

# MIKE 21 Flow Model FM

Parallelisation using GPU

Verification report



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## 1 Vision and scope

Release 2014 of MIKE by DHI includes a parallelisation of the hydrodynamic module of MIKE 21 Flow Model FM based on the Graphical Processor Unit (GPU) computing approach. In order to verify the implementation of this GPU parallelised version, a set of well-defined test cases have been established. For each of these test cases, the simulation results generated using the GPU version of MIKE 21 Flow Model FM are compared to the simulation results generated using the already existing, OpenMP parallelised version of MIKE 21 Flow Model FM.





## 2 Methodology

### 2.1 GPU parallelisation

The GPU version of MIKE 21 Flow Model FM uses the graphics card of the computer to perform the computational intensive calculations. The new GPU version of MIKE 21 Flow Model FM can also be applied for two-dimensional calculations in MIKE FLOOD. The utilisation of the GPU is based on the CUDA™ technology provided by NVIDIA®. The GPU version of MIKE 21 Flow Model FM can be executed on NVIDIA graphics cards with Compute Capability 2.0 or higher. Currently, only the hydrodynamic module of MIKE 21 Flow Model FM utilises the GPU. The additional calculations are performed on the CPU and these calculations are parallelised based on the shared memory approach, OpenMP. The numerical scheme and the basic implementation used in the GPU version of MIKE 21 Flow Model FM are identical to the scheme and implementation used in the OpenMP and MPI version of MIKE 21 Flow Model FM. The new GPU version of MIKE 21 Flow Model FM can also be applied for two-dimensional calculations in MIKE FLOOD.

### 2.2 Platform

The verification has been performed using a two core HP workstation with Intel® Core™ i3-2120 Processor (3.30 GHz), 8 GB of RAM and GeForce GTX TITAN graphics card. The operating system is Windows 7.

### 2.3 Verification procedure

The verification is based on the test cases described in section 3. For each test case, results are generated using the GPU parallelisation approach and using the OpenMP parallelisation approach of MIKE 21 Flow Model FM, and the results are afterwards compared. This comparison primarily considers the resulting dfsu files.

For each test case the comparison process consists of at least the first two of the following steps:

- 1. Comparing log files:** For each simulation MIKE 21 Flow Model FM generates a log file including statistical information for the results files. The statistical information contains minimum, maximum and mean value for each item. If the log files generated using the GPU approach and using the OpenMP approach are identical, or only differs slightly, the comparison is considered a success.
- 2. Comparing dfsu output files:** Each of the dfsu output files generated using the GPU approach is compared to the corresponding output file generated using the OpenMP approach. This is done using the DataCalculationFM tool, which produces a log file and a dfsu file, holding the differences between the two output files of interest. If the log file produced by this tool shows that the output files are identical, then the comparison is considered a success. If the output files are not identical, but differences are sufficiently small, then a visual inspection is done.
- 3. Visual inspection:** If the dfsu file produced by the DataCalculationFM tool shows that the differences are sufficiently small, and that they seem more or less random throughout the domain, then the comparison is considered a success. In case of any

doubt, the output files are compared manually for each time step for each dynamic item. If the two solutions show the same basic behaviour, then the comparison is considered a success. If there are many output time steps in the simulation, then the visual inspection is done by sampling.

## 3 Description of test cases

The set of verification test cases consists of all the examples for the hydrodynamics (HD) module and the transport (TR) module in MIKE 21 Flow Model FM included in the installation of MIKE Zero. Furthermore, an example for MIKE FLOOD included in the installation of MIKE Zero is considered. Finally, the set of test cases also includes some additional test cases which have been established for benchmarking of the MIKE 21 Flow model FM

### 3.1 Examples included in the installation of MIKE Zero

The test cases in this section are all included in the installation of MIKE Zero.

#### 3.1.1 MIKE 21 Flow Model FM examples

The list of MIKE 21 Flow Model FM examples used as verification test cases is shown in Table 3.1. This table also indicates in which folder the examples are located relative to the following path, which assumes a default MIKE Zero installation:

C:\Program Files (x86)\DHI\2014\MIKE Zero\Examples\MIKE\_21\FlowModel\_FM

Descriptions of these installation examples are found in the following manuals, which are all included in the installation of MIKE Zero:

- MIKE 21 Flow Model FM, Hydrodynamic Module, User Guide
- MIKE 21 Flow Model FM, Hydrodynamic Module, Step-by-Step Training Guide
- MIKE 21 Flow Model FM, Transport Module, User Guide

Table 3.1 MIKE 21 Flow Model FM installation examples used for verification

Module	Folder	Test case
HD	Lake	lake.m21fm
HD	Lake	LakeConnectedSourceSink.m21fm
HD	Oresund\Calibration_2	oresund.m21fm
HD	Structure	Sim1_Bank.m21fm
HD	Structure	Sim1_Weir.m21fm
HD	Structure	Sim2_Weir.m21fm
HD	Structure	Sim3_WeirQH.m21fm

Module	Folder	Test case
HD	Structure	Sim4_Dike_Constant.m21fm
HD	Structure	Sim4_Dike_Varying.m21fm
HD	Structure	Sim5_DepthCorrection_Varying.m21fm
TR	FunningsFjord	FunningsFjord.m21fm

### 3.1.2 MIKE FLOOD example

The following MIKE FLOOD example has been used as verification test case:

C:\Program Files (x86)\DHI\2016\MIKE Zero\Examples\MIKE\_FLOOD\  
FloodplainDemonstration\MIKE\_FLOOD\_FM.couple,

where the couple file directs to the m21big.m21fm file. A description of this test case is found in the MIKE FLOOD User Manual included in the MIKE Zero installation.

## 3.2 Mediterranean Sea

This test case has been established for benchmarking of the MIKE 21 Flow model FM.

### 3.2.1 Description

In the Western parts of the Mediterranean Sea tides are dominated by the Atlantic tides entering through the Strait of Gibraltar, while the tides in the Eastern parts are dominated by astronomical tides, forced directly by the Earth-Moon-Sun interaction.

### 3.2.2 Setup

The bathymetry is shown in Figure 3.1. Simulations are performed using four meshes with different resolution (see Table 3.2). The meshes are generated specifying the value for the maximum area of 0.01, 0.0025, 0.00125 and 0.0003125 degree<sup>2</sup>, respectively. The simulation period for the benchmarks covers 2 days starting 1 January 2004 for the simulations using mesh A, B and C. The simulation period is reduced to 6 hours for the simulations using mesh D.

At the Atlantic boundary a time varying level boundary is applied. The tidal elevation data is based on global tidal analysis (Andersen, 1995).

For the bed resistance, the Manning formulation is used with a Manning number of 32. For the eddy viscosity the Smagorinsky formulation is used with a Smagorinsky factor of 1.5. Tidal potential is applied with 11 components (default values).

The shallow water equations are solved using both the first-order scheme and the higher-order scheme in time and space.

The averaged time step for the simulations using Mesh A, B, C and D is 17.65s, 5.61s, 2.86s and 1.46s, respectively, for both the first-order scheme and the higher-order scheme in time and space.

Table 3.2 Computational mesh for the Mediterranean Sea case

Mesh	Element shape	Elements	Nodes	Max. area Degree <sup>2</sup>
Mesh A	Triangular	11287	6283	0.010
Mesh B	Triangular	80968	41825	0.005
Mesh C	Triangular	323029	164161	0.00125
Mesh D	Triangular	1292116	651375	0.0003125

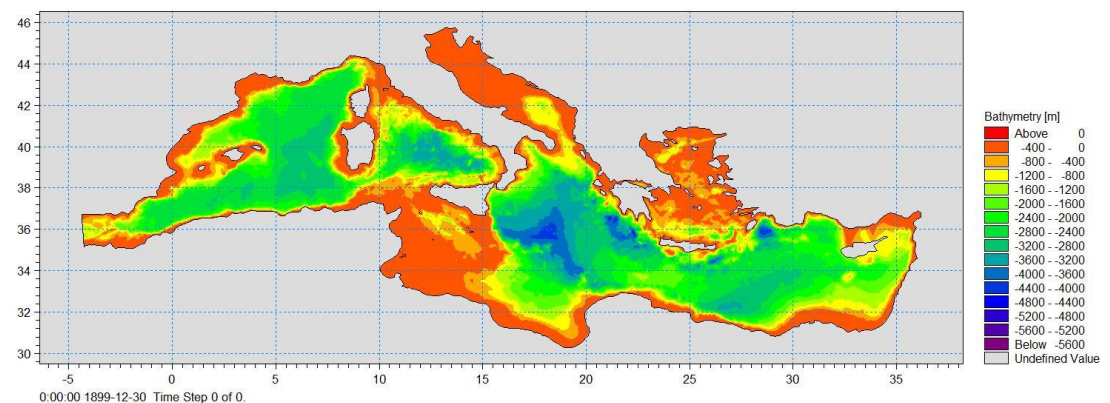


Figure 3.1 Bathymetry for the Mediterranean Sea case

### 3.2.3 Data and specification files

The data and specification files used for the present case are located in the directory:

Benchmarking\Mediterranean\_Sea

The tests are performed using the following specification files:

2004\_tide\_A\_1st.m21fm  
 2004\_tide\_B\_1st.m21fm  
 2004\_tide\_C\_1st.m21fm  
 2004\_tide\_D\_1st.m21fm  
 2004\_tide\_A\_2nd.m21fm  
 2004\_tide\_B\_2nd.m21fm

2004\_tide\_C\_2nd.m21fm

2004\_tide\_D\_2nd.m21fm

### 3.3 Ribe Polder

This test case has been established for benchmarking of the MIKE 21 Flow Model FM.

#### 3.3.1 Description

The model area is located, on the southern part of Jutland, Denmark, around the city of Ribe. The area is protected from storm floods in the Wadden Sea to the west by a dike. The water course Ribe Å runs through the area and crosses the dike through a lock.

The flood condition where the dike is breached during a storm flood is illustrated by numerical modelling. The concept applied to model the breach failure in the hydrodynamic model is based on prescribing the breach by a dynamic bathymetry that change in accordance with the relation applied for the temporal development of the breach. Use of this method requires that the location of the breach is defined and known at an early stage, so that it can be resolved properly and built into the bathymetry. The shape and temporal development of the breach is defined with a time-varying distribution along the dike crest. It is further defined how far normal to the crest line the breach can be felt. Within this distance the bathymetry is following the level of the breach, if the local level is lower than the breach level no changes are introduced. The area of influence of the breach will therefore increase with time.

The breach and flood modelling has been carried out based on a historical high water event (24 November, 1981), shown in Figure 3.2. Characteristic for this event is that high tide occurs at the same time as the extreme water level. Højer sluice is located about 40 km south of the breach, while Esbjerg is located about 20 km to the north. Based on the high water statistics for Ribe the extreme high water level has been estimated for an event having a return period of 10,000 years. The observed water level at Højer is hereafter adjusted gradually over two tidal cycles to the extreme high water level estimated for the given return periods at Ribe, as indicated in Figure 3.2. The water level time series established in this way are shown in Figure 3.2.

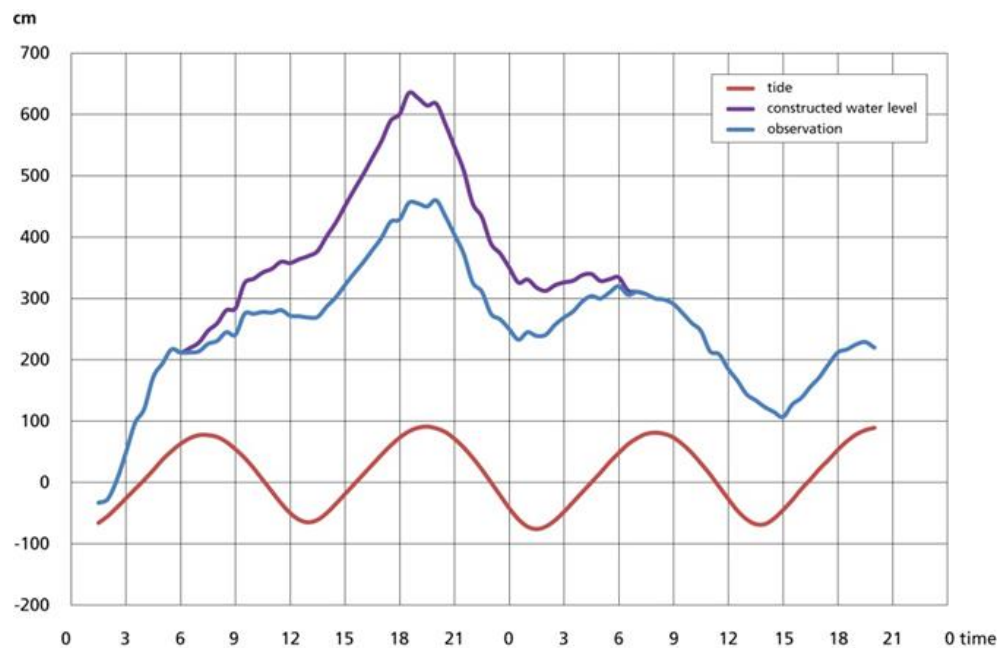


Figure 3.2 Runoff from the catchment is included as specified discharges given for the two streams Ribe Å and Kongeåen

The crossing between the dike and Ribe Å is shown in Figure 3.4. The crossing is in the form of a navigational chamber lock. It is represented in the model bathymetry as a culvert that can be closed by a gate. The points defining the dike next to the creek are modified to have increased levels in order to ensure a well-defined bathymetry where flow only occurs through the cells defining the creek proper. The sluice is defined as a check valve allowing only flow towards the sea.

### 3.3.2 Setup

The bathymetry is shown in Figure 3.3. The computational mesh contains 173101 elements. A satisfactory resolution of the breach is obtained by a fine mesh of structured triangles and rectangles as shown in Figure 3.4. The areas in- and offshore of the dike is defined by a relatively fine mesh to avoid instabilities due to humps or holes caused by large elements with centroids just outside the area of influence from the breach. The simulation period is 42 hours.

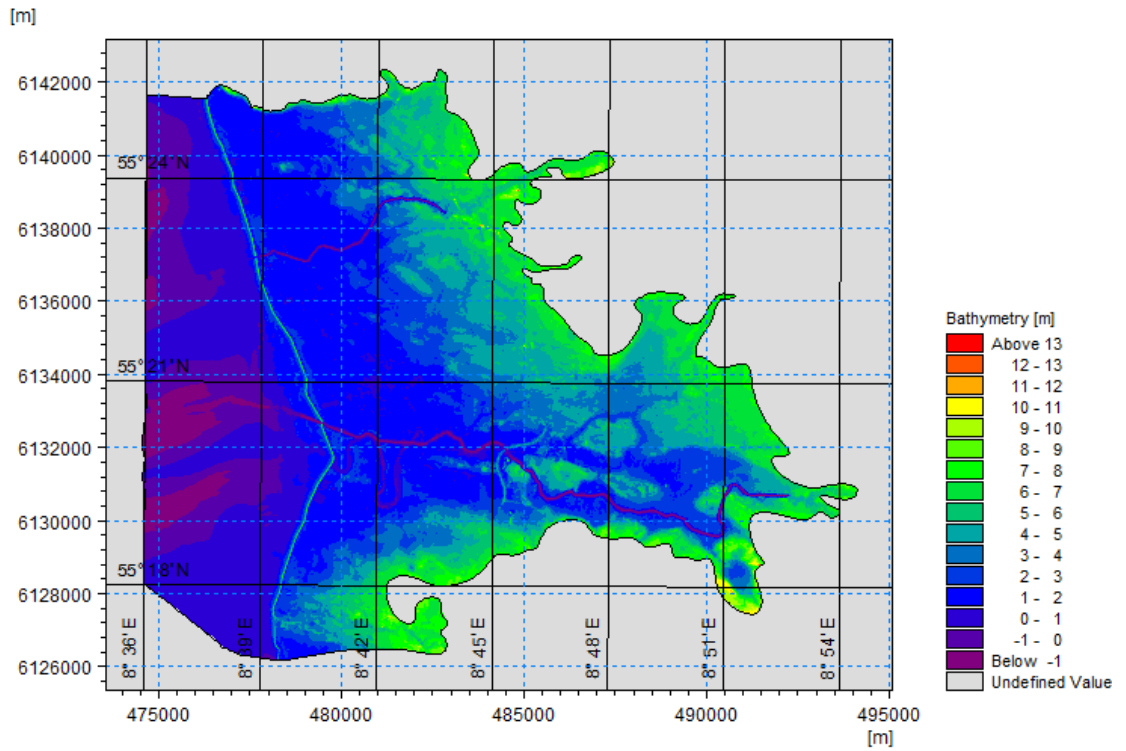


Figure 3.3 Bathymetry for the Ribe Polder case

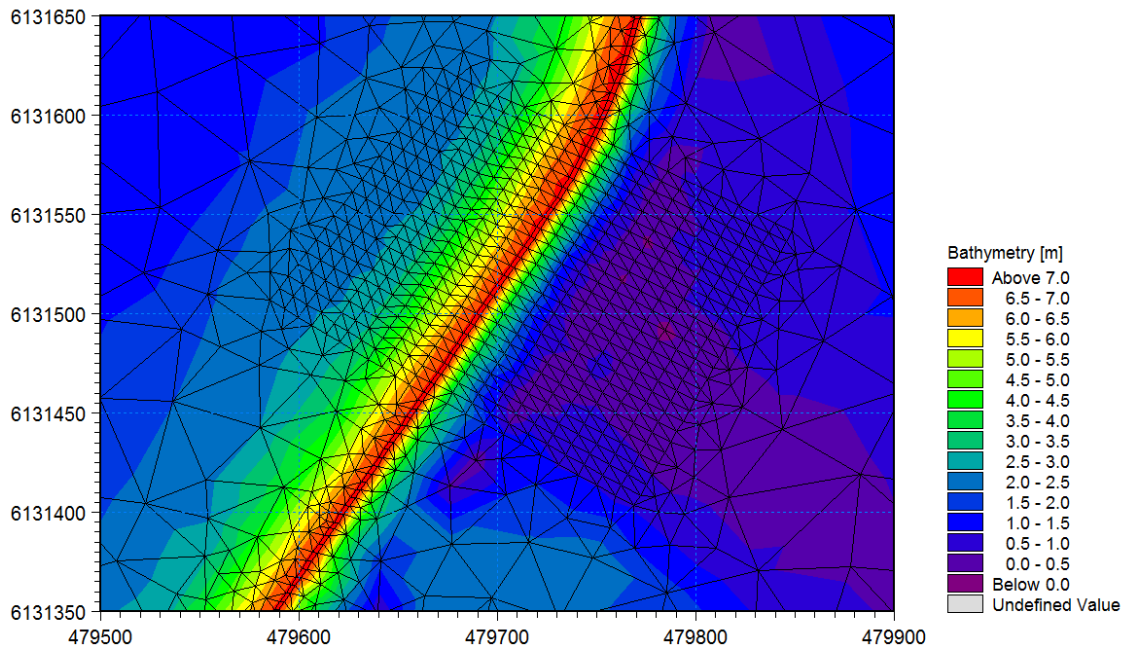


Figure 3.4 Close-up of the bathymetry

At the offshore boundary a time series of level variations is applied.

A constant discharge of  $9.384 \text{ m}^3/\text{s}$  and  $14.604 \text{ m}^3/\text{s}$ , respectively, are applied for the two streams Ribe Å and Kongeåen. For the bed resistance, the Manning formulation is used



with a Manning number of 20. For the eddy viscosity, the Smagorinsky formulation is used with a Smagorinsky factor of 0.28.

The shallow water equations are solved using both the first-order scheme and higher-order scheme in space and time.

The averaged time step is 0.21s for both the first-order scheme and higher-order scheme in space and time.

### 3.3.3 Data and specification files

The data and specification files used for the present case are located in the directory Benchmarking\Ribe\_Polder

The tests are performed using the following specification files:

Event\_10000\_1st.m21fm

Event\_10000\_2nd.m21fm

## 3.4 EA2D Test 8B

This test is Test 8B in the benchmarks test developed during the Joint Defra/Environment Agency research programme. This tests the package's capability to simulate shallow inundation originating from a surcharging underground pipe, at relatively high resolution. This test case has been established for benchmarking of the MIKE Flood using MIKE 21 Flow model FM for the 2D surface flow calculation.

### 3.4.1 Description

The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and shown in Figure 3.5. Ground elevations span a range of ~21m to ~37m.

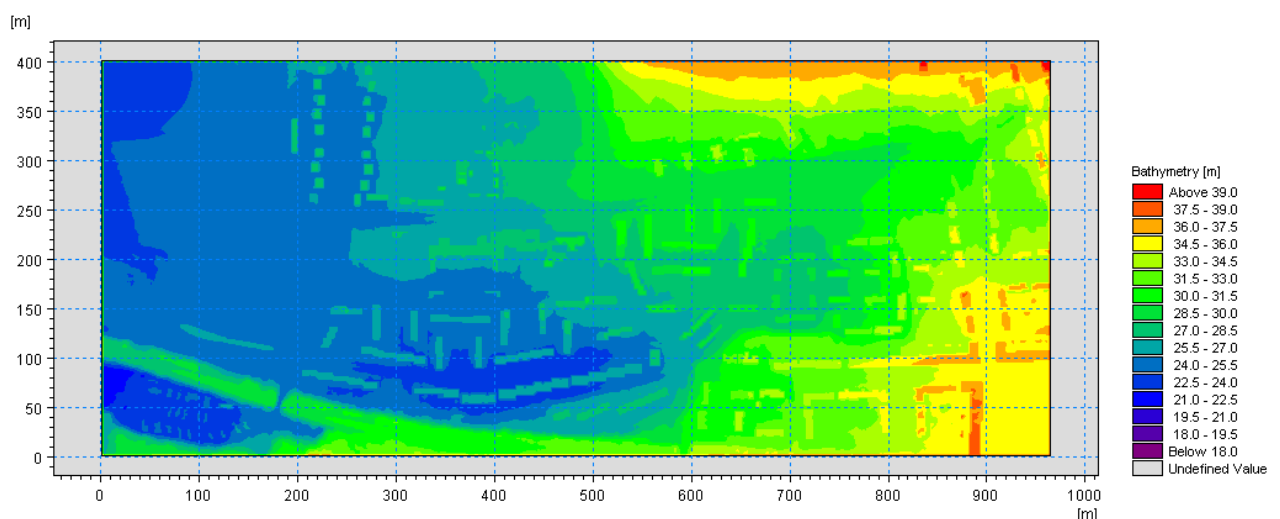


Figure 3.5 Bathymetry for the EA2D Test8B case

A culverted watercourse of circular section, 1400mm in diameter, ~1070m in length, and with invert level uniformly 2m below ground is assumed to run through the modelled area. An inflow boundary condition is applied at the upstream end of the pipe, illustrated in

Figure 3.6. A surcharge is expected to occur at a vertical manhole of  $1\text{m}^2$  cross-section located 467m from the top end of the culvert, and at the location (264896, 664747). For the downstream boundary condition free out fall (critical flow is assumed). The base flow (uniform initial condition) is 1.6 m/s. The manhole is connected to the grid in one point and the surface flow is assumed not to affect the manhole outflow.

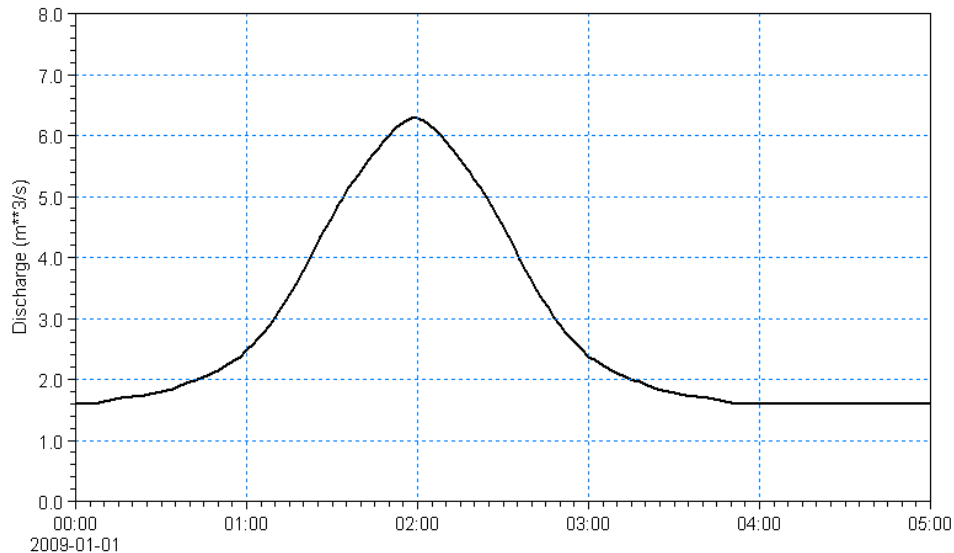


Figure 3.6 Inflow hydrograph applied for the EA2D Test8B at upstream end of culvert

DEM is a 0.5m resolution Digital Terrain Model (no vegetation or buildings) created from LiDAR data collected on 13th August 2009 and provided by the Environment Agency (<http://www.geomatics-group.co.uk>). Model grid resolution should be 2m (or ~97000 nodes in the  $0.388\text{ km}^2$  area modelled).

The presence of a large number of buildings in the modelled area is taken into account. Building outlines are provided with the dataset. Roof elevations are not provided.

A land-cover dependent roughness value is applied, with 2 categories: 1) Roads and pavements; 2) Any other land cover type. Manning's  $n = 0.02$  is applied for roads, and pavements  $n = 0.05$  everywhere else.

All boundaries in the model area are closed (no flow) and the initial condition is dry bed. The model is run until time  $T = 5$  hours to allow the flood to settle in the lower parts of the modelled domain.

### 3.4.2 Setup

Simulations are performed using four meshes with different resolution (see Table 3.3). The four meshes uses regular quadrilateral elements with grid spacing 2m, 1m, 0.5m and 0.25m, respectively. Mesh A corresponds to the original mesh used in the EA2D test, and the additional meshes are obtained by refining this mesh.

Table 3.3 Computational mesh for the EA2D Test 8B case

Mesh	Element shape	Elements	Nodes	Grid spacing metres
Mesh A	Quadrilateral	95719	96400	2
Mesh B	Quadrilateral	384237	385600	1
Mesh C	Quadrilateral	1539673	1542400	0.5
Mesh D	Quadrilateral	6164145	6169600	0.25

The shallow water equations are solved using the first-order scheme in time and space.

The averaged time step for the simulation using Mesh A, B, C and D is 0.27s, 0.15s, 0.76s and 0.025s, respectively.

### 3.4.3 Data and specification files

The data and specification files used for the present case are located in the directory:

Benchmarking\EA2D\_Test\_8B

The tests are performed using the following specification files:

Test8B\_quadratic\_2m.couple

Test8B\_quadratic\_1m.couple

Test8B\_quadratic\_0.5m.couple

Test8B\_quadratic\_0.25m.couple



## 4 Verification results

Following the test procedure described in section 2.3, the implementation of the GPU version of MIKE 21 Flow Model FM HD has been verified for the entire set of test cases presented in section 3. The simulations have been performed using the double precision version of the new GPU version of MIKE 21 Flow Model FM.

For the test cases without flooding and drying, the results generated using the GPU parallelisation approach are identical, or very close to identical, to the results generated using the OpenMP parallelisation approach. If the test case has extensive flooding and drying there might be small deviations in the results, but the basic behaviour of the generated solutions are the same. These small deviations observed for extensive flooding and drying is expected, since the flooding and drying concept is based on threshold values. This means that even a tiny difference in the water level can possibly affect whether or not an element is flooded or dry.

The remainder of this section will focus on the results for the test cases having extensive flooding and drying, since it is for these test cases that the largest differences between the GPU version and the OpenMP version are observed.

### 4.1 Ribe Polder

In the following some results for the Ribe Polder test case are presented. Figure 4.1 shows 2D plots of the maximum water depth during the entire simulation period using the 1<sup>st</sup> order scheme. Figure 4.2 shows a close-up of the maximum water current speed during the entire simulation period using the 1<sup>st</sup> order scheme. The close-up is at the location where the dike breaches. Figure 4.3 shows 2D plots of the difference in maximum water depth and maximum current speed during the entire simulation period between GPU version and OpenMP version, applying the 1<sup>st</sup> order scheme. It is seen that the differences between the results using the GPU version and the OpenMP version is very small.

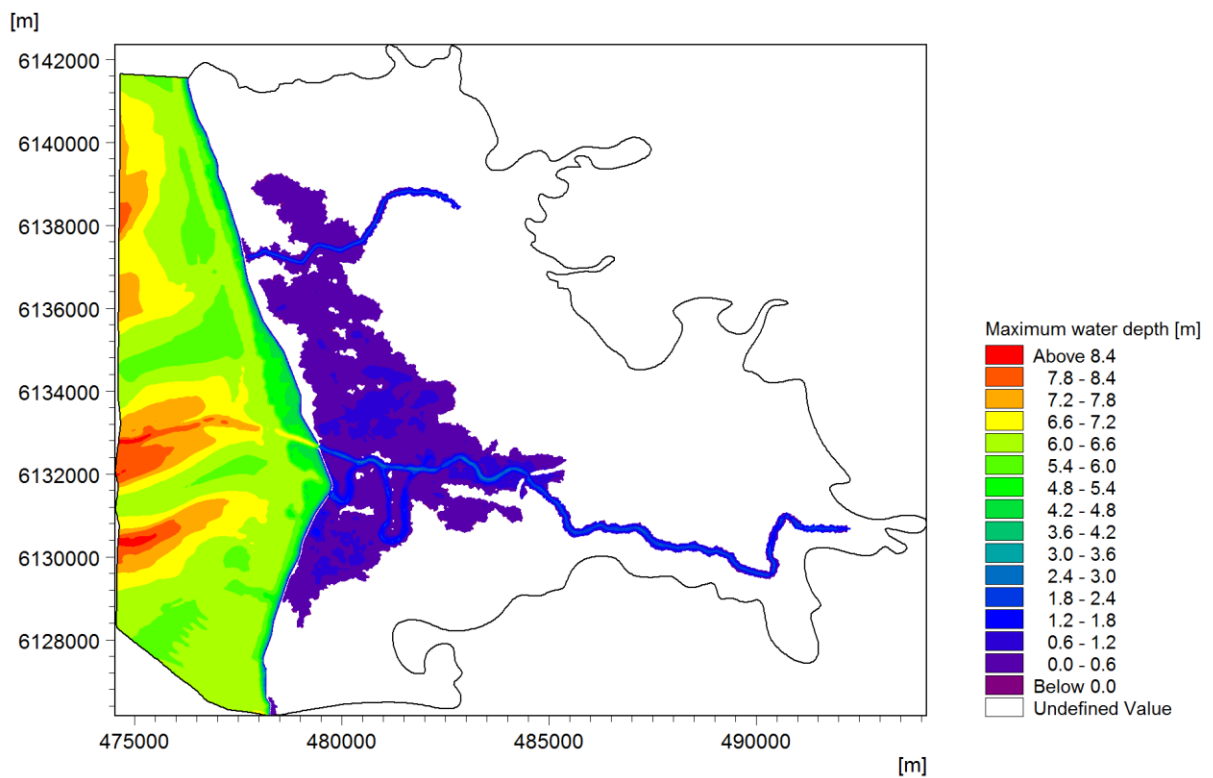
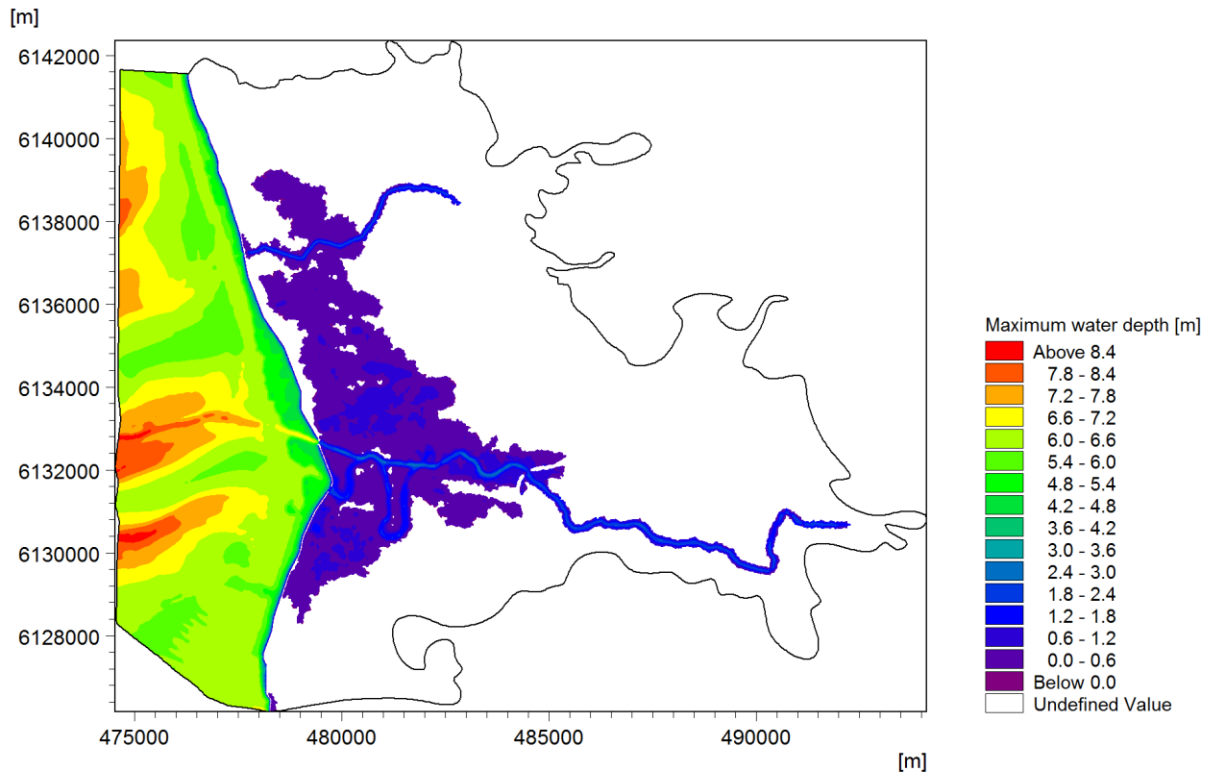


Figure 4.1 Maximum water depth during the entire simulation period using the 1<sup>st</sup> order scheme.  
 Top: GPU version  
 Bottom: OpenMP version

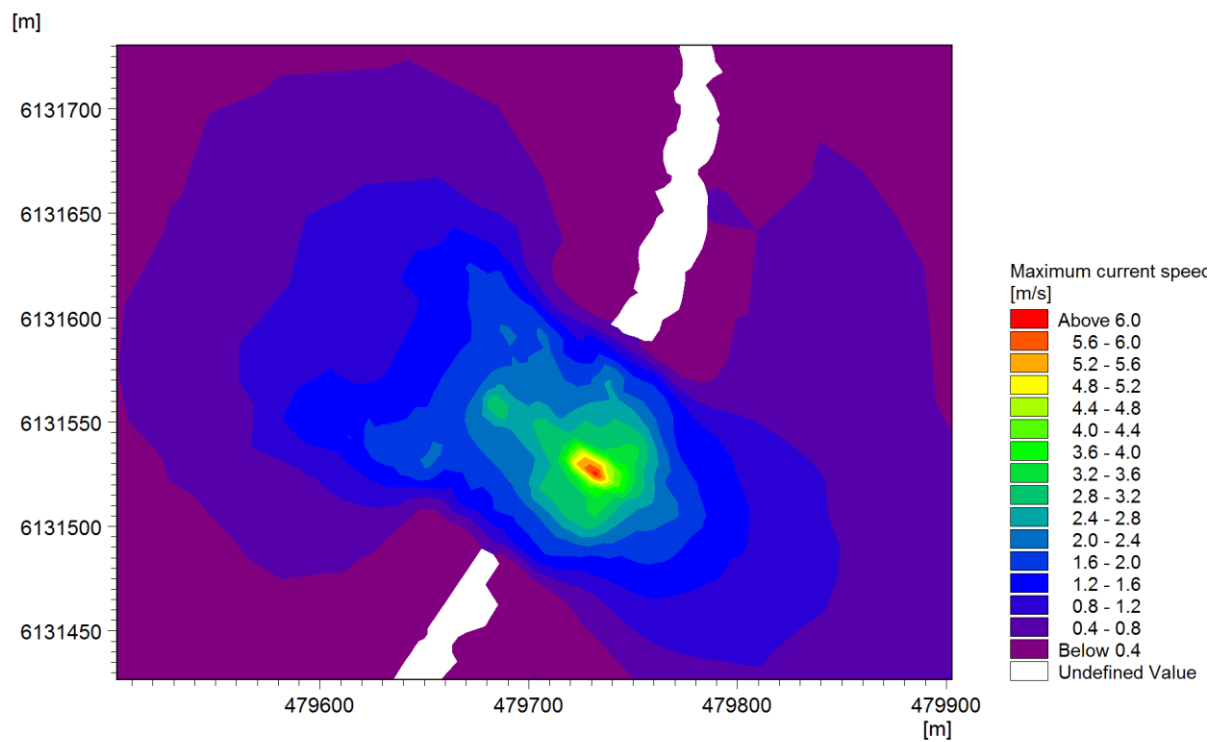
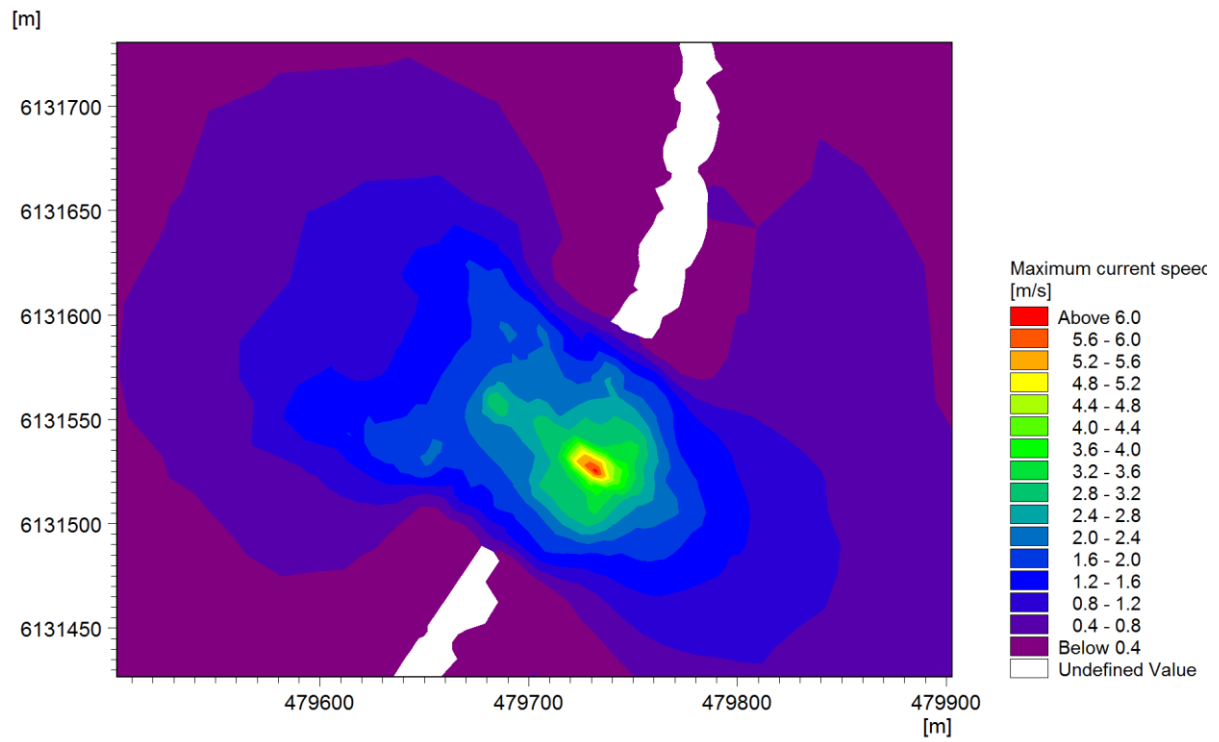


Figure 4.2 Maximum current speed during the entire simulation period at the location where the dike breaches. The 1<sup>st</sup> order scheme has been used.  
 Top: GPU version  
 Bottom: OpenMP version

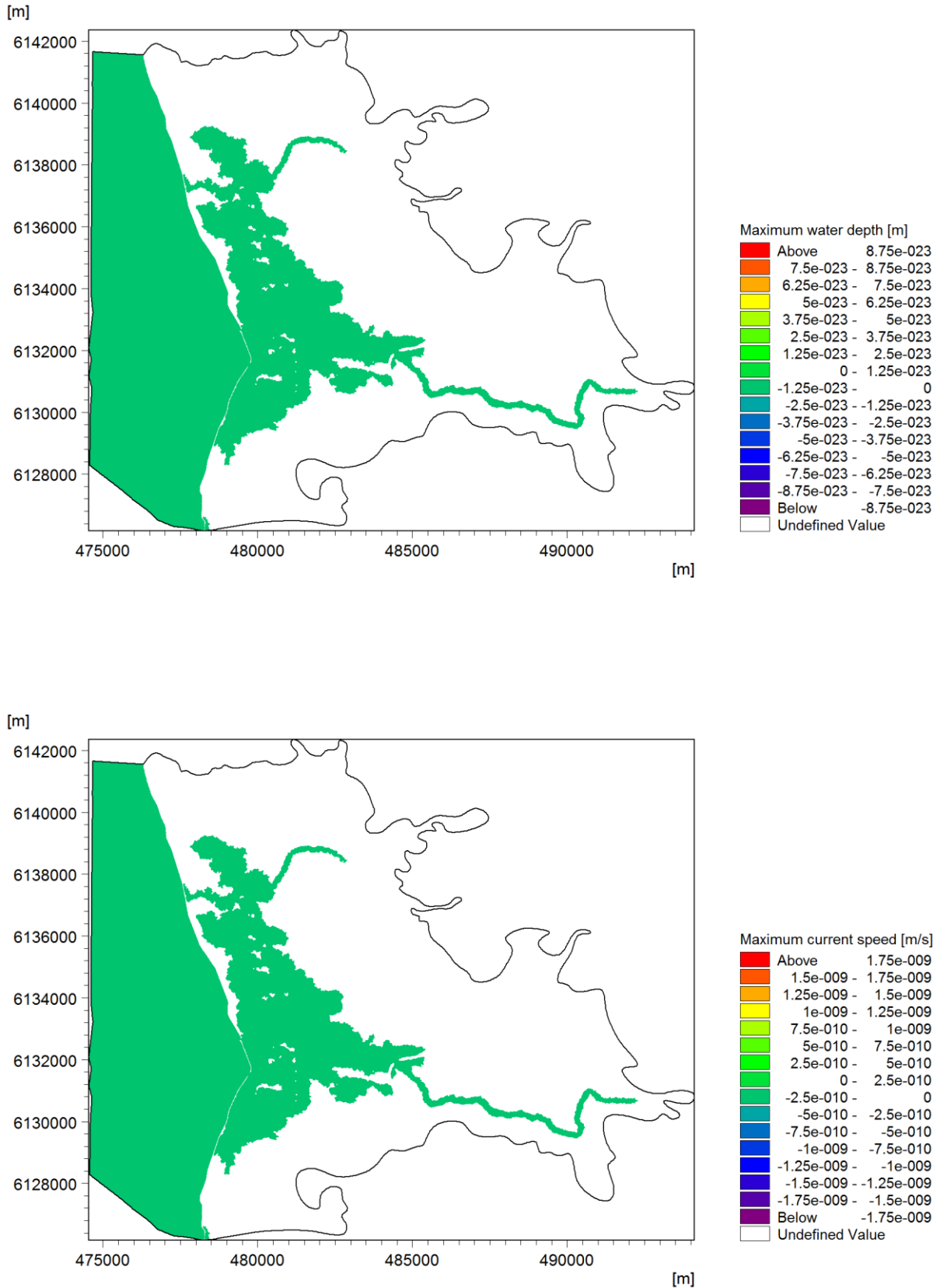


Figure 4.3 *Top:* Difference in maximum water depth during the entire simulation period between GPU version and OpenMP version, applying the 1<sup>st</sup> order scheme  
*Bottom:* Difference in maximum current speed during the entire simulation period between GPU version and OpenMP version, applying the 1<sup>st</sup> order scheme



## 4.2 EA2D Test 8B

In the following some results for the EA2D Test 8B test case with 2m grid spacing are presented. Figure 4.4 shows 2D plots of the surface elevation after 115 time steps. Figure 4.5 shows 2D plots of the maximum water depth during the entire simulation period using the 1st order scheme, and Figure 4.6 shows the current speed during the entire simulation period using the 1st order scheme. Figure 4.7 shows 2D plots of the difference in maximum water depth and maximum current speed during the entire simulation period between GPU version and OpenMP version, applying the 1st order scheme. In Figure 4.8 the surface elevation is compared at 3 different points in the domain. It is seen that the differences between the results using the GPU version and the OpenMP version is very small.

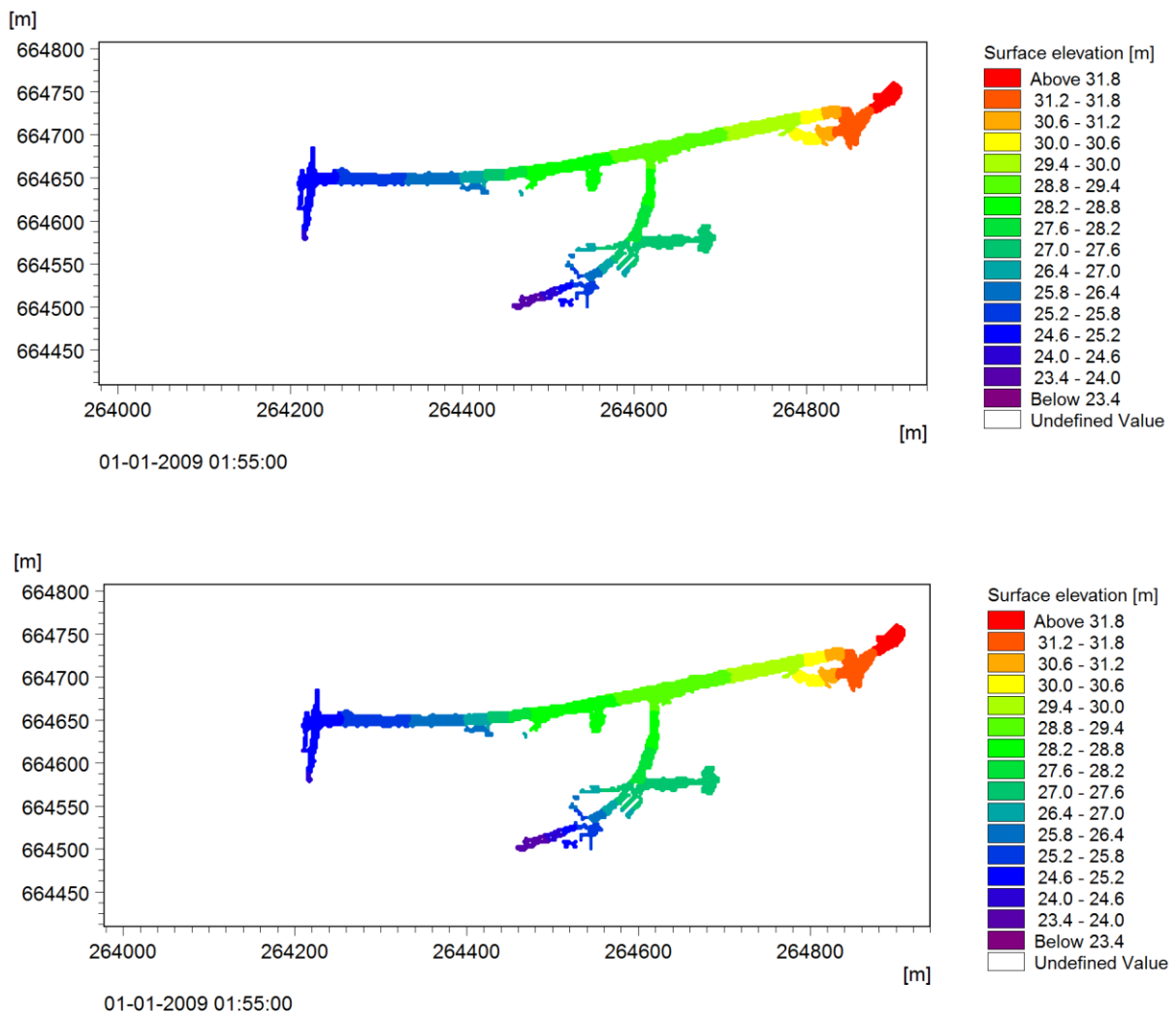


Figure 4.4 Surface elevation after 115 time steps using the 1<sup>st</sup> order scheme.  
 Top: GPU version  
 Bottom: OpenMP version

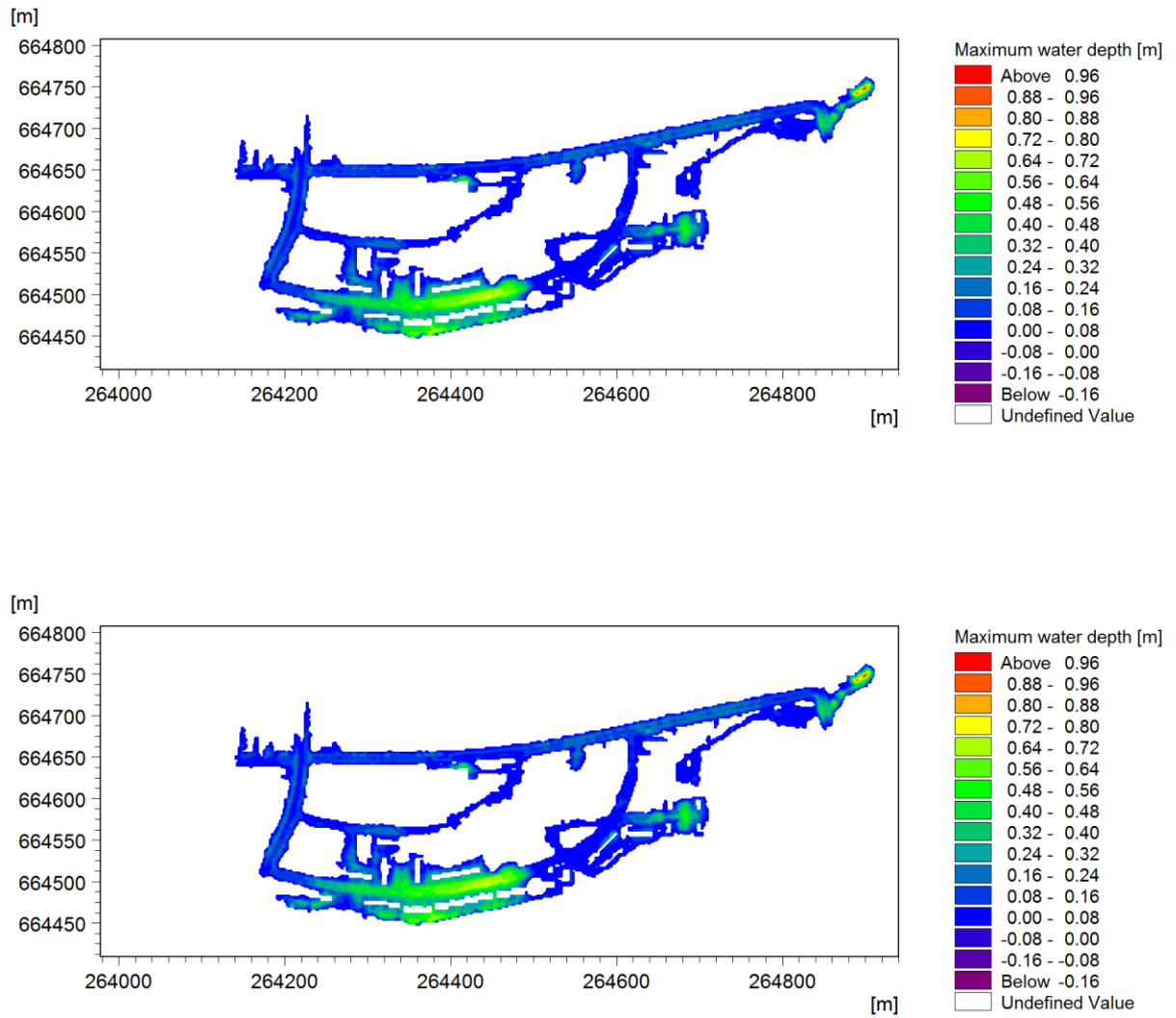


Figure 4.5 Maximum water depth during the entire simulation period using the 1<sup>st</sup> order scheme.  
*Top:* GPU version  
*Bottom:* OpenMP version

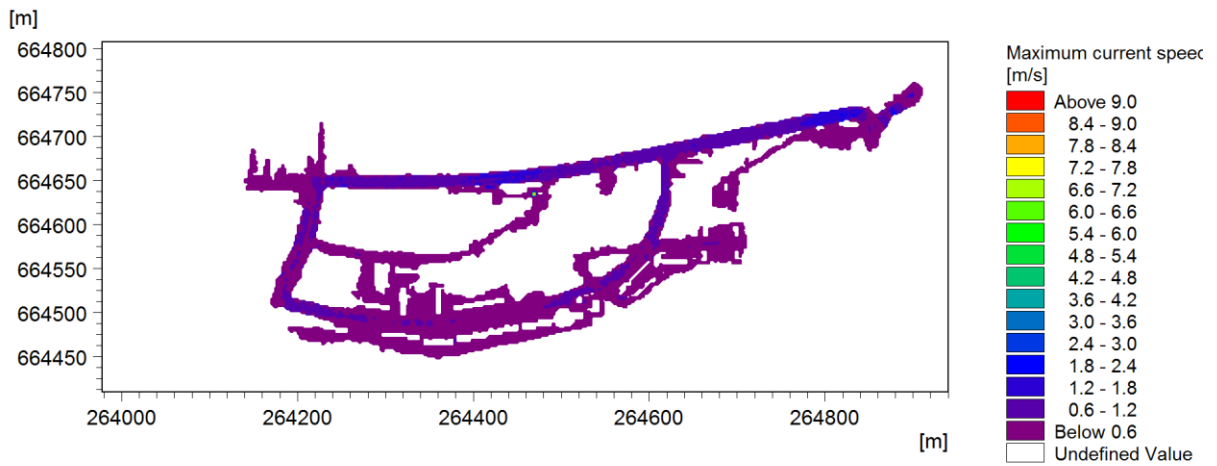
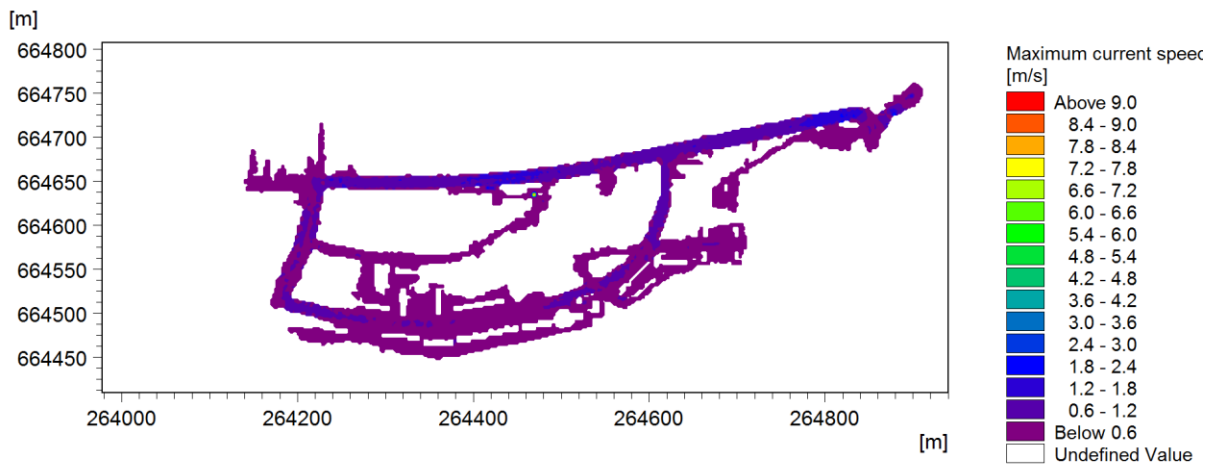


Figure 4.6 Maximum current speed during the entire simulation period using the 1<sup>st</sup> order scheme.  
 Top: GPU version  
 Bottom: OpenMP version

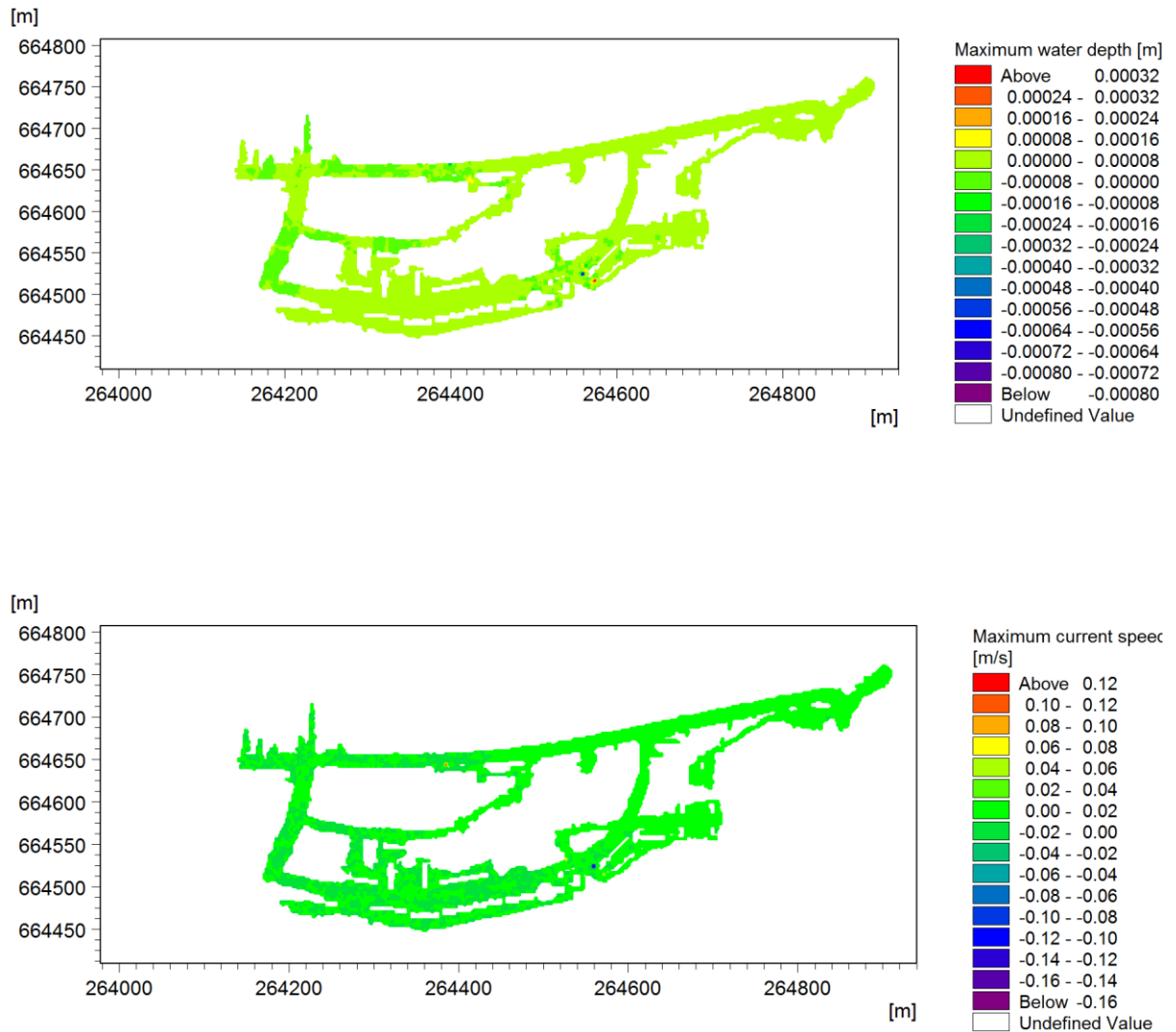


Figure 4.7 *Top:* Difference in maximum water depth during the entire simulation period between GPU version and OpenMP version, applying the 1<sup>st</sup> order scheme  
*Bottom:* Difference in maximum current speed during the entire simulation period between GPU version and OpenMP version, applying the 1<sup>st</sup> order scheme

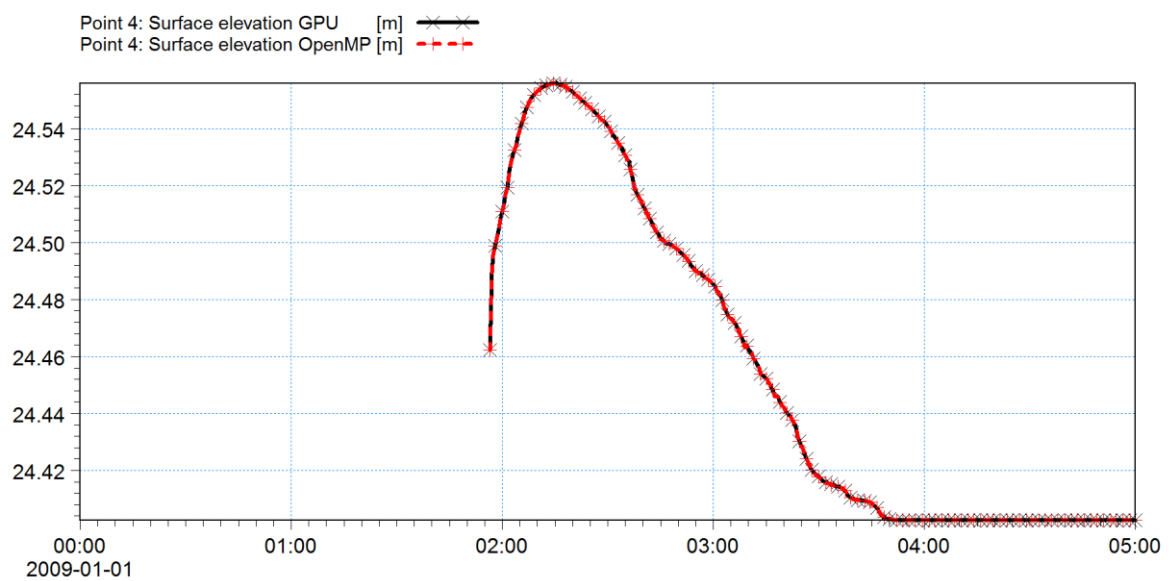
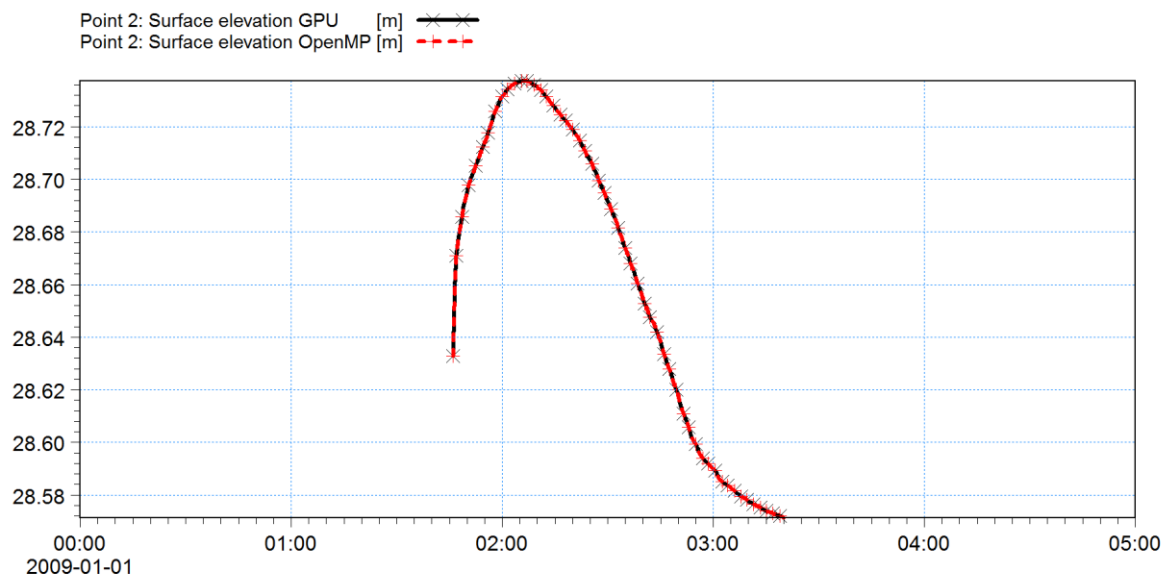
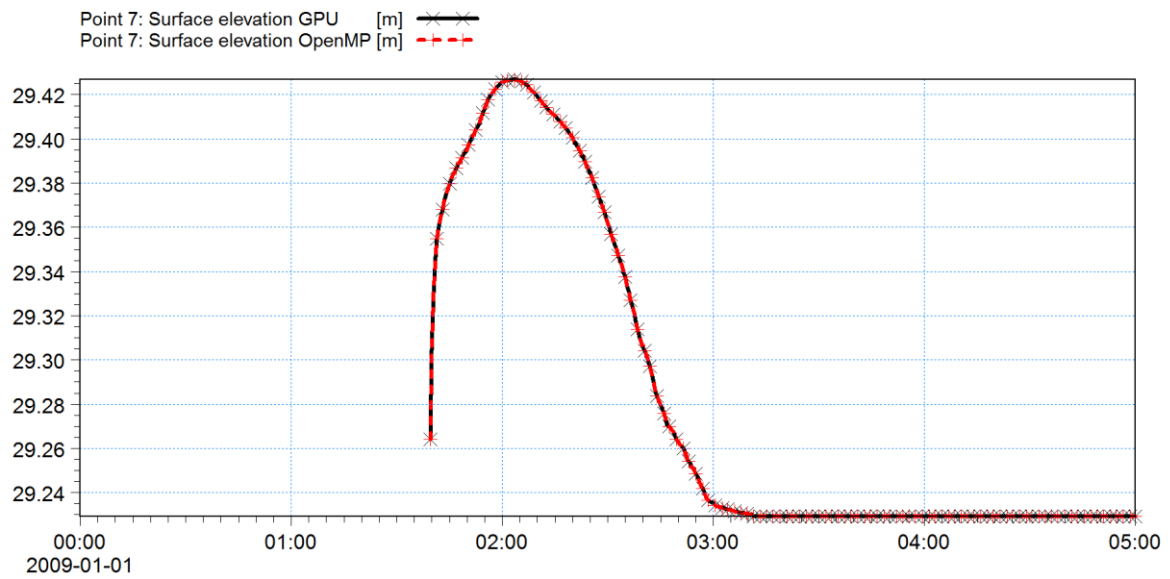


Figure 4.8 Surface elevation during the entire simulation period at 3 different points in the domain

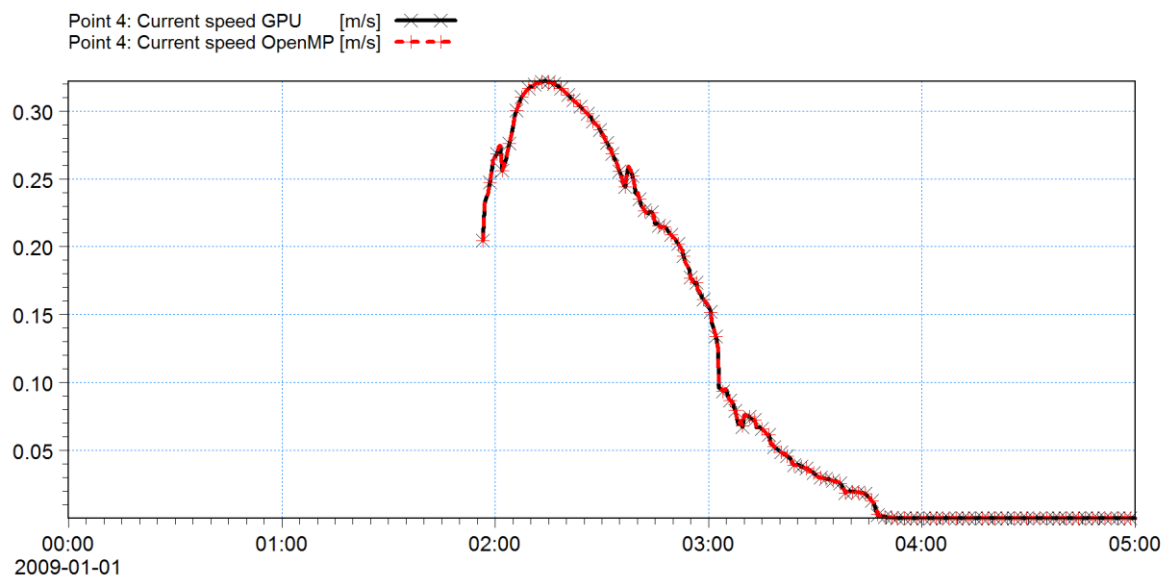
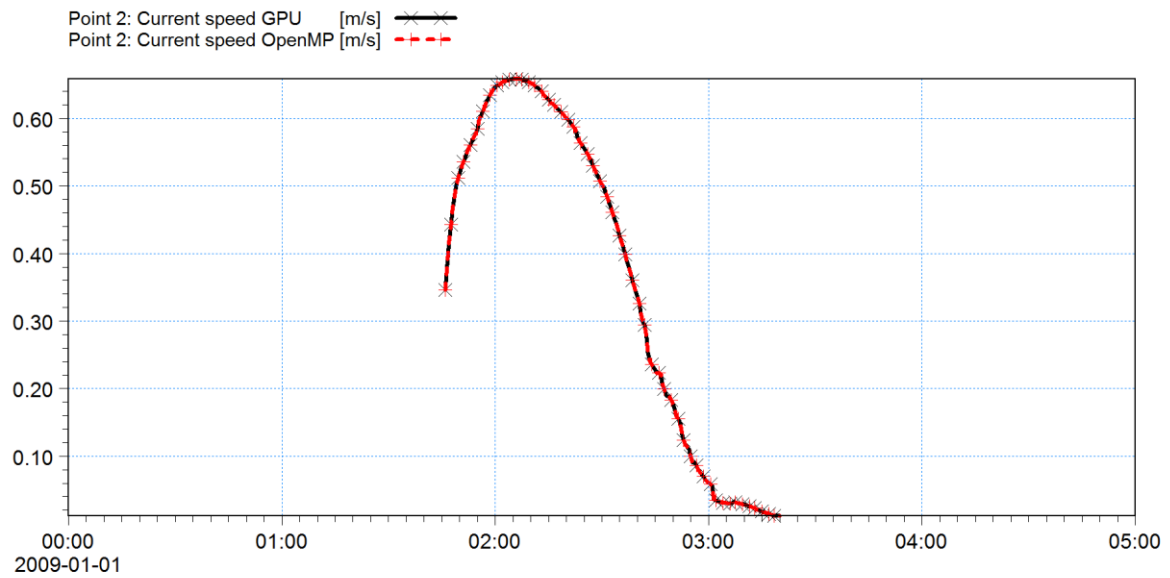
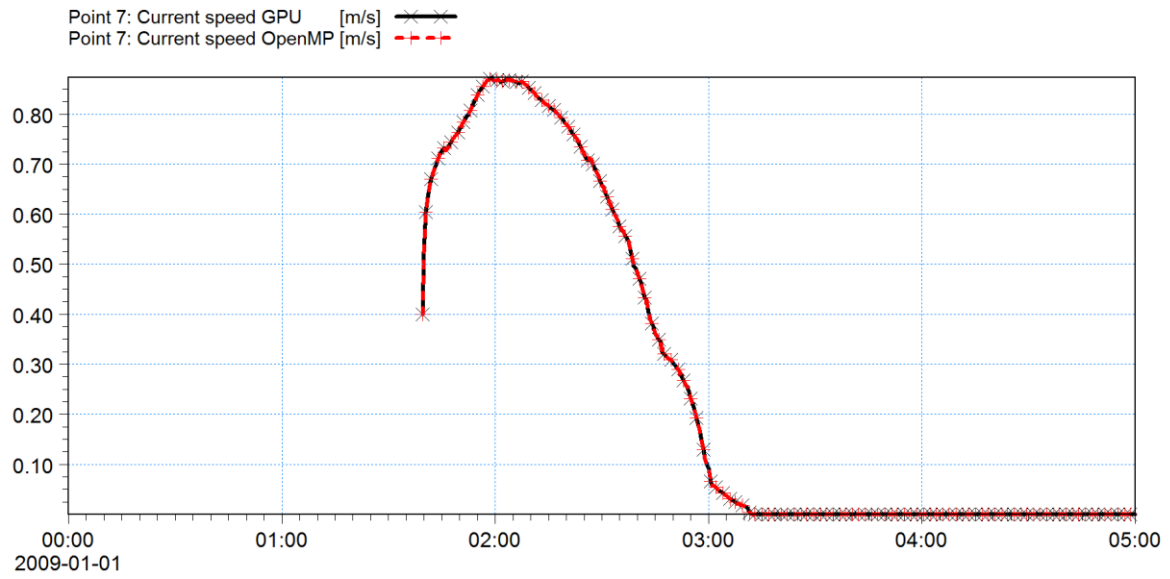


Figure 4.9 Current speed during the entire simulation period at 3 different points in the domain

## 5 Conclusions

The basic implementation of the numerical scheme of the MIKE 21 Flow Model FM GPU version is identical to the OpenMP version of MIKE 21 Flow Model FM. However, due to performance reasons, there are some differences in the implementation of the GPU version. For some accumulated values this causes rounding errors, which for the primary variables can be up to the sixth significant digit. This is the reason that the simulation results generated using the GPU version might differ slightly from the simulation results generated using the OpenMP version. However, the basic behaviour between the two versions is the same.

Furthermore, for the simulations with extensive flooding and drying the results might contain small differences, since the flooding and drying technique is based on thresholds, meaning that even a tiny difference can influence whether or not an element is flooded or dry.





## 6 References

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