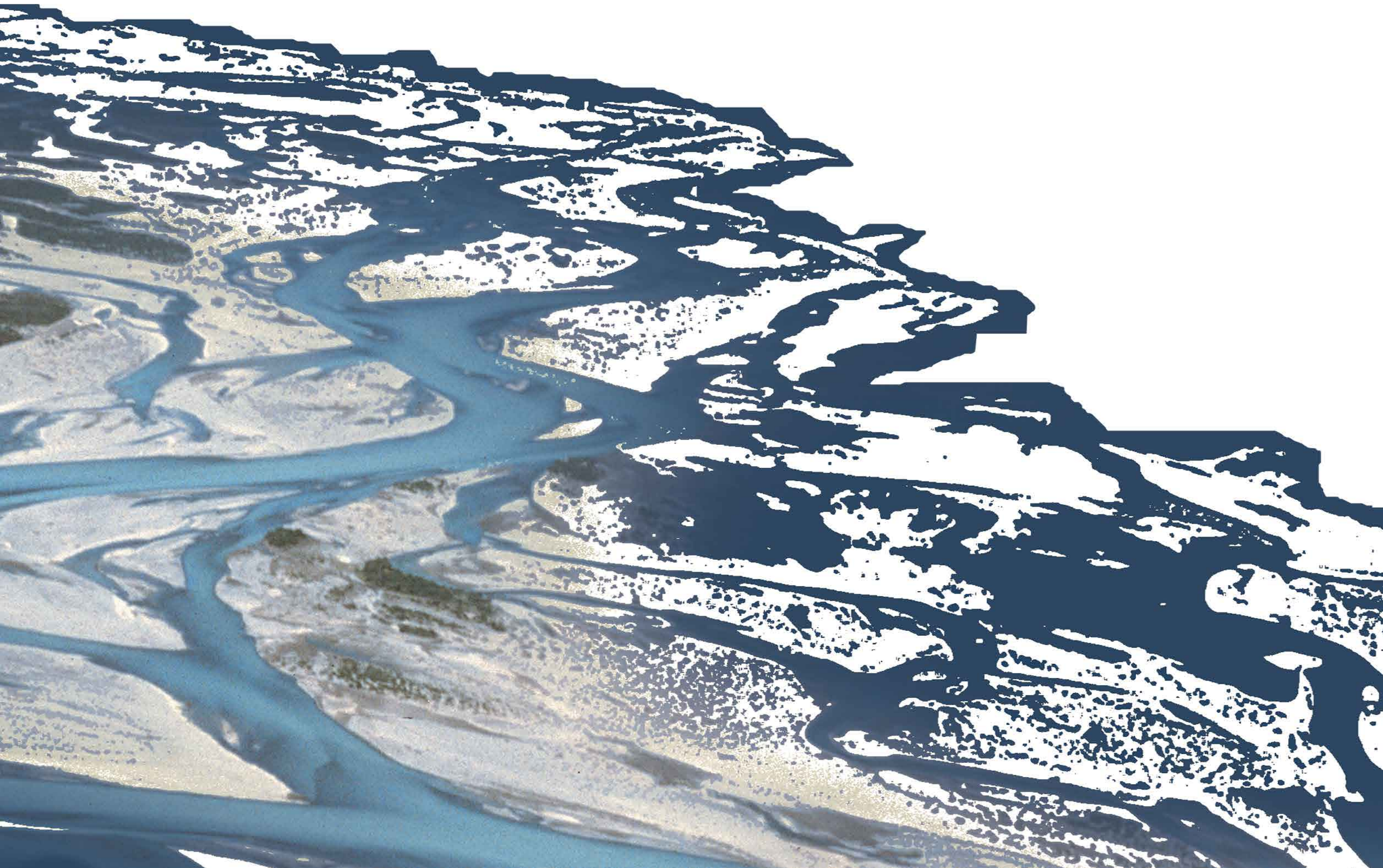
BASEMENT

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

SYSTEM MANUALS

VERSION 3.1
November 2020



Preamble

VERSION 3.1.1

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For Website:

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For Software:

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

TUTORIALS & TEST CASES

VERSION 3.1
November 2020

Contents

1

Tutorials

1.1 Hydrodynamics and sediment transport at the river Flaz

1.1.1 Introduction

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

1.1.2 Computational Mesh

The computational mesh of the Flaz is imported from the tutorial of BASEMENT version 2.8. The 2dm file has been modified as explain in the pre-processing tutorial for small meshes in the User manual. There are two stringdefs for the inflow and outflow boundaries. The mesh has 14’457 cells, 7’446 vertices and the interpolation method “weighted” is used to convert the mesh from version 2.8 to a 3 compatible computational mesh. Figure 1.1 shows the bottom elevation of the river Flaz used in this tutorial.

1.1.3 Hydraulics

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

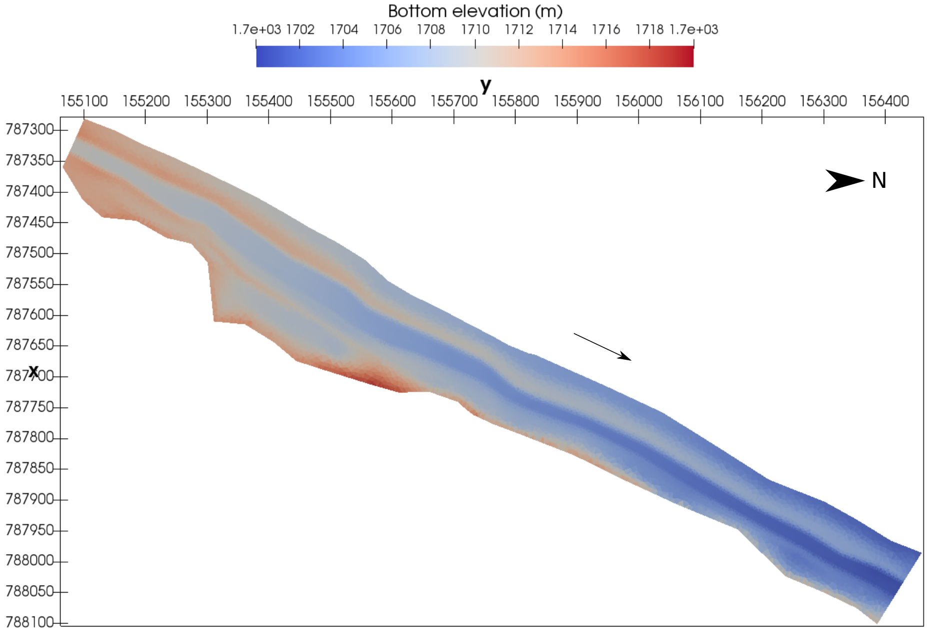


Figure 1.1 *Planar view of the initial bottom elevation of the river Flaz*

1.1.3.1 Setup the Configuration File model.json

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

```
{
   "SETUP":{
        "simulation_name":"Flaz_steady_state",
        "DOMAIN": {
            "PHYSICAL_PROPERTIES": {...},
            "BASEPLANE_2D": {
                "GEOMETRY": {...},
                "HYDRAULICS": {
                    "PARAMETER": {...},
                    "FRICTION": {...},
                    "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, BOUNDARY for the flow conditions and INITIAL for the condition at time t=0.0.

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

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

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

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

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

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

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

1.1.3.2 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",
```

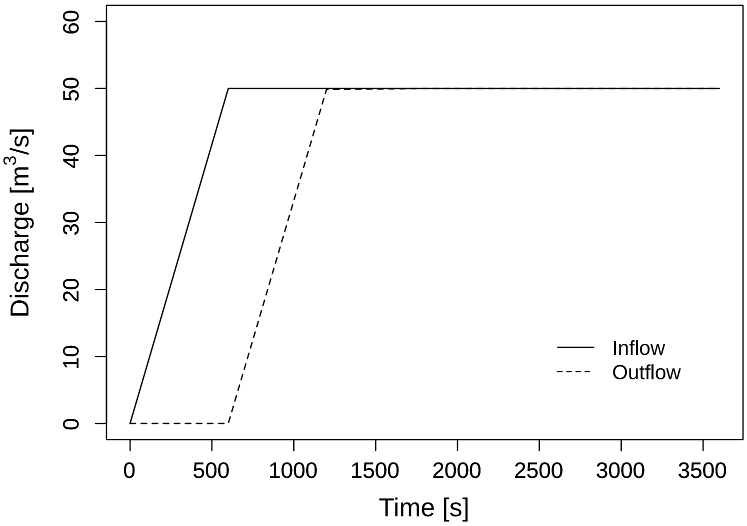


Figure 1.2 *Inflow and outflow hydrograph at boundaries*

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

1.1.3.3 Set up the Configuration File results.json

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

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

1.1.3.4 Steady Flow Simulation

The simulation results are stored inside the results.h5 binary. By calling the python script BMv3NodestringResults.py available on the BASEMENT Website, the discharge values at boundaries are extracted and stored in the Discharge.csv file, where the rows are the time steps and the columns represents the stringdef in their definition order (inside the .2dm file). The steady state is reached after 1200 seconds (Figure 1.2).

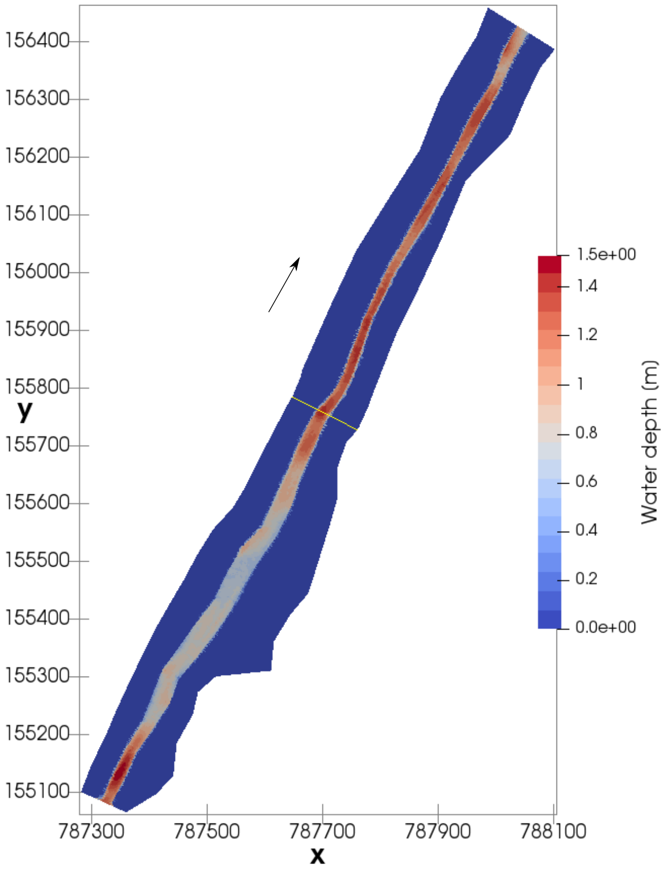


Figure 1.3 *Water depth at the end of the steady flow simulation (t=3600 s) with the cross section location (yellow line)*

1.1.3.5 Model Calibration

The calibration of the friction value is done by comparing the water surface elevation between BASEMENT version 3 and version 2.8 at a cross section located in the middle of the channel (Figure 1.3). The water surface elevation and the water depth values along the cross section were obtained using the software ParaView.

The resulting water depth and water surface elevation are compared in Figure 1.4. The steady flow simulation of BASEMENT version 3 provides similar results to those obtained with BASEMENT version 2.8. There is no need to modify the friction value defined in Section 1.1.3.1.

1.1.3.6 Unsteady Flow Simulation

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

```
"INITIAL":{
```

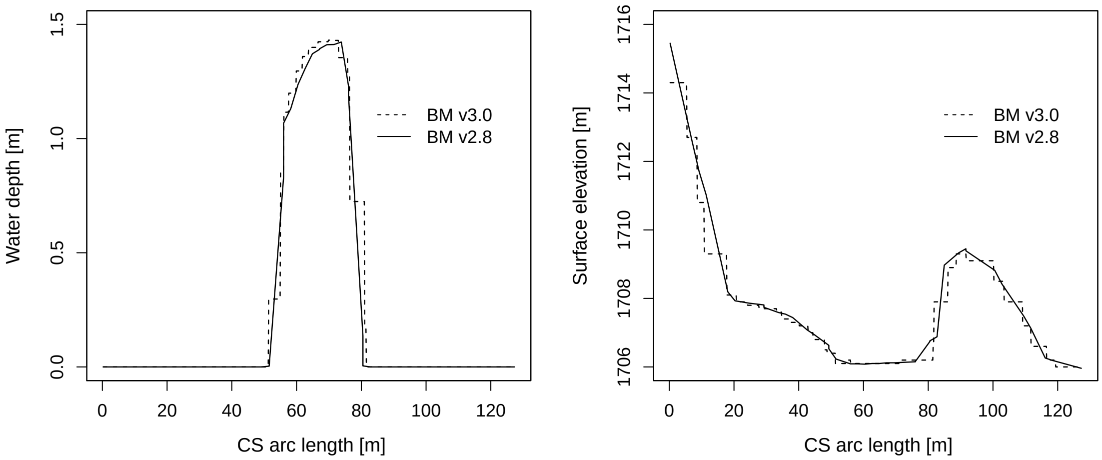


Figure 1.4 *Cross sectional view of the water depth and surface elevation facing the opposite flow direction at the end of the steady flow simulation (t=3600 s)*

```
        "type": "continue",
        "file": "../run/Flaz_steady_state_results.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.

1.1.4 Morphology

1.1.4.1 Setup the Configuration File model.json

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

```
{
```

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

Inside the morphology block, the initial conditions look like:

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

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

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

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

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

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

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

```
"BEDLOAD": {
                        "FORMULA": {
                            "type": "MPM_like",
                            "factor":1.0,
                            "coefficient":3.2,
                            "exponent":1.6,
                            "critical_value":0.047
                        },
                        "BOUNDARY":{
                            "STANDARD": [
                                {
                                    "name": "inflow_MOR",
```

```
                                    "string_name": "Inflow",
                                    "type": "transport_capacity",
                                    "boundary_factor": 0.8
                                },
                                {
                                    "name": "outflow_MOR",
                                    "string_name": "Outflow",
                                    "type": "equilibrium_out",
                                    "reference_bed_elevation": 1700.68
                                }
                            ]
                        },
                        "DIRECTION": {
                            "LATERAL_SLOPE": {
                                "factor": 1.5
                            }
                        }
                    }
```

1.1.4.2 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"
        ]
    }
}
```

1.1.4.3 Results

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

1.1.5 Passive tracers

1.1.5.1 Setup the Configuration File model.json

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

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

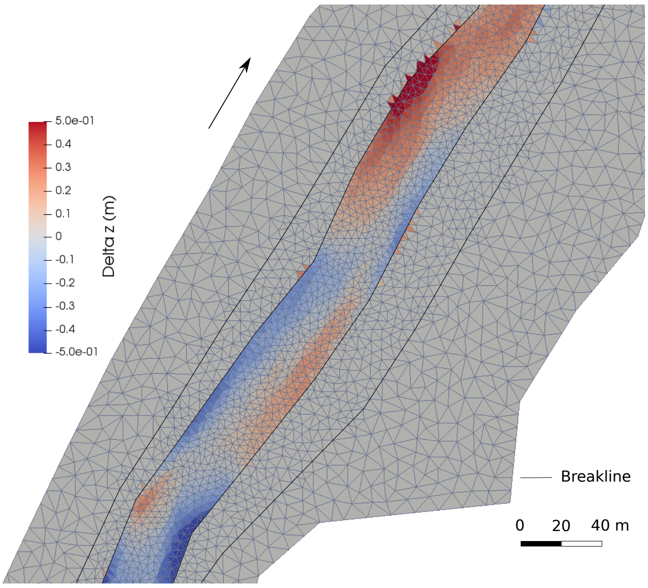


Figure 1.5 *Planar view of the widening part of the river Flaz with the change in bed elevation (Delta z) due to the flood event at the end of the morphodynamic simulation (t= 84'000 s)*

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

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

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

"BOUNDARY":{
  "STANDARD": [
  { "name": "tracer_inflow",
```

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

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

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

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

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

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

A source block within the tracers block would look like:

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

```
      "region_name": "one",
      "sink": "exact" }
    ]
```

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

1.1.5.2 Setup the Configuration File simulation.json

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

```
{
    "SIMULATION":{
        "TIME": {
            "start": 0.0,
            "end": 3600,
            "out": 600
        },
        "OUTPUT": [
            "water_surface",
            "flow_velocity_abs",
            "ns_hyd_discharge",
            "bottom_elevation",
            "spec_discharge",
            "water_depth",
            "tracer1",
            "tracer2",
            "tracer3"
        ]
    }
}
```

1.1.5.3 Set up the Configuration File results.json

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

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

1.2 Post-Processing

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

1.2.1 ParaView

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

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

1.2.2 Extract Data from Result File

This tutorial shows how to extract values from the stringdefs, i.e. boundaries to obtain the results of Figure 1.2. The python script BMv3NodestringResults.py can be downloaded from www.basement.ethz.ch and should be saved inside the scenario directory generated. The python script will read the stringdef data stored inside the _results.h5 file and convert them into a delimited text format (.csv). The data calculated at the stringdef are the discharge [m^3/s], the mean water surface elevation (wse) [m], the wetted area [m^2], the mean bottom elevation [m], reference elevation (talweg) [m], wetted geometric length [m], total water volume stored in cells of the stringdef [m^3], total conveyance of cells [m^3/s], the morphological flux [m^3/s] and the bedload transport capacity [m^3/s].

To generate the .csv text file:

1. Save the BMv3NodestringResults.py file inside the scenario directory
2. Open a command window
3. Change folder and go inside the scenario directory
4. Call the python script with

```
$ python BMv3NodestringResults.py
```

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

2

Test cases

2.1 Introduction and Backends

2.1.1 Introduction

The test cases present well-defined hydro- and morphodynamic numerical simulations that are used to asses the performance and accuracy of the simulations with BASEMENT version 3. The test cases have an analytical solution to which the numerical solution is compared in order to evaluate the accuracy of the results. The numerical simulations are executed on different backends that influence the performance of the simulation.

2.1.2 Backends

Different backends are used to execute the simulations of the test cases. The different backends are: a central processing unit (CPU) with a sequential application on 1 core, CPU with parallel applications (OpenMP) on 2, 4, 8, 16 and 32 cores and graphic processing units (GPU) with a compute unified device architecture (CUDA) with single and double precision. The features of the GPU card are shown in Table 2.1.

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

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

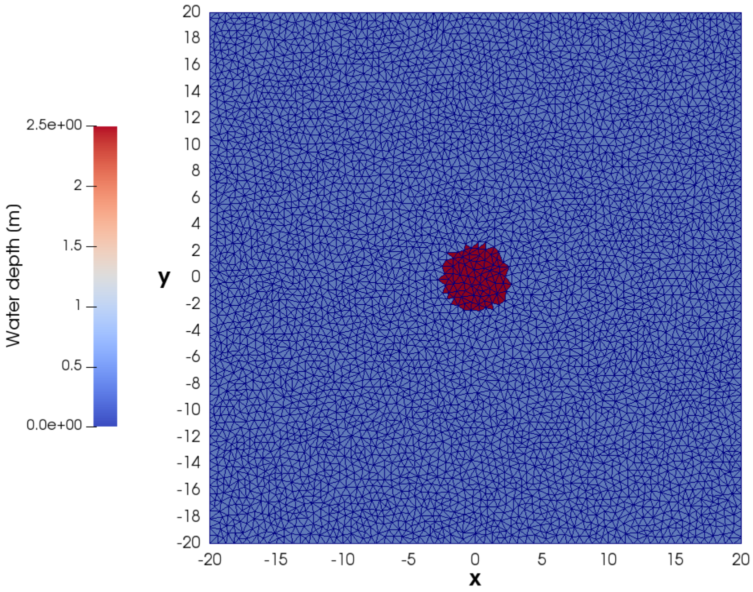


Figure 2.1 *Computational domain of the circular dam break (10k cells) with initial water depth.*

2.2 Circular dam break

2.2.1 Description

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

2.2.2 Geometry and Initial Conditions

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

2.2.3 Results

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

The results on Figure 2.2 show how the solution obtained with BASEMENT version 3 (first order HLLC method) correctly converges to the reference solution as the grid is refined. The cylindrical symmetry of the wave propagation in BASEMENT is maintained, even if water surface modulations are observed along the primary shock wave.

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

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

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

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

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

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

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

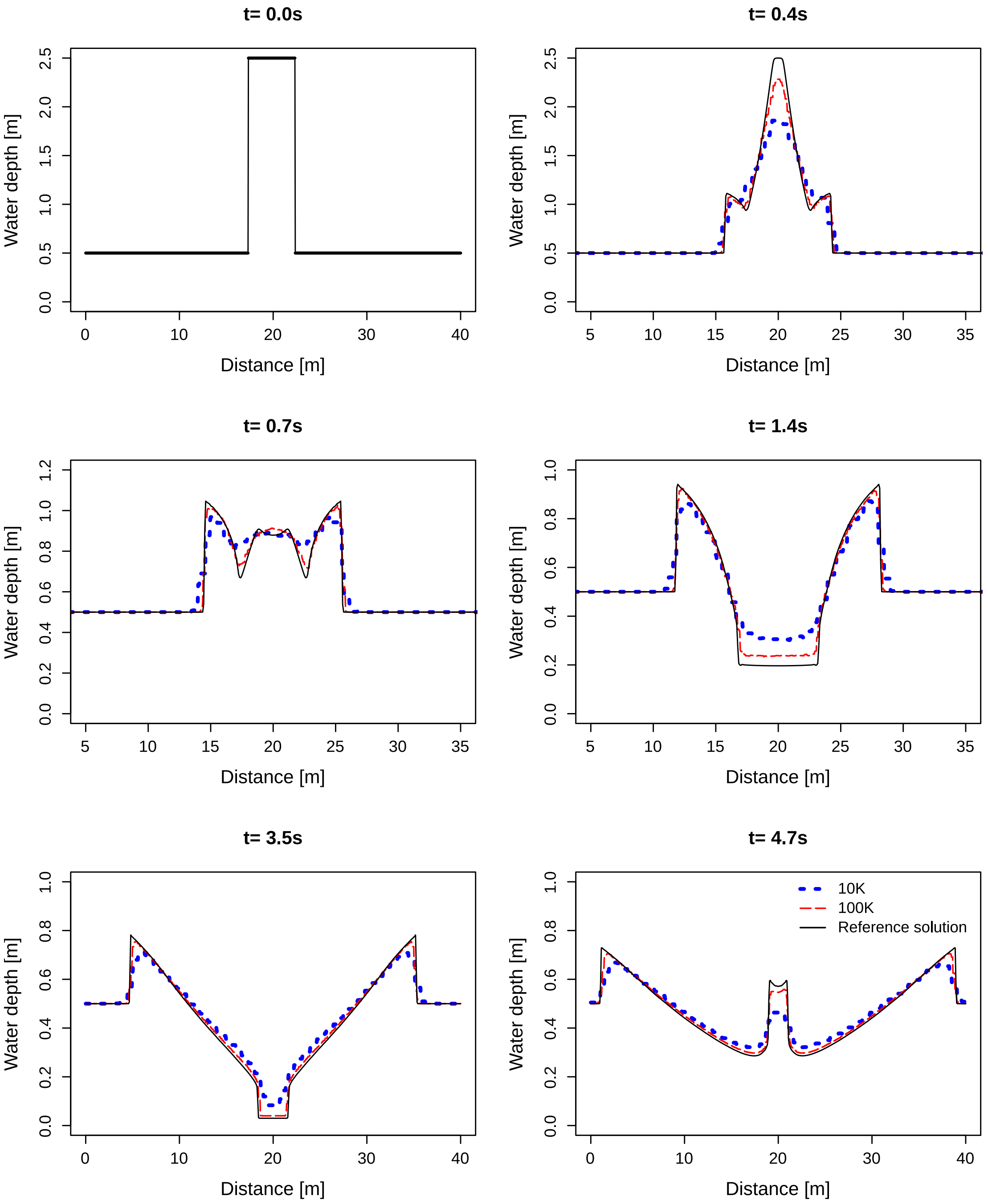


Figure 2.2 *Snapshots of the water depth evolution along the reference cross-section. Comparison between BASEMENT simulations with a computational grid of 10k cells, 100k cells and the reference solution of Toro (2001).*

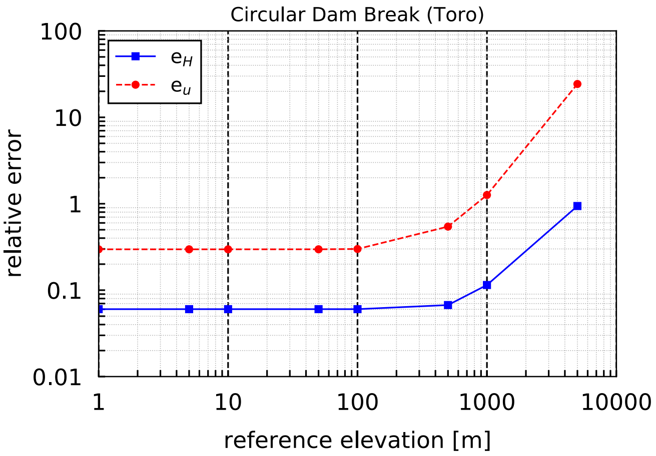


Figure 2.3 *Relative error compared to the reference solution of Toro (2001)*

2.2.4 Performance

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

2.2.4.1 Ubuntu

Tables 2.4, 2.5 and 2.6 contain the execution time and speedup of all the simulations performed on different backends under Linux. The backends belong to two cathegories, either in Central Processor Units (CPU) or Graphics Processor Units (GPU). The CPU run simulations exclusively with double precision, while GPU can perform simulations with single or double precision. More details are explained in Section 2.1.2.

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

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
10k	0.16	0.19 (1.49x)	0.11 (2.46x)	0.07 (3.33x)	0.04 (4.18x)	0.03 (5.31x)
50k	1.88	1.08 (1.73x)	0.57 (3.29x)	0.33 (5.70x)	0.20 (9.31x) (	0.15 12.68x)
100k	5.44	3.06 (1.77x)	1.62 (3.35x)	0.89 (6.12x)	0.52 (10.4x) (	0.35 15.47x)
500k	63.63	34.49 (1.85x)	17.71 (3.59x)	9.28 (6.86x)	5.06 (12.57x)	3.07 (20.72x)
1000k	190.39	101.66 (1.87x)	51.83 (3.67x)	26.98 (7.06x)	14.36 (13.26x)	8.75 (21.77x)

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

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

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

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

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

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

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

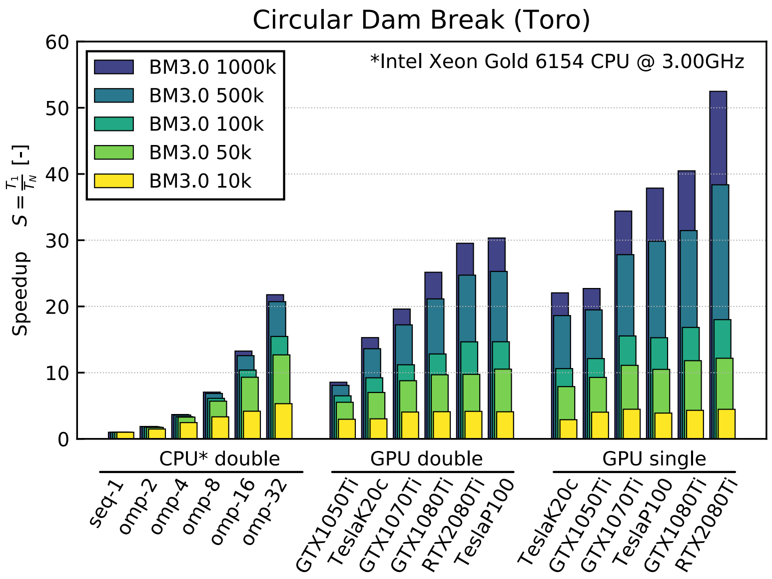


Figure 2.4 *Speedup for CPU (double precision) and GPU (single and double precision) backends for the circular dam break test case.*

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

Figure 2.4 shows the speedup achieved by the different backends. The sequential and OpenMP backends were run on processors of type Intel Xeon Gold 6154 (3.00GHz) with two sockets and with 18 cores per socket. The largest speedups are obtained for certain GPU cards using single precision. But also by using the GPU backend with double precision, the simulation time can be reduced significantly compared to sequential computation. It should be noted that the results of simulations with single and double precision can vary greatly depending on the problem. Further, it can be observed that the speedup greatly depends on the problem size. For smaller mesh, the speedup obtained by increasing the number of cores or by using GPU cards can be limited. The speedup increases particularly for meshes with a fine resolution (500K and 1000K) using GPU.

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

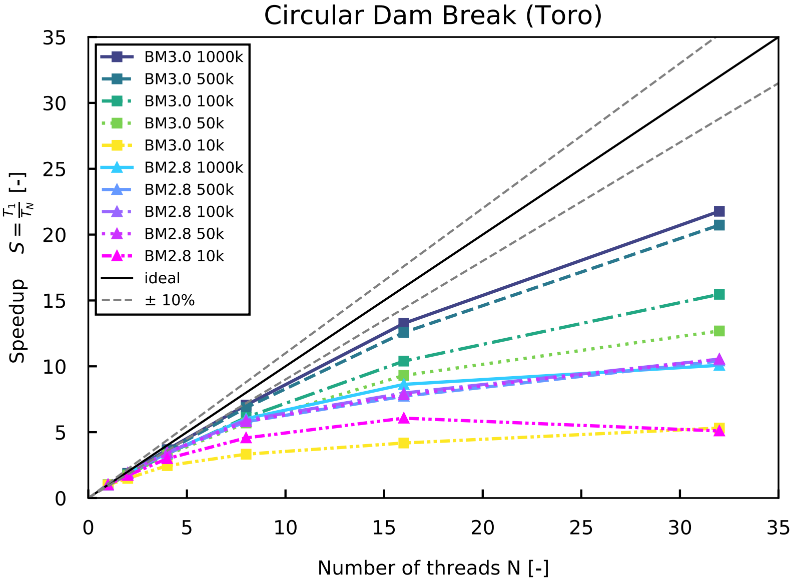


Figure 2.5 *Speedup of the computational time [T_N] using different number of threads (CPU) compared to the time of the sequential backend Xeon1 [T_1] for the circular dam break*

to a plateau.

2.2.4.2 Windows

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

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

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
10k	0.23	0.14 (1.67x)	0.08 (3.0x)	0.09 (2.49x)
50k	2.80	1.58 (1.77x)	0.98 (2.84x)	0.81 (3.44x)
100k	8.08	4.73 (1.71x)	3.16 (2.56x)	2.58 (3.13x)
500k	95.01	51.78 (1.83x)	30.55 (3.11x)	23.62 (4.02x)

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double
1000k	275.02	149.84 (1.84x)	90.00 (3.06x)	67.25 (4.09x)

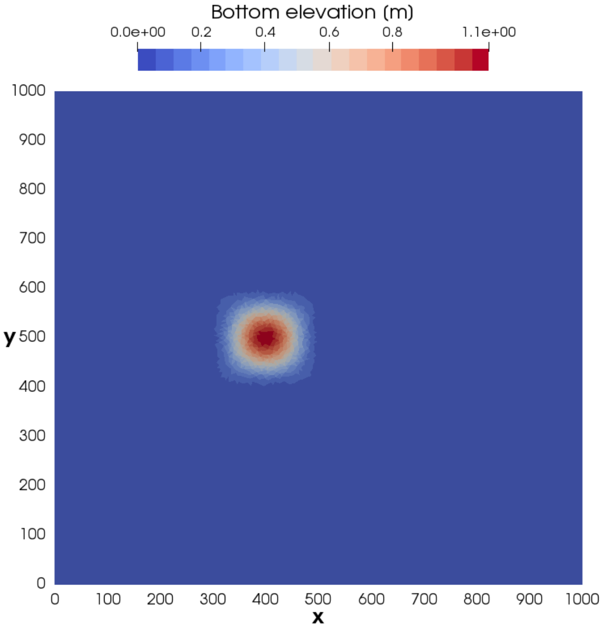


Figure 2.6 *Initial bottom elevation of the conical dune, maximum elevation of 1.1 m at [x=400, y=500].*

2.3 Conical Dune

2.3.1 Description

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

2.3.2 Geometry and Initial Conditions

The computational mesh is a squared area of size 1000 x 1000 m with an initial bottom elevation $z_{B,initial}$ (see Figure 2.6):

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

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

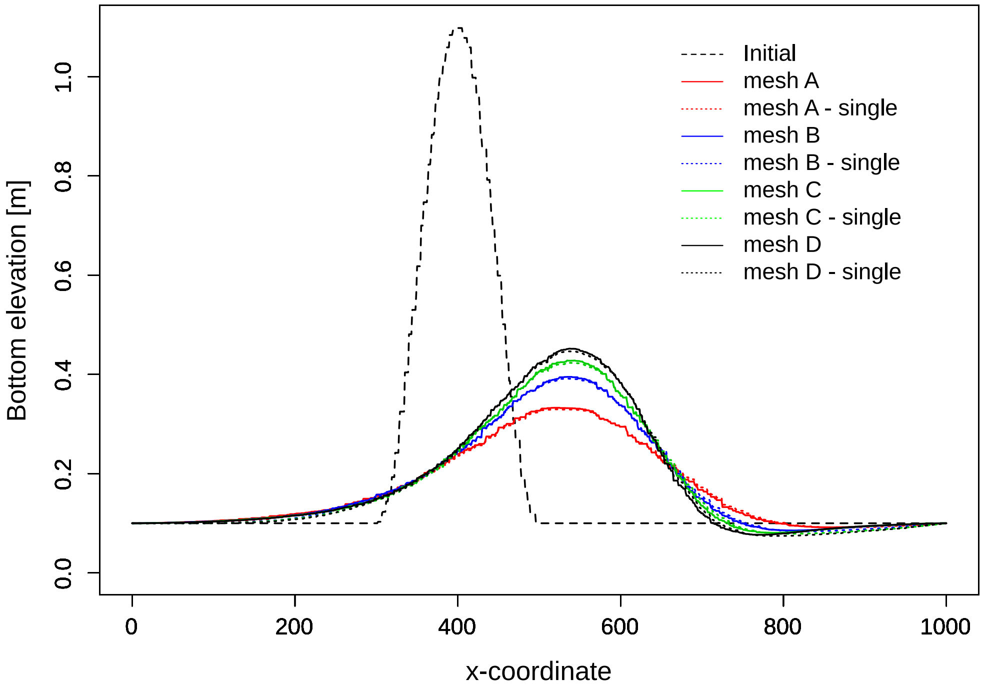


Figure 2.7 *Longitudinal bottom elevation profile at y= 500 m for initial conditions and after 100h of simulation for the meshes A, B, C and D with double and single precision*

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

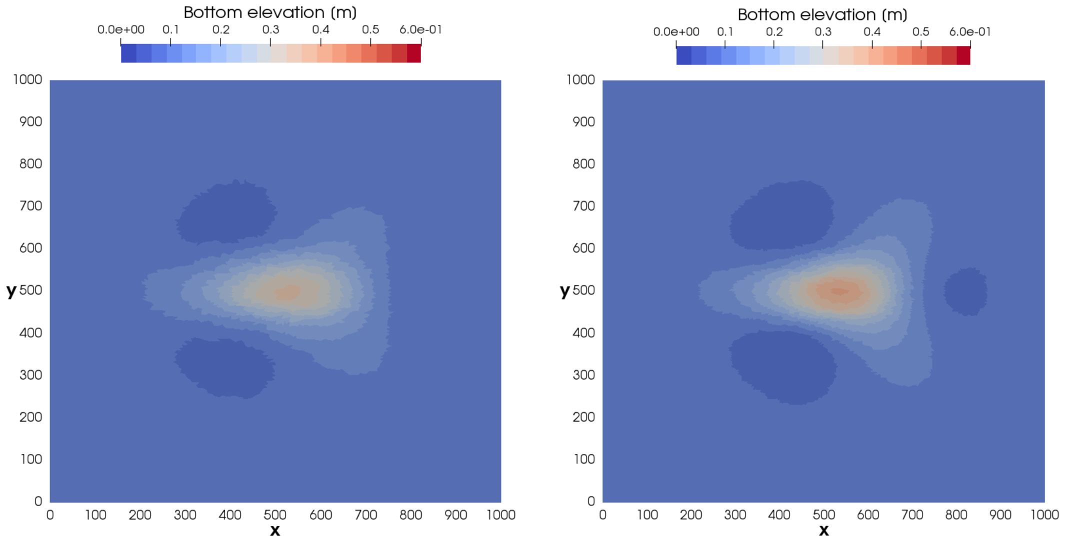
$$\alpha_s = arctan\left(\frac{3\sqrt{3}(m_G - 1)}{9m_G - 1}\right) \tag{2.4}$$

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

2.3.3 Results

Figure 2.7 shows the bed elevation profile at $y = 500$ m along the x-coordinates at the beginning and after 100 h of the simulation for the four different meshes (A, B ,C and D) performed with double and single precision. The results are exactly the same for all processor types, except for the simulation performed with CUDA-single, where the values are slightly different due to the reduced precision.

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



mesh A

mesh B

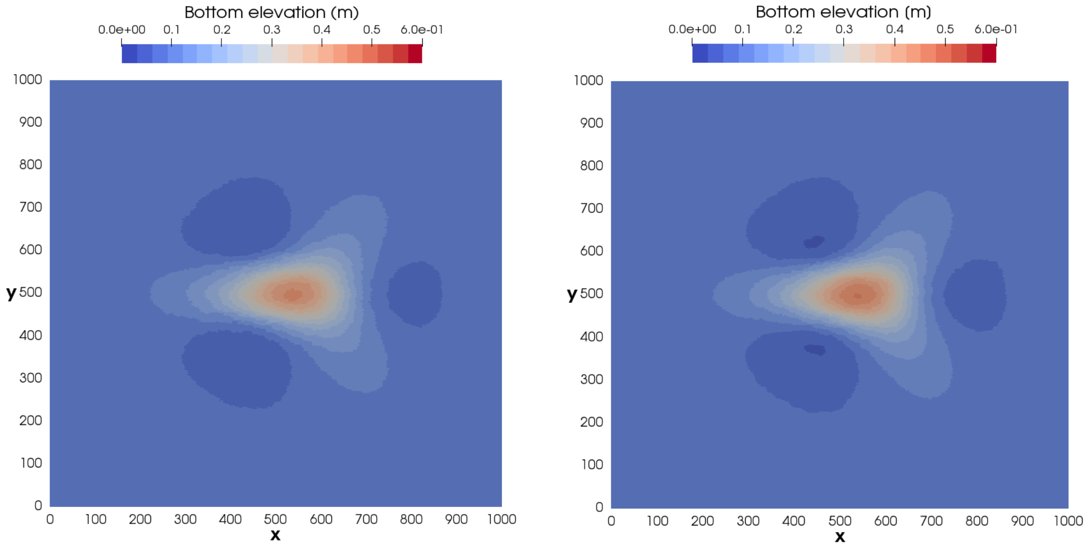
Figure 2.8 *Planar view of the bottom elevation after 100 hours of simulation for the meshes A and B.*

the different meshes using the backend types CPU and GPU-double. The spread angle α_s is measured between $y = 500$ m and the line passing through the initial conical dune center point and the farthest point in the x-direction where the conical dune spread for a similar bottom elevation (Figure 2.8 and Figure 2.9). The spread angle was measured at time t=25h, 50h, 75h and 100h for each mesh size and the mean value is reported in Table 2.8. The accuracy of the simulations is assessed by the relative deviation between the measure spread angle α_s and the spread angle defined by de Vriend (1987) $\alpha_{s,ref}$.

Table 2.8 *Summary of the simulation results performed with CPU and GPU double at t=100h for different computational meshes*

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

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



mesh C

mesh D

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

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

2.4.1 Description

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

2.4.2 Geometry and initial conditions

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

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

2.4.3 Results

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

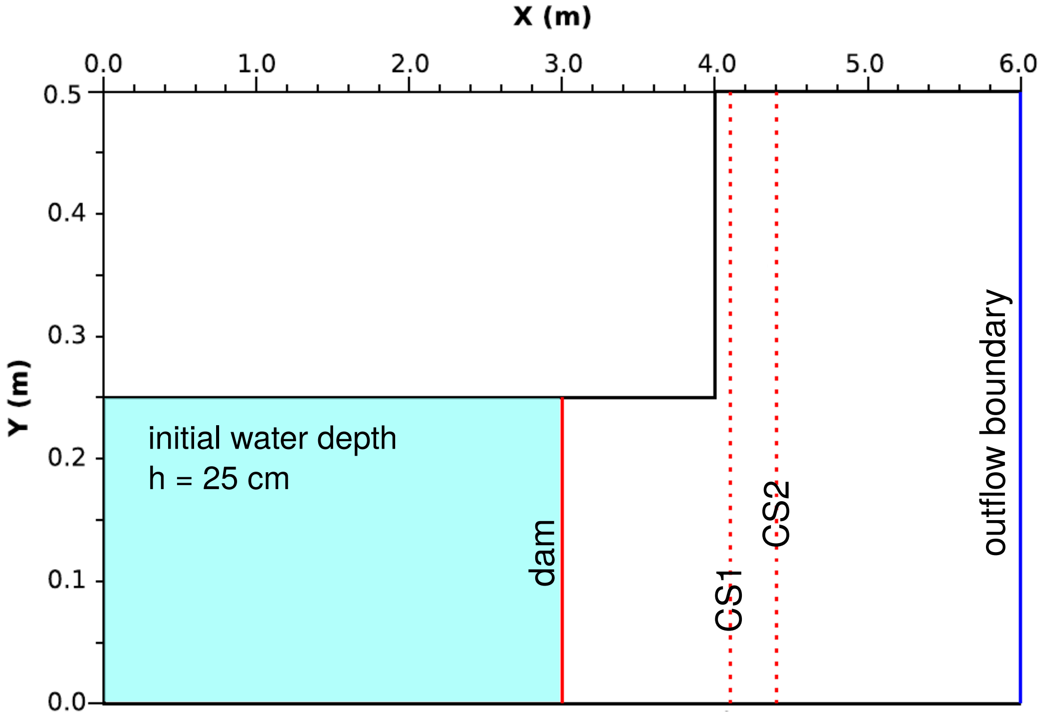


Figure 2.10 *The numerical test setup for the dam-break flow in a L-shaped channel with a mobile-bed. Experimental and numerical bed elevations are compared along cross-sections CS1 and CS2. Modified from Siviglia et al. (2013).*

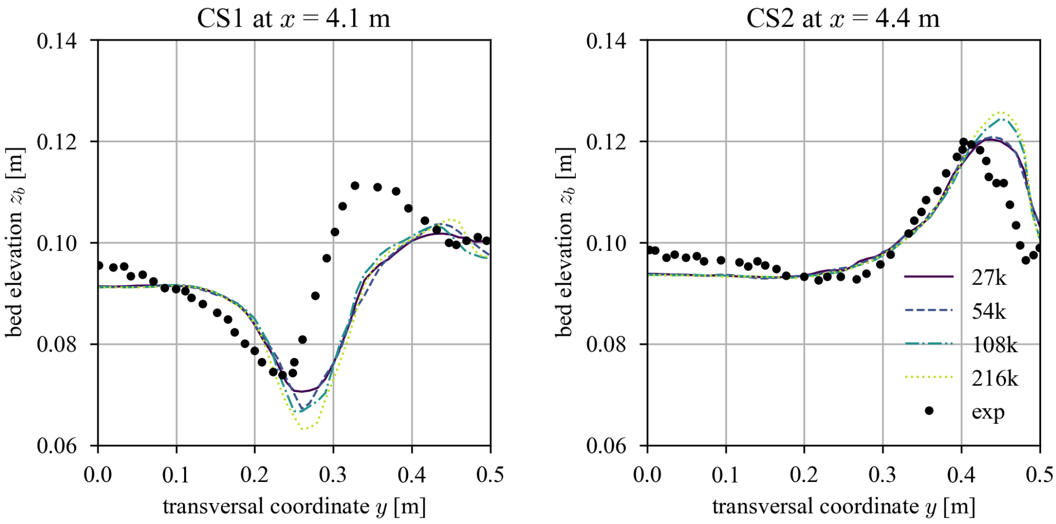


Figure 2.11 *Experimental and numerical bed elevation are compared at cross-sections CS1 and CS2.*

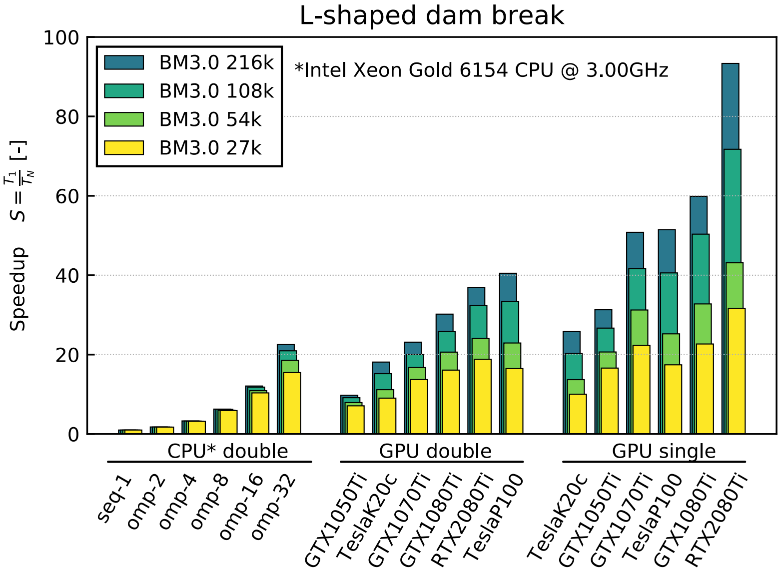


Figure 2.12 *Speedup of the computational time [T_N] for CPU (double) and GPU (single and double) compared to the time of the sequential backend Xeon1 [T_1] for the L-shaped dam break test case.*

2.4.4 Performance

2.4.4.1 Ubuntu

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

Table 2.9 *Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for CPU simulations (Intel Xeon Gold 6154, 3.00GHz)*

Mesh size	Xeon 1 Double	Xeon 2 Double	Xeon 4 Double	Xeon 8 Double	Xeon 16 Double	Xeon 32 Double
30k	43.8	25.2 (1.7x)	13.7 (3.2x)	7.4 (5.9x)	4.2 (10.4x)	2.8 (15.5x)
60k	97.7	56.1 (1.7x)	30.4 (3.2x)	16.3 (6.0x)	9.0 (10.9x)	5.3 (18.5x)

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

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

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

Table 2.11 *Computational time (s) and speedup S (inside brackets) of the L-shaped dam break simulations for GPU simulations*

Mesh size	Xeon 1 Double	GTX 1050 Single	GTX 1050 Double	GTX 1070 Single	GTX 1070 Double	GTX 1080 Single	GTX 1080 Double
30k	43.8	2.6 (16.6x)	6.2 (7.1x)	2.0 (22.3x)	3.2 (13.7x)	1.9 (22.7x)	2.7 (16.1x)
60k	97.7	4.7 (20.7x)	12.4 (7.9x)	3.1 (31.2x)	5.8 (16.7x)	3.0 (32.8x)	4.7 (20.69x)
90k	357.3	13.4 (26.7x)	39.1 (9.1x)	8.6 (41.6x)	17.9 (20.0x)	7.1 (50.3x)	13.8 (25.8x)
120k	1096.3	35.0 (31.3x)	112.4 (9.8x)	21.6 (50.8x)	47.4 (23.1x)	18.3 (59.9x)	36.3 (30.2x)

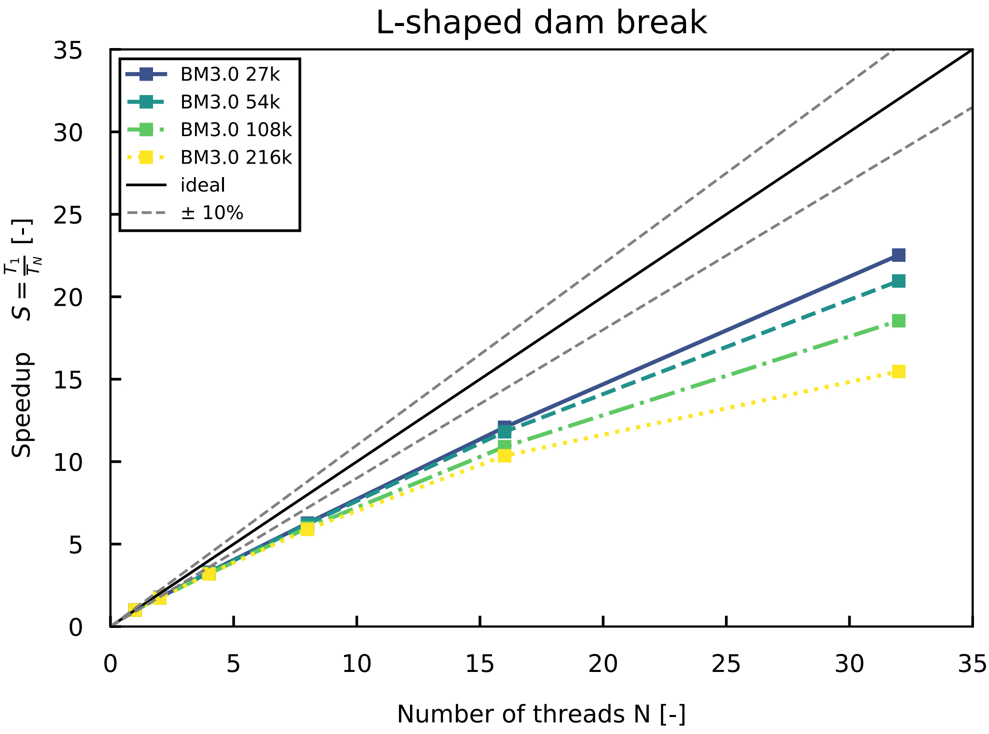


Figure 2.13 *Speedup of the L-shaped dam break test case performed on CPU for an increasing number of threads and different mesh sizes*

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

2.4.4.2 Windows

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

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

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

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

3

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VERSION 3.1
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1

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THE BASIC LIBRARY FUNCTIONS
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