to generation of the connections:

- lateral_connections_created.dat = the coupling connection file,
- lateral_connections_stats.shp = shapefile for visualizing the generated connections using GIS-software,
- lateral_connections_stats.txt = tab-deliminated text file for visualizing the generated connections with other software.

3. In the model file, set the tag: *conections_automatic = no.* Set the tag: *conections_filename = yes.*

The connections are shown as green lines in Figure 7.5 and are drawn from the middle of each 2D boundary edge orthogonal to the imaginary line between the dykes of two neighboured cross-sections. (These green lines should be as short as possible in order to minimize gaps and overlapping areas of the 1D and 2D meshes).

If the connections are set-up correctly in the connections file, then enter its name in the corresponding tag in the COUPLING_LATERAL-block and de-activate the automatic generation of connections:

```
connections_filename  = lateral_connections_created.dat
connections_automatic = no
```

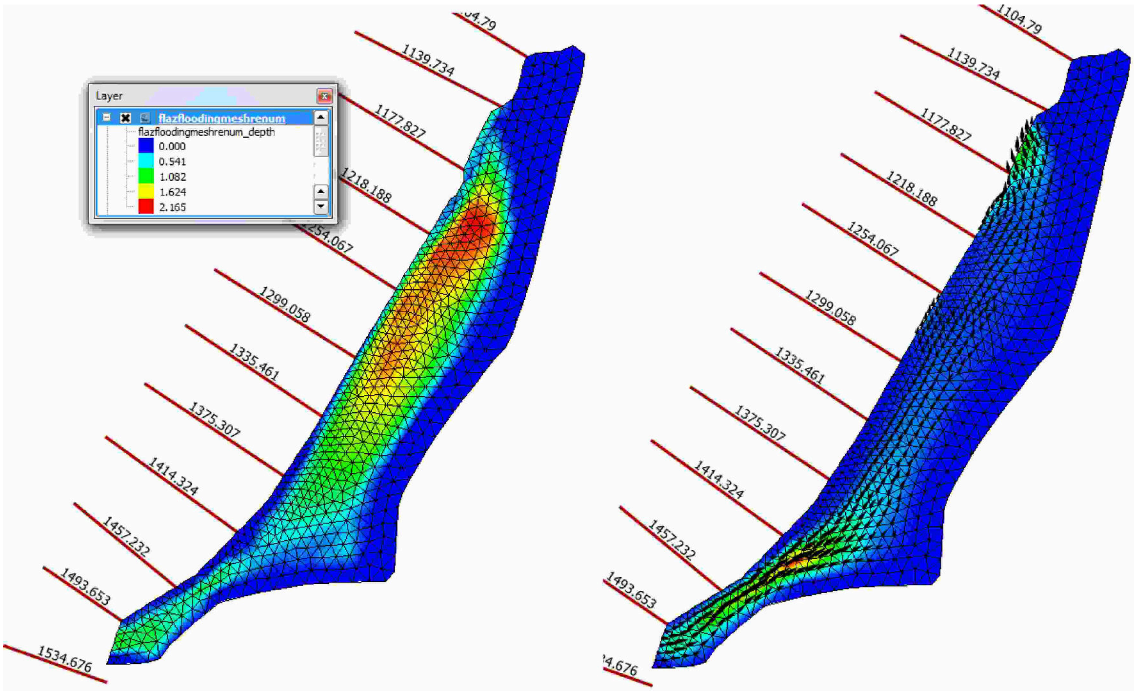


Figure 7.6 *Computed water depths (left) and velocity vectors (right) in the floodplain at steady-state conditions. Water enters the floodplain at the lower left and leaves it at the upper right.*

7.1.4 Perform coupled simulation

Run the simulation with the BASEchain and BASEplane sub-domains connected via the COUPLINGS-block. Be aware that the mesh files, the model file, the coupling connections file and all other input files have to be in the same folder. The defined outputs will also be written into the same folder. The computed water depths (left) and velocities (right) of the steady-state simulation are shown in Figure 7.6. The water enters the floodplain at the lower left, flows through the floodplain and leaves it at the upper right by overtopping the dyke into the river channel.

To check if the water mass balance is fulfilled, we can simply check the inflow and outflow of the 1D model. Both must have the same value, since the water discharges leaving and entering the 1D model over the dykes cancel out to zero during steady-state conditions.

8

Vegetation dynamics and bedload transport

8.1 Vegetation dynamics and bedload transport

8.1.1 Introduction

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

8.1.2 Computational Mesh

The computational mesh of the Alpine Rhine river was created ad-hoc to show the main model functionalites with the vegetation module activated and for application with BASEMENT version 3. The mesh has 9799 number of cells with 5149 vertex. The MATID was defined on the gravel bars, the main channel, and the banks to differentiate the bed properties. Figure 8.1 shows the bed elevation of the river used in the simulation.

8.1.3 Morphology with Vegetation

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

The setup of the configuration files follows the same procedure seen in the Flaz tutorial for hydrualics and morphology (Section 3.1.3.1 and Section 3.1.4.1). Here only the vegetation part is shown in detail.

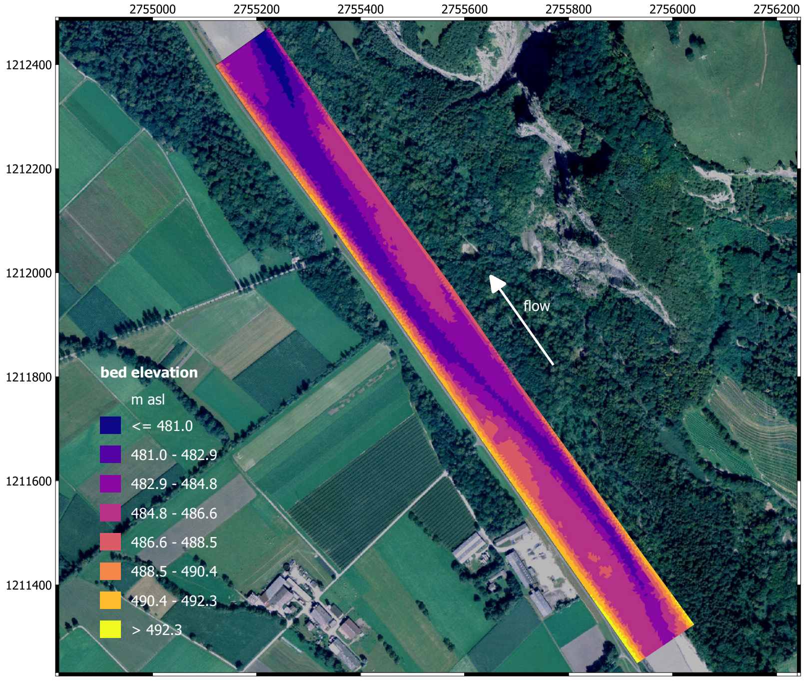


Figure 8.1 *Planar view of the initial bottom elevation of the Alpine Rhine river*

8.1.3.1 Setup the Configuration File model.json

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

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

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

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

In this tutorial the vegetation was placed only in the gravel bars and using different charactieristics for each of the bar (Figure 8.2). It is important that the sum of the aboveground and belowground biomass equal 1 at maximum. The biomass values are dimensionless, while the rooting depth is expressed in meter.

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

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

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

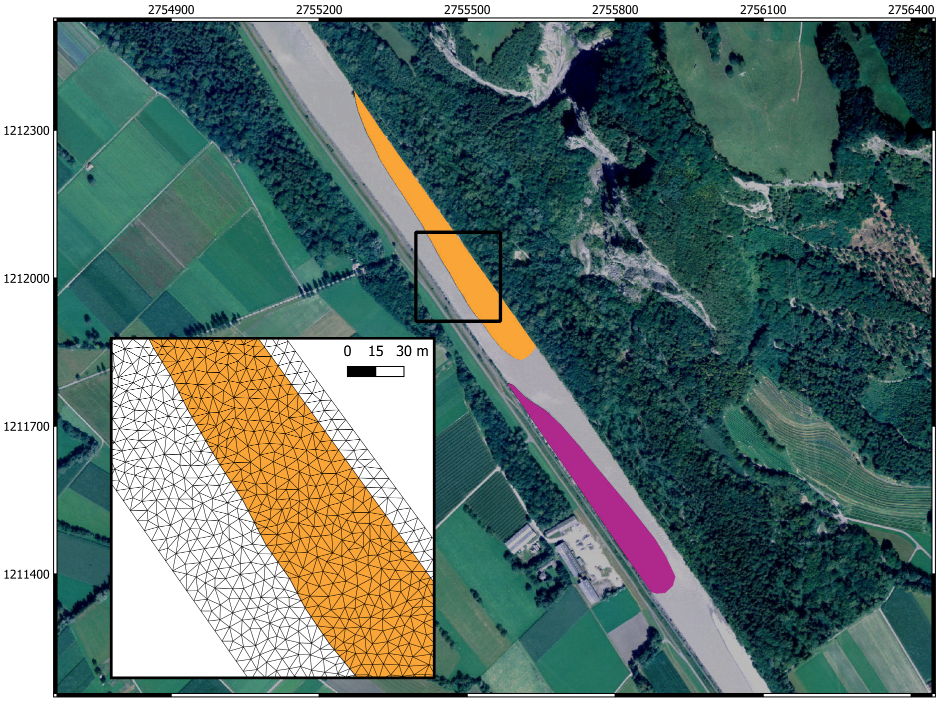


Figure 8.2 *Initial location of vegetation on the two bars and an extract of the computational mesh used.*

8.1.3.2 Setup the Configuration File simulation.json

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

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

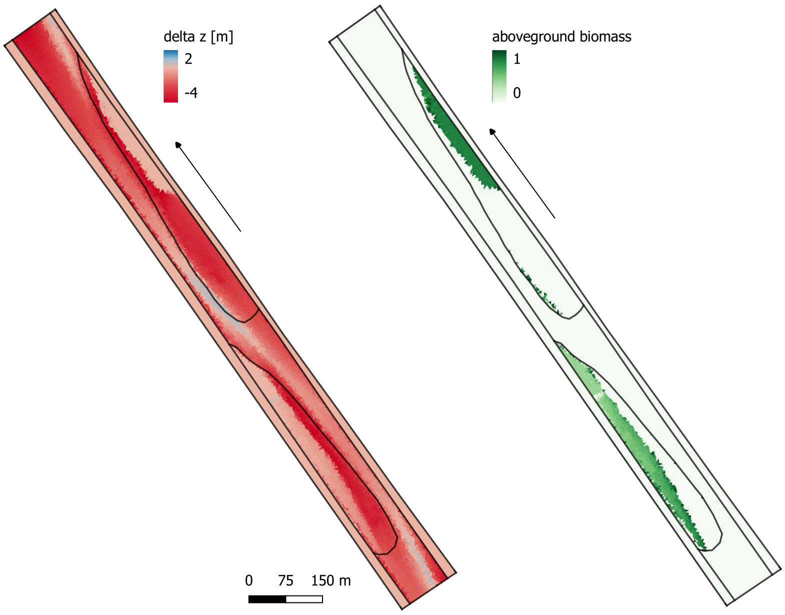


Figure 8.3 *Results for the bed elevation and the aboveground biomass after the flood (at t=111600 s). Breaklines are highlighted in black.*

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

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

8.1.3.3 Set up the Configuration File results.json

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

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

8.1.3.4 Results

An example of the results of the simulation of the 2005 flood in the Alpine Rhine river considering vegetation is shown in Figure 8.3. Vegetation is removed in most parts of the bars as a result of uprooting, while the aboveground biomass of surviving vegetation changed because of erosion and deposition processes, which modify biomass redistribution.

9

References

BASIC SIMULATION ENVIRONMENT
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APPENDIX

VERSION 4.0
FEBRUARY 2023

1

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File: aclocal.m4 (only for ICU4C)
Section: pkg.m4 - Macros to locate and utilise pkg-config.

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Pcre2

```
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-------------

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

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The basic library functions are written in C and are freestanding. Also
included in the distribution is a just-in-time compiler that can be used to
optimize pattern matching. This is an optional feature that can be omitted when
the library is built.


THE BASIC LIBRARY FUNCTIONS
---------------------------

Written by:       Philip Hazel
Email local part: Philip.Hazel
Email domain:     gmail.com

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PCRE2 JUST-IN-TIME COMPILATION SUPPORT
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Written by:       Zoltan Herczeg
Email local part: hzmester
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STACK-LESS JUST-IN-TIME COMPILER
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End
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Pegtl-2

```
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        recombine or relink the Application with a modified version of
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        the Linked Version to produce a modified Combined Work, in the
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        Corresponding Source.

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        computer system, and (b) will operate properly with a modified
        version of the Library that is interface-compatible with the
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    of the GNU GPL, and only to the extent that such information is
    necessary to install and execute a modified version of the
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    with a modified version of the Linked Version. (If you use option
    4d0, the Installation Information must accompany the Minimal
    Corresponding Source and Corresponding Application Code. If you
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Qwt

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Qwt License
                           Version 1.0, January 1, 2003

The Qwt library and included programs are provided under the terms
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exceptions:
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    1. Widgets that are subclassed from Qwt widgets do not
       constitute a derivative work.

    2. Static linking of applications and widgets to the
       Qwt library does not constitute a derivative work
       and does not require the author to provide source
       code for the application or widget, use the shared
       Qwt libraries, or link their applications or
       widgets against a user-supplied version of Qwt.

       If you link the application or widget to a modified
       version of Qwt, then the changes to Qwt must be
       provided under the terms of the LGPL in sections
       1, 2, and 4.

    3. You do not have to provide a copy of the Qwt license
       with programs that are linked to the Qwt library, nor
       do you have to identify the Qwt license in your
       program or documentation as required by section 6
       of the LGPL.


       However, programs must still identify their use of Qwt.
       The following example statement can be included in user
       documentation to satisfy this requirement:

           [program/widget] is based in part on the work of
           the Qwt project (http://qwt.sf.net).

----------------------------------------------------------------------


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    is invoked, then you must make a good faith effort to ensure that,
    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
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    be optional: if the application does not supply it, the square
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  4. You may copy and distribute the Library (or a portion 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
creates an executable that is a derivative of the Library (because it
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contains portions of the Library), rather than a "work that uses the
library".  The executable is therefore covered by this License.
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
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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
distribute the object code for the work under the terms of Section 6.
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whether or not they are linked directly with the Library itself.

  6. As an exception to the Sections above, you may also combine or
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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
    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) Use a suitable shared library mechanism for linking with the
    Library.  A suitable mechanism is one that (1) uses at run time a
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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
    the user installs one, as long as the modified version is
    interface-compatible with the version that the work was made with.

    c) Accompany the work with a written offer, valid for at
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    specified materials from the same place.

    e) Verify that the user has already received a copy of these
    materials or that you have already sent this user a copy.
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  For an executable, the required form of the "work that uses the
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which the executable runs, unless that component itself accompanies
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  It may happen that this requirement contradicts the license
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Shapelib

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Zlib

ZLIB DATA COMPRESSION LIBRARY

zlib 1.2.12 is a general purpose data compression library. All the code is
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(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
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.
```

```
If you use the zlib library in a product, we would appreciate *not* receiving
lengthy legal documents to sign.  The sources are provided for free but without
warranty of any kind.  The library has been entirely written by Jean-loup
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and which are not combined with it such as to form a larger program,
in or on a volume of a storage or distribution medium, is called an
"aggregate" if the compilation and its resulting copyright are not
used to limit the access or legal rights of the compilation's users
beyond what the individual works permit.  Inclusion of a covered work
in an aggregate does not cause this License to apply to the other
parts of the aggregate.

  6. Conveying Non-Source Forms.

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

    a) Convey the object code in, or embodied in, a physical product
    (including a physical distribution medium), accompanied by the
    Corresponding Source fixed on a durable physical medium
    customarily used for software interchange.

    b) Convey the object code in, or embodied in, a physical product
    (including a physical distribution medium), accompanied by a
    written offer, valid for at least three years and valid for as
    long as you offer spare parts or customer support for that product
    model, to give anyone who possesses the object code either (1) a
    copy of the Corresponding Source for all the software in the
    product that is covered by this License, on a durable physical
    medium customarily used for software interchange, for a price no
    more than your reasonable cost of physically performing this
    conveying of source, or (2) access to copy the
    Corresponding Source from a network server at no charge.

    c) Convey individual copies of the object code with a copy of the
    written offer to provide the Corresponding Source.  This
    alternative is allowed only occasionally and noncommercially, and
    only if you received the object code with such an offer, in accord
    with subsection 6b.

    d) Convey the object code by offering access from a designated
    place (gratis or for a charge), and offer equivalent access to the
    Corresponding Source in the same way through the same place at no
    further charge.  You need not require recipients to copy the
    Corresponding Source along with the object code.  If the place to
    copy the object code is a network server, the Corresponding Source
    may be on a different server (operated by you or a third party)
    that supports equivalent copying facilities, provided you maintain
    clear directions next to the object code saying where to find the
    Corresponding Source.  Regardless of what server hosts the
    Corresponding Source, you remain obligated to ensure that it is
    available for as long as needed to satisfy these requirements.
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    e) Convey the object code using peer-to-peer transmission, provided
    you inform other peers where the object code and Corresponding
    Source of the work are being offered to the general public at no
    charge under subsection 6d.

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

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

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

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

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

  Corresponding Source conveyed, and Installation Information provided,
in accord with this section must be in a format that is publicly
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    its purpose remains meaningful.

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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
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 combine 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
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copyright notice for the Library among them, as well as a reference
directing the user to the copy of this License.  Also, you must do one
of these things:

    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) Use a suitable shared library mechanism for linking with the
    Library.  A suitable mechanism is one that (1) uses at run time a
    copy of the library already present on the user's computer system,
    rather than copying library functions into the executable, and (2)
    will operate properly with a modified version of the library, if
    the user installs one, as long as the modified version is
    interface-compatible with the version that the work was made with.

    c) 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
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    d) 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.

    e) 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 materials to be distributed need not include anything that is
normally distributed (in either source or binary form) with the major
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which the executable runs, unless that component itself accompanies
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