Guidelines on Modelling Roads and Bicycle Paths for Surface Drainage

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

CONTENTS

1 Introduction

This study addresses the question:

- What is the best way to model a roadway?

assuming that the aim is to realistically simulate the ability of a roadway to convey surface runoff.

The approach was to define a general test setup that could be used for systematic identification of the best method. The setup must allow quantitative evaluation of method performance according to defined criteria.

In this study, the defined criteria used in evaluating the performance of a method were:

- Result accuracy
- Computation time
- Data requirements
- Ease of setup

1.1 Data

Real-life data from an area in Denmark was used in building the general model setup in the study. The use of actual data limits the generic nature of the setup. Nevertheless, actual data for a road and its surroundings reflects the non-uniform configuration of a real-life area as opposed to a uniform defined setup of e.g. a perfectly aligned roadway and smooth surrounding terrain.

The following datasets were used for the road model:

- DTM (Digital Terrain Model). Hydraulically-corrected model of the terrain downloaded from https://download.kortforsyningen.dk/
- *Matrikel kort*. Coarse-resolution land-use data downloaded from https://download.kortforsyningen.dk/
- Land use. High-resolution land-use data from HOFOR
- Sewer model. Sewer model data in MIKE Urban from HOFOR
- Rainfall. CDS design rainfall for current 100- and 10-year events derived using https://ida.dk/sites/default/files/regional_cds_ver_3_2_1.xls

1.2 The General Test Setup

Actual data used in the study were for the road Ruten located in Tingbjerg, Copenhagen.

Model Extent

To define the test model domain, the hydrological boundaries and sewer areas of Ruten were delineated (Figure 1 left). The delineation was used to define the model domain for Ruten, as well as quantify the surface runoff it drains.

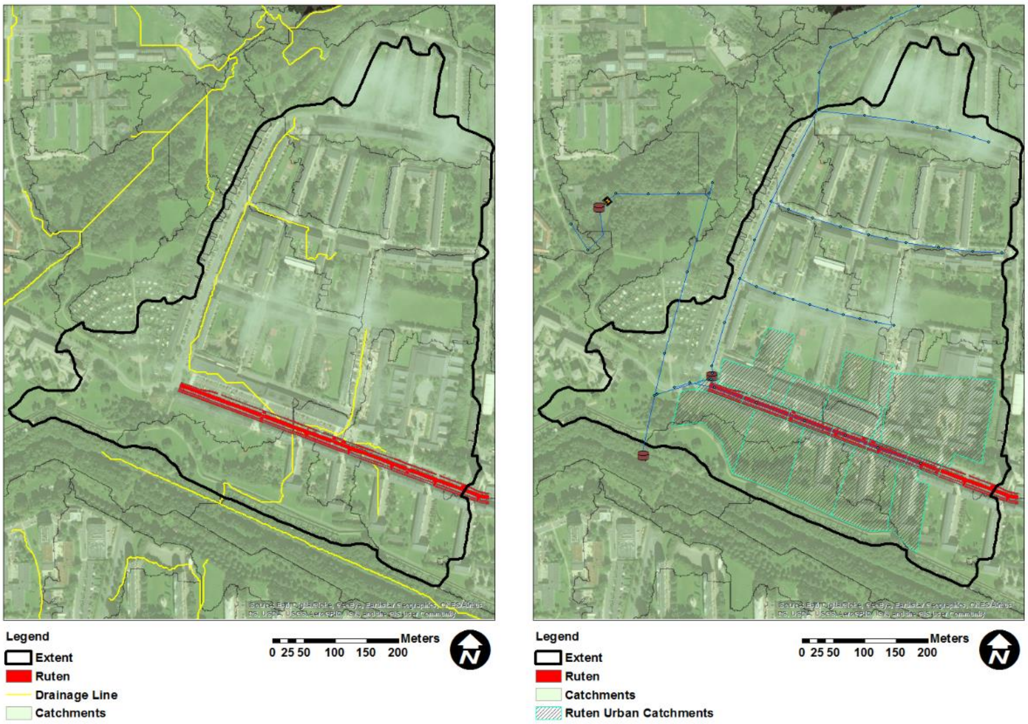

Figure 1 The extent of the test setup (thick black outline) based on the contributing surface areas to Ruten (in red) derived through hydrological catchment delineation based on topography (left figure). The urban catchments (hatched areas) draining to Ruten were based on the sewer model (right figure).

Flow Input

Rainfall runoff was calculated using sewer model catchments in MIKE Urban (Figure 1 right). Surface runoff values were needed to approximate realistic flows occurring over or towards roadways of such dimensions as Ruten in Denmark.

Design rainfall was used as boundary input to the catchments in MIKE Urban. The corresponding sewer flows draining the Ruten area were then extracted from network simulation results (Figure 2). This extracted discharge time series was used as boundary input to the 2D road model (Figure 3). This is based on the assumption that the flow during a particular event going through the sewer system over Ruten will instead be conveyed overland through the roadway (Figure 2). The pipe discharge downstream of Ruten was extracted and used as input to the Ruten test models, described in subsequent sections.

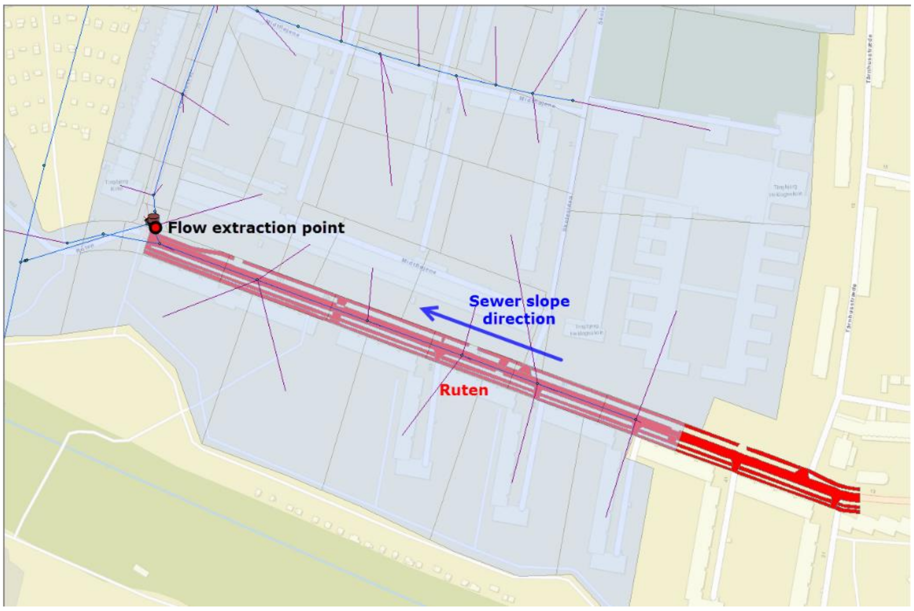

Figure 2 Location of the discharge extraction point from the MIKE Urban model. The extracted discharge was used as boundary input to the 2D test models applied at the upstream point of the road Ruten.

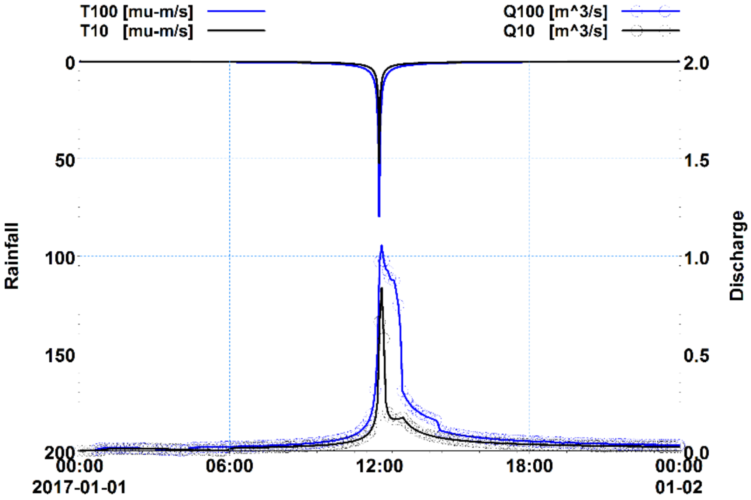

Figure 3 Design rainfall (T100 and T10), and corresponding sewer discharges (Q100 and Q10) used as surface flow inputs to the 2D road model.

Inflow to the road from the 100-year rain event (blue lines in Figure 3) represents the extreme event scenario for the tests, while inflows from the 10-year rainfall (black lines in Figure 3) represents the design scenario for combined sewer systems in the country.

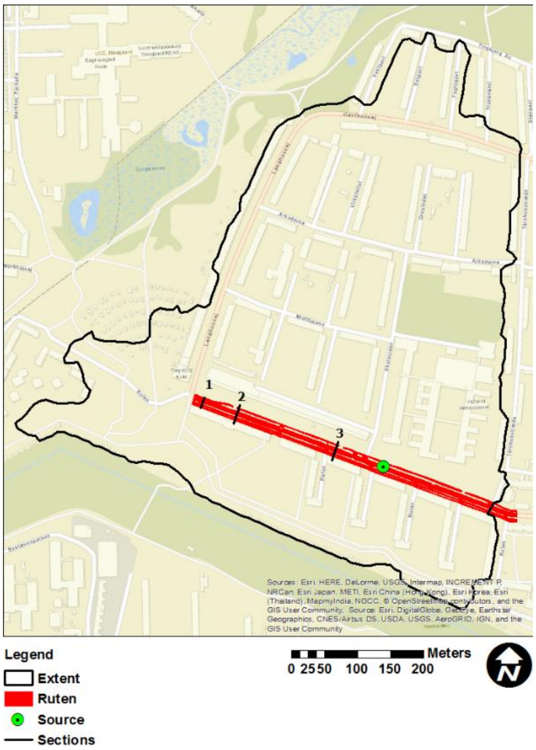

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Figure 4 Inflow to the 2D Ruten model was applied at the top of the road (see green dot). Model results at three sections (black line segments) were extracted for quantitative evaluation of road model performance.

Result Extraction

Model results from a set of locations along Ruten were extracted for each model setup and used to compare the performance of the various setups against each other.

The model setup against which the others were compared (i.e. Base) was the 0.4-m grid MIKE 21 Classic model using the calculation grid with the finest resolution based on available DTM data. The parameters compared were:

- Discharge and total flow volume through road sections (Sections 1, 2 and3)
- Maximum current speed over Ruten road area
- Maximum water depth over Ruten road area

Model Types

The model types tested varied in terms of the following parameters:

- Calculation grid size
- Calculation grid type and engine

1.3 Tests and Results

A summary of the main model setups in the evaluation is shown in Table 1 below. Setup #1, the classic grid 2D model with a grid resolution of 0.4 m was considered the Base model against which the other models were compared in this study. Classic and flexible mesh (FM) models were used in the tests, and performance evaluation was based on deviations of model scenario results from Base model results.

Table 1 Summary of model setups used in the study.

Setup No.	Model	Classic Grid Size [m]	FM Element Size [m2]	FM Quad. Element Size [m2]
1 (Base)	**MIKE 21**	**0.4**		
2	MIKE 21	1		
3	MIKE 21	5		
4	MIKE 21	10		
5	MIKE 21	20		
6	MIKE 21 FM		~0.16	
7	MIKE 21 FM		~1	
8	MIKE 21 FM		~25	
9	MIKE 21 FM		~100	
10	MIKE 21 FM		~400	
11	MIKE 21 FM			0.16
12	MIKE 21 FM			1
13	MIKE 21 FM			25
14	MIKE 21 FM			100
15	MIKE 21 FM			400

1.3.1 Discharge and Flow Volumes

Model results for discharge magnitudes and flow volumes through the selected road sections (Figure 4) were the main parameters used in the evaluation of model performance.

Classic and flexible mesh (FM) models were used in the tests. Two sets of FM models were tested—one set using meshes with triangular elements, and another with quadrangular elements (i.e. squares) mimicking the classical grid.

The following tables (Table 2-Table 4) summarise key statistics on discharge and flow volume results extracted from the various model setups. Further discussion on the results are presented in succeeding sections.

Table 2 Classic grid models result summary for varying resolutions. The 0.4-m grid size model was considered the Base model against which the others were compared.

Setup No.	Grid Size	Elapsed Time [h]	Road Section	Qpeak [m3/s]	Qpeak Error [%]	Volume [m3]	Volume Error [%]
#1 Base	**0.4**	**48.24**	**1**	**0.228**	**-**	**1507.68**	**-**
			2	**0.421**	**-**	**2874.64**	**-**
			3	**0.606**	**-**	**4646.56**	**-**
#2	1	6.37	1	0.203	**-11.09**	1381.43	-8.37
			2	0.404	**-4.05**	2875.04	**0.01**
			3	0.628	**3.60**	4812.98	**3.58**
#3	5	0.16	1	0.107	-52.96	1483.95	**-1.57**
			2	0.326	-22.63	3064.50	6.60
			3	0.671	10.62	4419.08	-4.90
#4	10	0.09	1	0.063	-72.49	923.41	-38.75
			2	0.252	-40.20	2656.98	-7.57
			3	0.872	43.91	6569.47	41.38
#5	20	0.08	1	0.110	-51.87	365.56	-75.75
			2	0.216	-48.83	1743.74	-39.34
			3	0.410	-32.37	3254.09	-29.97

Table 3 Triangular mesh models result summary for varying resolutions. The 0.4-m Classic grid model was considered the Base model against which the others were compared (see Table 1). Note that sizes are only approximate for triangular elements.

Setup No.	Element Size [m]	Elapsed Time [h]	Road Section	Qpeak [m3/s]	Qpeak Error [%]	Volume [m3]	Volume Error [%]
#12	1	58.17	1	0.211	**-7.48**	1486.97	**-1.37**
			2	0.410	**-2.56**	3000.63	**4.38**
			3	0.672	10.88	4237.77	-8.80
#13	5	0.43	1	0.133	-41.67	1606.76	6.57
			2	0.365	-13.22	3587.17	24.79
			3	0.745	22.94	4571.05	**-1.62**
#14	10	0.07	1	0.048	-78.94	568.25	-62.31
			2	0.207	-50.91	1325.86	-53.88
			3	0.581	**-4.21**	5184.27	11.57
#15	20	0.02	1	0.108	-52.56	882.19	-41.49
			2	0.303	-28.10	2366.03	-17.69
			3	0.000	-100.00	0.00	-100.00

Table 4 Quadrangular mesh models result summary for varying resolutions. The 0.4-m Classic grid model was considered the Base model against which the others were compared (see Table 1).

Setup No.	Element Size [m]	Elapsed Time [h]	Road Section	Qpeak [m3/s]	Qpeak Error [%]	Volume [m3]	Volume Error [%]
#7	1	31.93	1	0.193	**-15.39**	1405.32	**-6.79**
			2	0.376	**-10.65**	2875.65	**0.04**
			3	0.716	18.05	4686.89	**0.87**
#8	5	0.60	1	0.124	-45.84	1327.51	-11.95
			2	0.306	-27.27	3091.73	7.55
			3	0.663	**9.37**	4545.94	-2.17
#9	10	0.03	1	0.145	-36.60	929.86	-38.32
			2	0.300	-28.79	2008.65	-30.13
			3	0.824	35.95	6491.27	39.70
#10	20	0.01	1	0.163	-28.53	778.15	-48.39
			2	0.520	23.37	2985.09	3.84
			3	0.480	-20.85	4269.51	-8.11

Grid Size

The size of the calculation grid is an important parameter in 2D modelling. Tests were performed to quantify the impact of changing grid size on 2D road model performance.

Classic grid models

For classic grid model set, cross-section plots from computation grids of different resolutions at the three selected sections across Ruten are shown in Figure 5. The plots visually illustrate the effect of grid coarsening to elevations and cross section representation. The lines in red are the road sections for the Base model, and the other lines show the same road cross sections from the other model calculation grids.

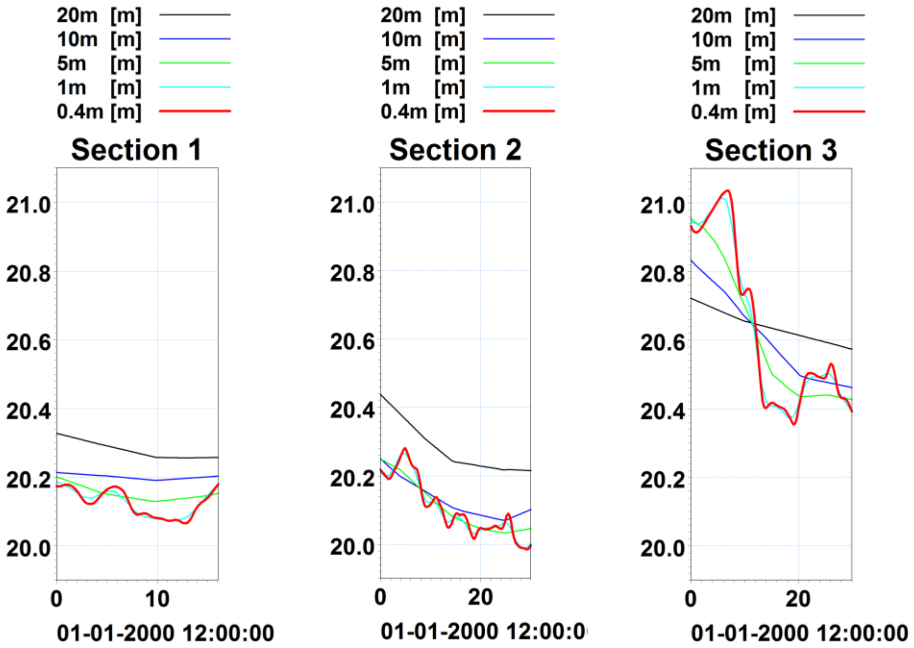

Figure 5 Comparison of cross section profiles at 3 sections along Ruten for different 2D Classic grid resolutions. The red lines show cross sections from the Base model.

The effect of coarser grid resolutions is visually apparent in plots of the road sections in Figure 5. A grid size of 1 m, around double the 0.4 m base resolution, still shows comparable profiles to the Base model. But in general, terrain variations are dampened with grid coarsening, such that local maxima and minima are reduced or lost, even with a relatively fine grid size of 5 m. Nevertheless, the general dip of the road across a section is maintained, such that tilt direction remains consistent despite coarser grids of up to 20 m.

Figure 6 to Figure 8 show plots of discharge (left figures) and accumulated discharge (right figures) results from the various model setups at the 3 road sections along Ruten. Results from the Base model are indicated by the red curves.

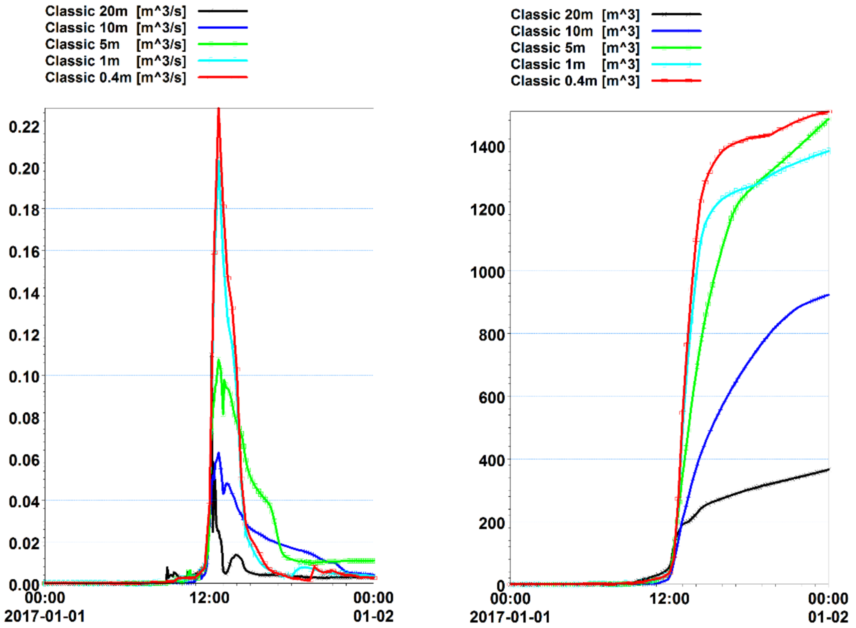

Figure 6 Section 1 comparison of discharge and accumulated discharge for different 2D Classic grid resolutions.

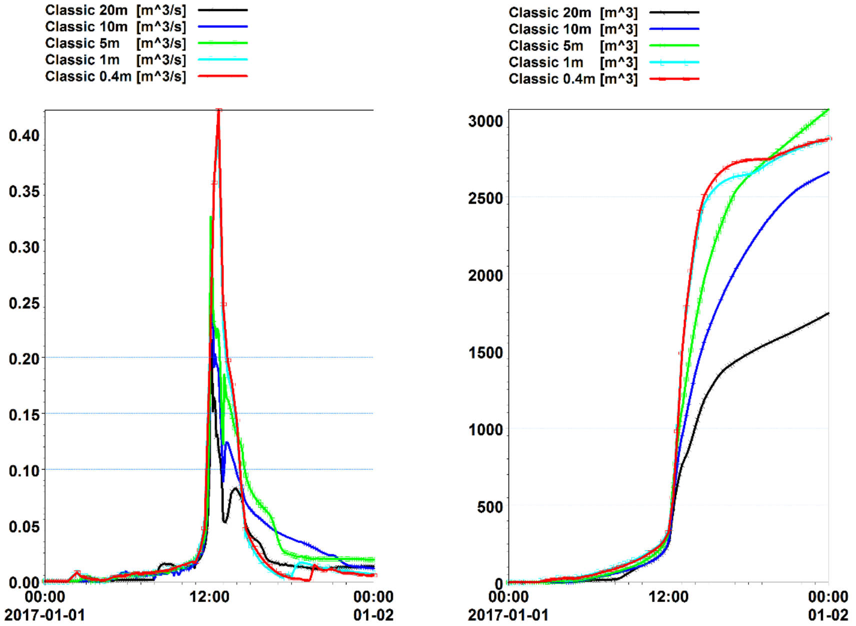

Figure 7 Section 2 comparison of discharge and accumulated discharge for different 2D Classic grid resolutions.

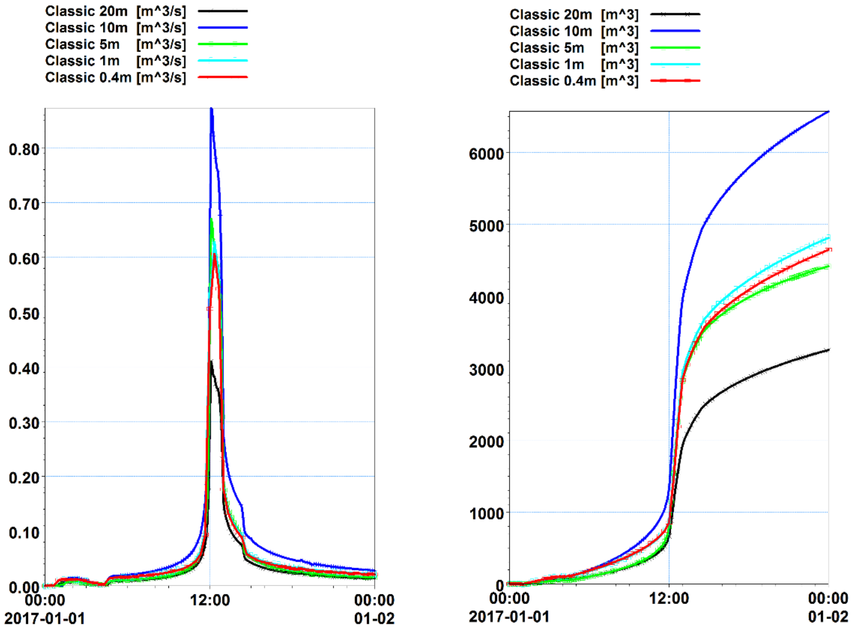

Figure 8 Section 3 comparison of discharge and accumulated discharge for different 2D Classic grid resolutions.

Grid coarsening generally resulted into reduced conveyance in terms of discharge magnitude and volume along the road as observed in the figures.

Note that at section 3, the inconsistent increased conveyance with the coarser 10-m grid size (see Figure 8) was likely due to the grid not reflecting the splitting of the flows between the roadway and the shoulder (Figure 9).

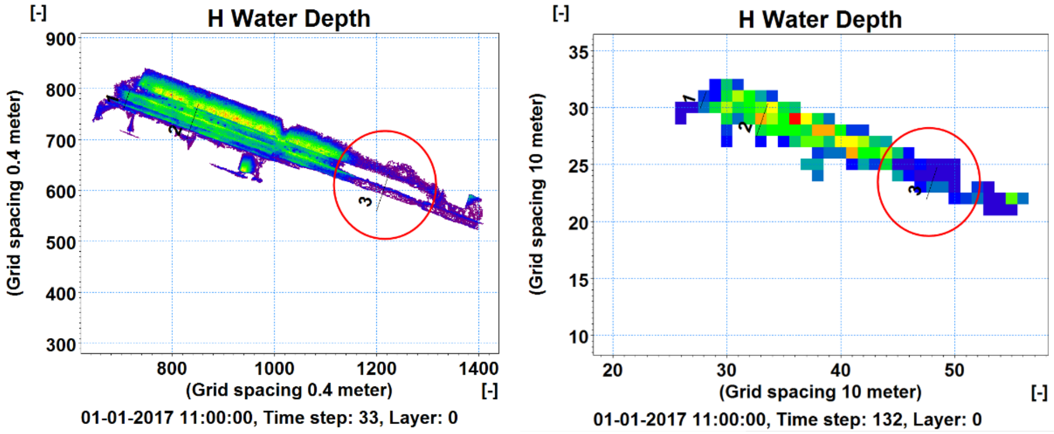

Figure 9 Plots of calculated depths along Ruten for the Base model (left) and the 10-m grid model (right) showing the location of Section 3.

The splitting of the flows at section 3 near the inflow point was not reflected in the 10-m grid model, and thus the coarser model had a larger flow cross section through the result extraction line, which was maintained throughout all the test setups (i.e. the same section length).

Table 2 summarises some statistics for extracted results from the various 2D classic grid model setups for more detailed evaluation of model performance against the Base setup. From the summary, the 1-m grid road model performed the best in terms of peak discharge and flow volume results, with errors for peak discharge ranging from 4-11%

and volume errors of 0.01-8%. However, the 5-m grid performed similarly well especially when computation time is considered.

Compared to the 1-m grid, the total volume conveyed through the road sections for the 5-m grid model were very similar, with errors ranging from 2-7%. The peak discharge errors were however more significant reaching 53% at one point (Section 1). Nevertheless, this may be offset by the significant gain in computation speed (40 times) when using the 5-m compared to the 1-m grid model.

When conveyed volume is the main consideration, the 5-m grid model of Ruten performs strongly compared to the other models in the test, resulting to low flow volume errors while allowing for fast computation speeds 40 times faster than the 1-m grid model.

Flexible Mesh (FM) Models

For flexible meshes comprised of triangular elements, the effect of surface interpolation with larger element sizes was consistent with that for classic grids (see Figure 10).

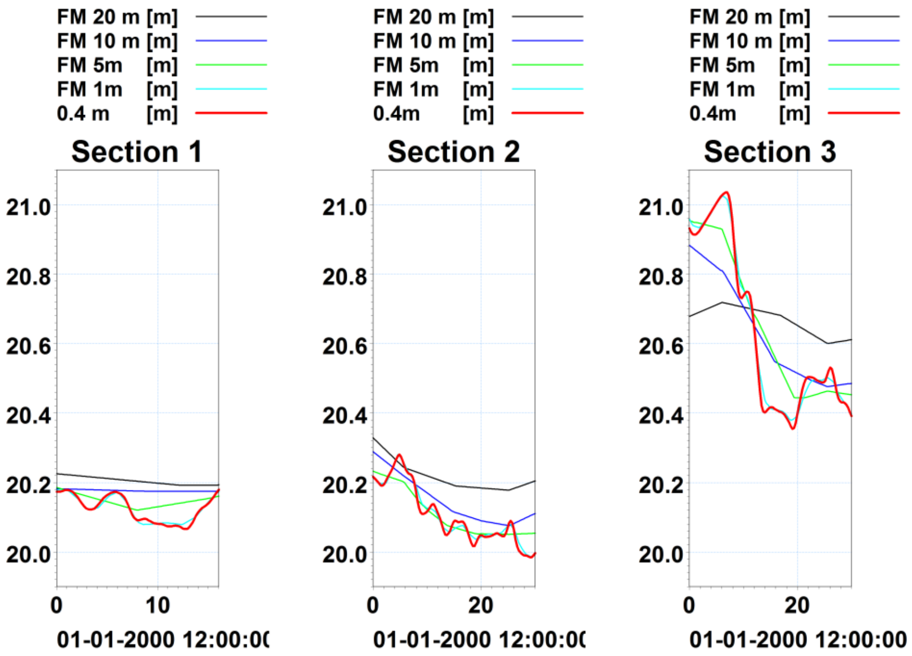

Figure 10 Comparison of cross-section profiles at 3 sections of Ruten for different 2D FM mesh resolutions compared against the Base model grid (in red).

Smoothing of local depressions and peaks across the road sections was also apparent. However, deviation from base data values (i.e. 0.4 m grid) with coarsening were less with meshes than with grids, as illustrated by comparison of the cross-section plots for 10-m (in blue) and 20-m (in black) resolutions on the left and middle plots in Figure 5 and Figure 10.

The advantage of the 1-m resolution (i.e. 1-m^2 element size) model in terms of result accuracy was also observed with the mesh models. For FM setups, the stronger performance with the finer (~1 m2) resolution was also observed. However, the computation speed of the ~25-m2 mesh model was significantly faster compared to that of the ~1-m2 mesh model. There was a speed-up factor improvement 135 from the 1-m to 5-m resolution triangular FM model set, and 53 for the quadrangular FM model set. This may heavily tip the scale in favour of using the coarser (i.e. 5-m resolution) FM model over the finer one especially when conveyance volumes are more important than flow magnitudes in the analysis.

Compared to the Base model, the 1-m resolution mesh models performed poorly in terms of computation speed, taking longer or almost as long as the Base model computation. This may be attributed to the FM models using adaptive time steps that can become as small as 0.001 s when the FM computation tries to maintain relatively low CFL values. Moreover, computations with the FM models did not employ available parallel computing options.

Thus, 5-m grid resolution FM models of Ruten perform strongly compared to the other FM setups when flow volumes are of importance. They produce low flow volume errors while allowing for fast computation speeds 53-135 times faster than the 1-m resolution FM models.

In general, much coarser grid and mesh sizes (i.e. 10-20 m) performed poorly in terms of comparability of discharge and volume results to the Base model (0.4-m grid). Mean errors of more than 40% for both peak discharge and flow volume were observed with the coarser models, with one scenario (Setup #15) completely diverging (i.e. 100% error) from Base model results. With coarser grids ranging from 10 -20 m in size, the quadrangular mesh performed better on average than the classic and triangular mesh in terms of both peak discharge and flow volume accuracy.

Grid Type

Discharge magnitudes and flow volumes across the 3 road sections were also examined to evaluate the performance of various model grid types. The figures below show comparison plots of discharge and flow volume values at the 3 road sections from each model grid type (i.e. classic, triangular FM, or quadrangular FM) for each model grid resolution.

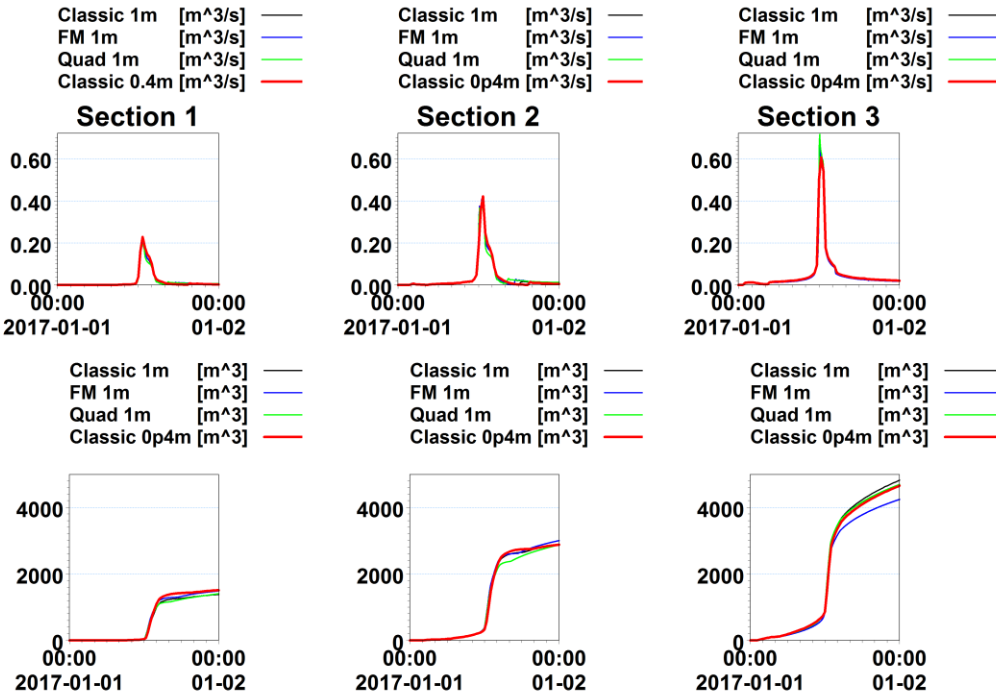

Figure 11 Comparison of discharge and accumulated volume at the 3 road sections for different 1-m resolution 2D grid types. Note that triangular mesh elements are only approximately 1 m2.

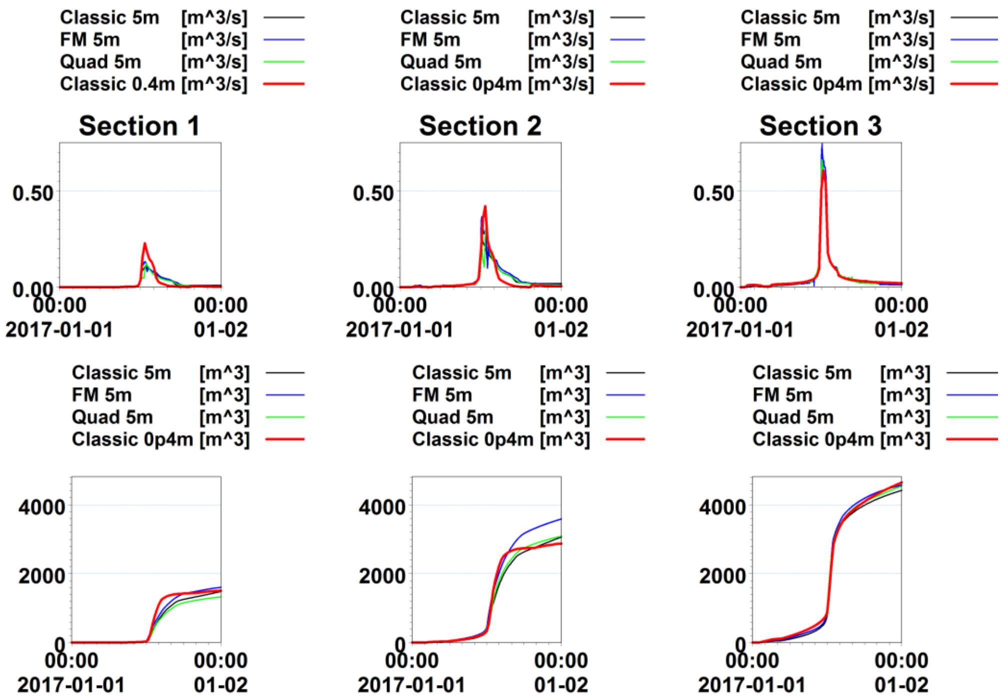

Figure 12 Comparison of discharge and accumulated volume at the 3 road sections for different 5-m resolution 2D grid types. Note that triangular mesh elements are only approximately 25 m2.

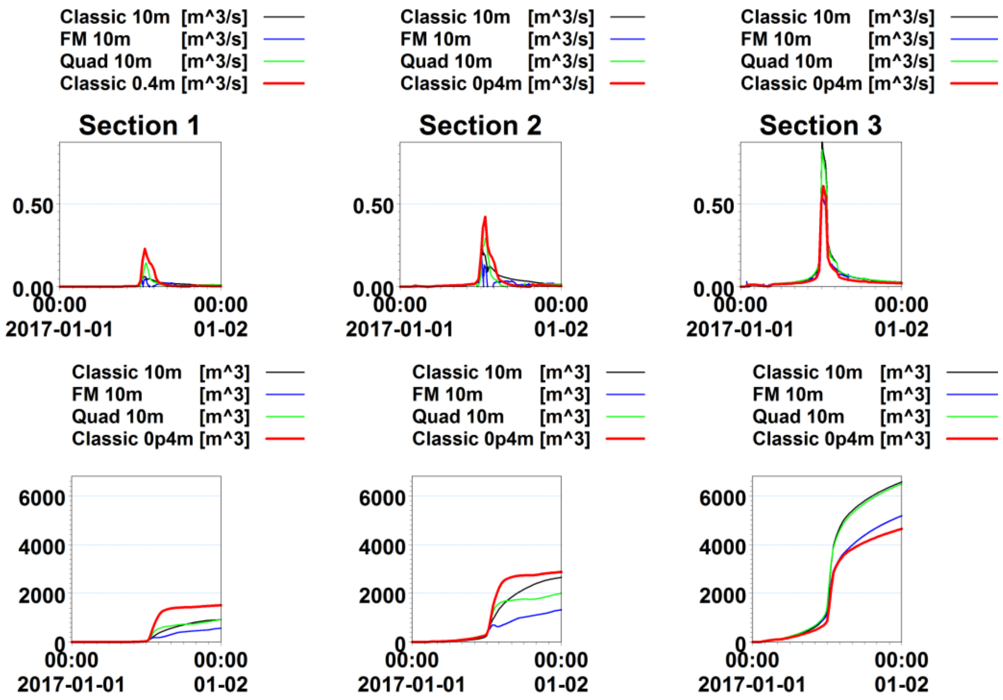

Figure 13 Comparison of discharge and accumulated volume at the 3 road sections for different 10-m resolution 2D grid types. Note that triangular mesh elements are only approximately 100 m2.

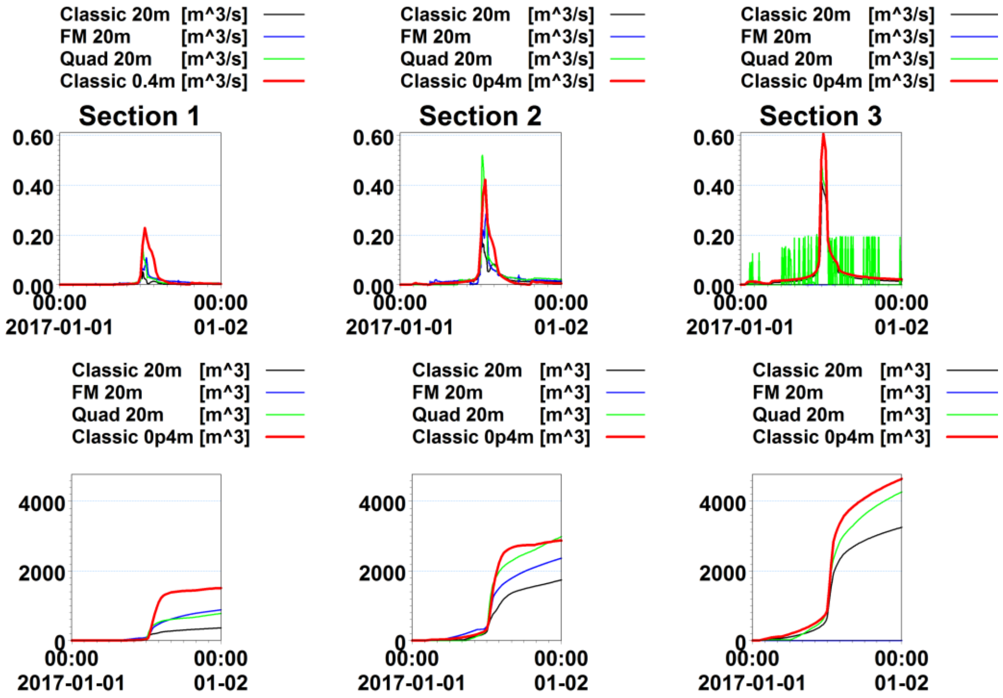

Figure 14 Comparison of discharge and accumulated volume at the 3 road sections for different 20-m resolution 2D grid types. Note that triangular mesh elements are only approximately 400 m2.

From a cursory examination of the plots, result errors among the different grid types remain similar up to the 5-m resolution model set (Figure 11 and Figure 12). Result error differences become more apparent by a resolution of 10-m and coarser (Figure 13 and Figure 14). In Figure 14, the overall performance of the triangular mesh model was greatly reduced by the complete diversion from Base results in road section 3 for the 20-m mesh.

The plots below aggregate the calculated errors at the 3 road sections for each model setup. They indicate that the performance of the various grid types with respect to peak discharge and flow volume errors became more similar with finer grid/mesh resolutions as indicated by less spread in error data points at finer gird/mesh sizes.

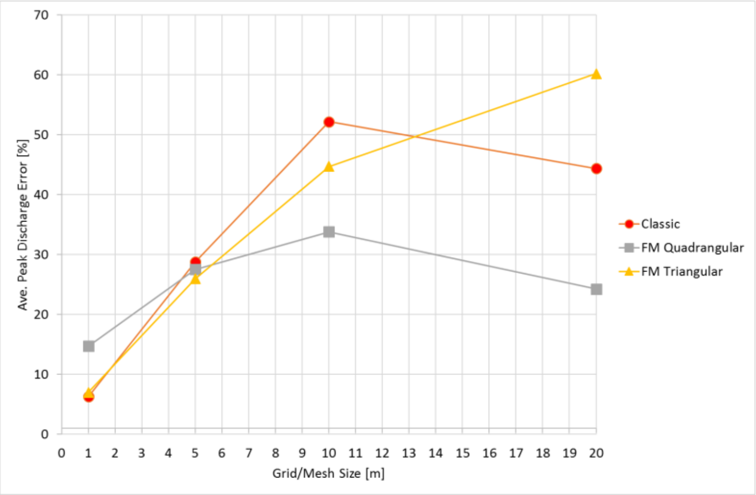

Figure 15 Plots of average absolute peak discharge error variation with grid size for the different grid types tested for Ruten. Error values were averaged among the 3 road sections.

In terms of peak discharge, the quadrangular FM model performed generally better than either the classic or triangular FM models (see grey line in Figure 15).

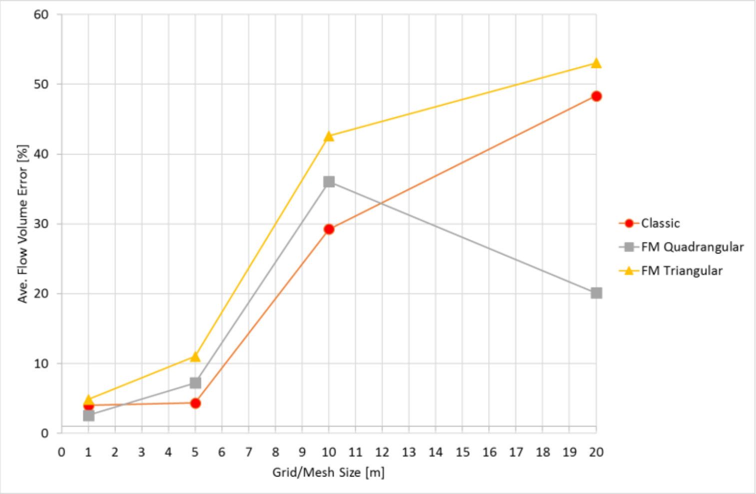

Figure 16 Plots of average absolute flow volume error variation with grid size for the different grid types tested for Ruten. Error values were averaged among the 3 road sections.

With respect to flow volumes, both the classic grid and quadrangular FM models perform better than the triangular FM model (Figure 16). However, when considering computation time, the Classic model performed better overall compared to the FM models, with differences of around 3-9 times faster (Figure 17). The longer computation times with the FM models may be attributed to their use of adaptive time steps that can become very small as the calculation engine tries to maintain computational stability.

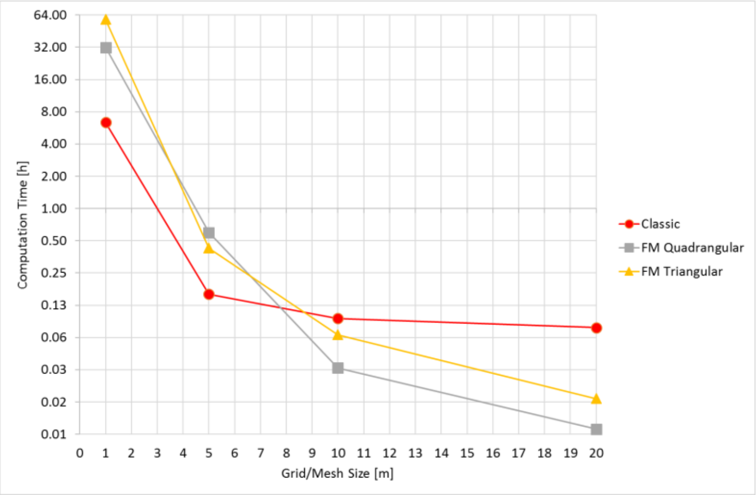

Figure 17 Plots showing variation of computation time to grid/mesh resolution for the different grid types tested for Ruten. Note that parallelisation and hybrid computing were not used for the FM (mesh) models in the tests.

Thus, with respect to grid type, accuracy in terms of peak discharge and flow volumes and fast computation times (without application of speed-up techniques) are best afforded using Classic grid models when using high resolutions (1-5 m), and Quadrangular FM models when using low resolutions (10-20 m).

1.3.2 Maximum Depth and Speed

Water depths and flow velocities will be important considerations when road sections are made to convey overland flows for flood management, as certain depths and velocities would prohibit use of the road for passage of vehicles or pedestrians.

Thus, in this study, computed depths and current speeds over the modelled road area were used as comparison parameters for model performance evaluation. For model result comparison, spatially-distributed values of water depth and current speed were extracted from the various 2D model results over the Ruten road section. As before, the 0.4-m grid Classic grid model was used as the Base model for comparison and model evaluation.

Grid Size

The figures below (Figure 18 to Figure 20) show map plots of maximum depth and current speed statistics over Ruten from results of the various model setups tested in the study.

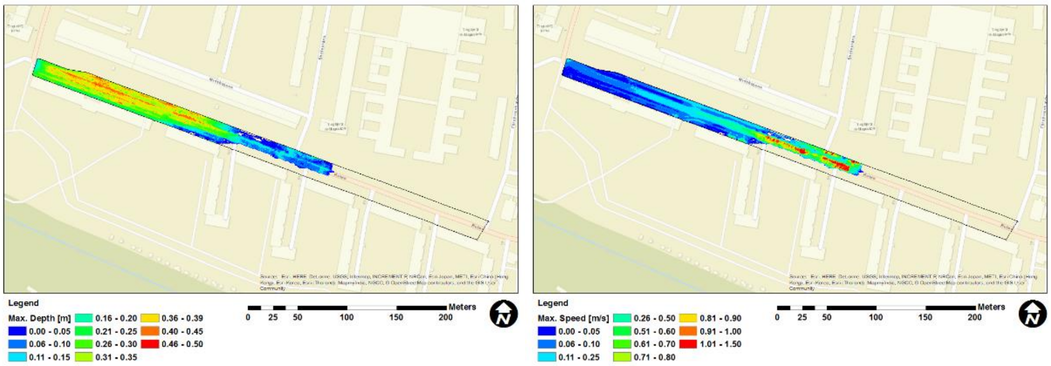

Figure 18 Maximum depth (left) and speed (right) results over Ruten from the Base (Classic 0.4 m-resolution) model.

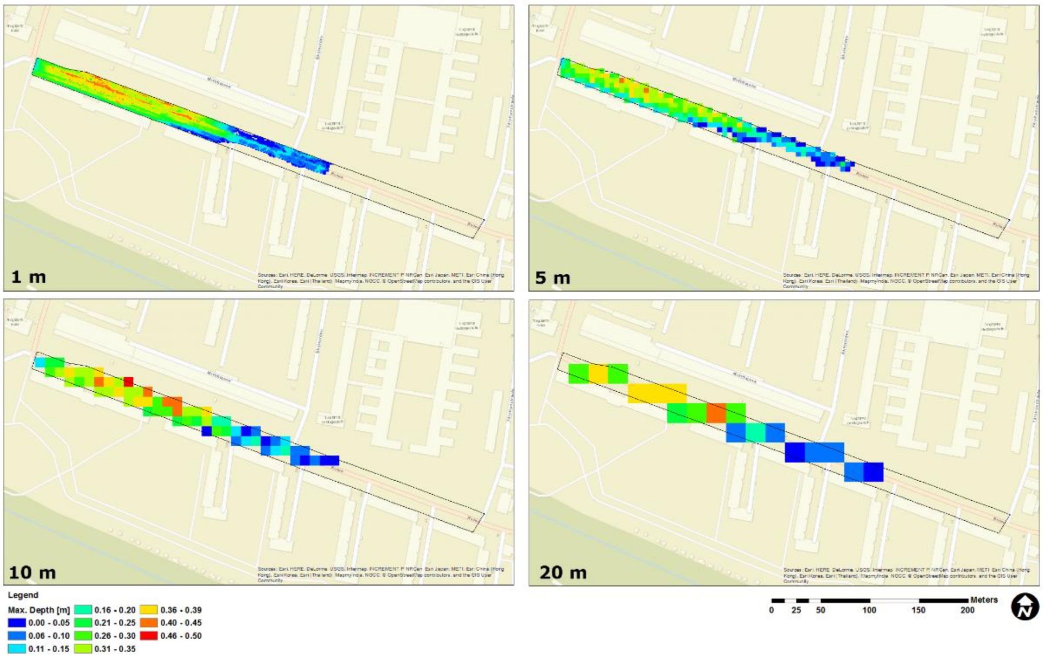

Figure 19 Plots of Maximum depth results over Ruten from the 1-, 5-, 10-, and 20-m resolution Classic grid models.

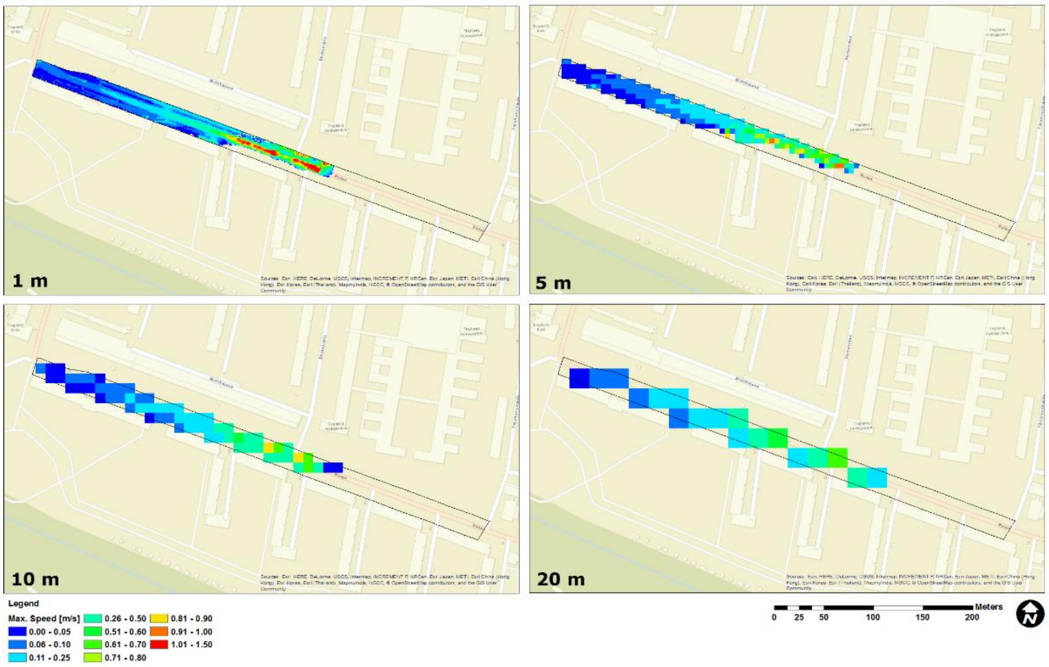

Figure 20 Plots of maximum speed results over Ruten from the 1-, 5-, 10-, and 20-m resolution Classic grid models.

The effects of grid coarsening are visually apparent from Figure 19 and Figure 20, which show extracted spatially-distributed results from models of varying resolution tested in the study. Grid coarsening caused averaging and loss of detail on the spatial distribution of flow parameter values over the model area.

A summary of key statistics on spatially-distributed maximum depths and current speeds over Ruten is presented in Table 5 for easier quantitative comparisons among the different models.

Table 5 Summary of statistics on spatially-distributed maximum depths and current speeds over Ruten for the various model setups. The 0.4-m resolution Classic grid model was considered the Base model against which the others were compared.

Setup No.	Grid Size [m]	Wet Area [m2]	Area % Error	Max. Depth [m]	Depth % Error	Max. Speed [m/s]	Speed % Error
#1 Base	**0.4**	**5 823**		**0.468**		**1.442**	
#2	1	5 878	**0.95**	0.450	**-3.76**	1.337	-7.27
#3	5	5 625	**-3.39**	0.404	**-13.67**	0.977	-32.23
#4	10	6 300	8.20	0.455	**-2.75**	0.807	-44.05
#5	20	7 200	23.66	0.424	**-9.44**	0.631	-56.21
#6	1 (Quad.)	5 282	-9.28	0.422	-9.80	1.395	**-3.24**
#7	5(Quad.)	5 200	-10.69	0.368	-21.28	1.762	22.18
#8	10 (Quad.)	5 600	**-3.82**	0.382	-18.32	0.838	-41.88
#9	20 (Quad.)	5 600	**-3.82**	0.408	-12.75	0.408	-71.69
#10	~1 (Triang.)	5 265	-9.57	0.446	-4.67	2.520	74.81
#11	~5 (Triang.)	5 212	-10.48	0.385	-17.64	1.138	**-21.04**
#12	~10 (Triang.)	5 087	-12.64	0.357	-23.72	1.225	**-15.04**
#13	~20 (Triang.)	5 317	-8.69	0.373	-20.30	0.689	**-52.22**

In terms of grid size, there is a trend towards improved performance with higher grid/mesh resolutions with respect to flood extent, and maximum depth and speed results, for the different types of models (i.e. Classic and FM).

Grid Type

In terms of grid type, Table 5 indicates that either Classic grid or triangular mesh models preform the best, depending on the result parameter of interest, when maximum water depth and current speed values are of high importance in the analysis.

Classic grid models performed the best with respect to simulating spatially-distributed flow extent and maximum depths in Ruten, while triangular mesh FM models resulted into lower errors for maximum current speeds over the road area. These observations are also illustrated in Figure 21 and Figure 22 below.

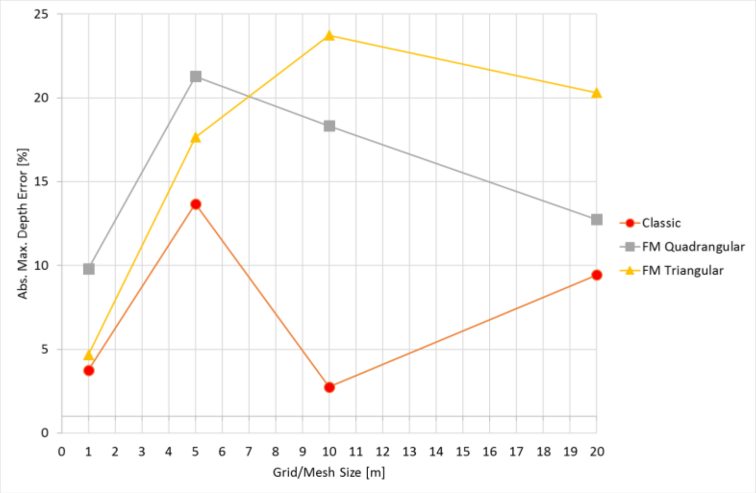

Figure 21 Plots of absolute maximum depth error variation with grid size for the different grid types tested for Ruten.

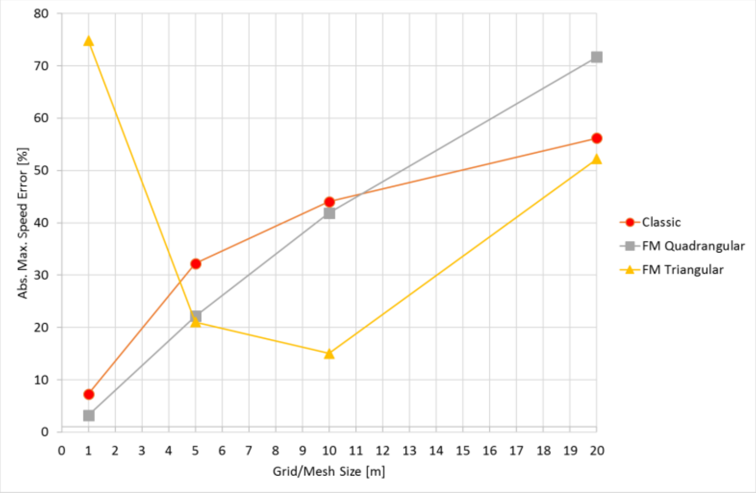

Figure 22 Plots of absolute maximum current speed error variation with grid size for the different grid types tested for Ruten.

In Figure 22, the high maximum speed error for the 1-m resolution triangular mesh model may indicate localised instability, and thus improvement of the model setup should be explored.

1.4 Summary of Findings

Without using parallelisation or hybrid computing techniques, Classic grid models of reasonable resolution performed best in modelling Ruten.

Based on the tests in this study, grid resolutions of 1-5 m performed best with respect to result accuracy in terms of peak discharges and flow volumes through the road section, as well as maximum depth and current speed results over the road area in Ruten.

Based on the study, and considering computation speed as an important consideration, the Classic 5-m grid resolution model is recommended for modelling a roadway such as Ruten. It performed strongly in terms of flow volumes conveyed through the roadway as well as maximum depths simulated over the road area. Reasonable performance was also observed in terms of discharge magnitudes through the road section. Simulation of maximum speeds over the road area was poorer compared to other model types, but speed-up factors with the 5-m grid model were encouraging at 40 times compared to the fastest lower resolution(i.e.1-m grid) model, and around 2.5 times faster than the fastest FM model of a similar resolution (i.e. 5 m). This was, however, without the use of parallelisation or hybrid computing techniques for the FM models.

When calculation time is not a key factor, 1-m resolution grid and mesh models are recommended. Application of speed-up techniques for FM models may tip the scale towards the use of these model types when using high-resolution (e.g. 1 m) computation grids.

Ruten has an average width of 6 m, including the bike path and walkways on either side. Grid resolutions between 1-5 m afford at least one grid element spanning the roadway width, and thus a reasonable grid resolution could be a size that allows for a continuous chain of grids along the roadway. Further tests on this is suggested by modelling other roadways of widths and alignments different from that of Ruten.