Benchmark study of numerical model grids to study historic floods of the river Rhine

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Abstract

Up until now, structured curvilinear grids are commonly used for hydraulic modelling. However, this grid type has several disadvantages such as staircase representations along closed boundaries and unnecessary high resolution in sharp inner bends. A so called ‘flexible mesh’ can overcome these limitations, since different shapes of grid cells can be used. However, model performance is not directly clear. Several different grid types are compared based on model performance and computation time. This shows that an unstructured grid with curvilinear grid cells in the summer bed and triangles in the floodplains is the most appropriate mesh for 2DH hydraulic modelling. A curvilinear grid in the summer bed ensures high resolution in the channel cross direction, while less grid cells are needed compared to a complete triangular grid. This has a beneficial effect on computation time.

1. Introduction

At present, Dutch water policy is changing from a probability exceedance approach towards a risk based approach. This new approach considers not only the probabilities of floods due to multiple failure mechanisms. It also considers the consequences of a flood, which results in a significant increase of safety levels in areas with high population density, large economic value or vulnerable infrastructure (Van der Most, Slootjes, & Schasfoort, 2014). While a maximum recurrence time of 1/1,250 years was defined for the river areas in the current probability exceedance approach, the newly risk based approach leads to safety levels of dikes along the Dutch Rhine branches between 1/300 and 1/100,000 years (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2014)

At present, the traditional flood frequency method (based on extrapolation of historical records of only 110 years) is used to compute discharges corresponding to any return period. However, due to the short data set of measured discharges this method yields large uncertainties in predicting design discharges corresponding to extremely large recurrence times. This uncertainty can be reduced by extending the historical records of yearly maximum discharges of the river Rhine backward in time. In order to do so, historic floods are going to be be reconstructed using hydraulic models. The aim of the flood reconstructions is to extend the current measured discharge series with modelled historical events. Reconstructed schematizations of the historical events will be used in two-dimensional (2DH) hydraulic numerical models.

Up until now, structured curvilinear grids are commonly used for hydraulic modelling and discretizing the model domain. However, staircase representation of closed boundaries is not always unavoidable. Additionally, in sharp inner bends gridlines are focused leading to unnecessarily small grid cells (Kernkamp et al., 2011). This unnecessary high resolution has a negative effect on computation time and is especially a problem when embanked areas are included in the model domain. In this study we will investigate which way of modelling, in particular which grid, leads to a sufficient accurate, though computationally fast river model. We will study if a flexible mesh is a good alternative for the curvilinear grid cells. In a flexible mesh, different grid shapes may be used (e.g. curvilinear cells, triangles, pentagons). Therefore, a flexible mesh may overcome the problem of high resolution in sharp inner bends by coupling curvilinear grid cells in the river branches with triangular grid cells in the embanked areas. The coupling between curvilinear and triangular grid cells allows a great increase in grid size in areas with low interest. However, the performance of a flexible mesh is not immediately clear, since the unstructured grid of a flexible mesh requires another numerical solution method than a structured curvilinear grid. Therefore, several grid types will be compared in terms of model performance and computation time. After comparing the different grids, a recommendation will be given which grid is most appropriate for 2DH hydraulic modelling of a relatively large river area including floodplains and embanked areas. This grid will in further studies used to simulate several historic floods in order to extend the dataset of measured maximum discharges of the river Rhine.

2. Method

The effect of different grid types on model performance and computation time is investigated on an stretch of the Rhine river with a length of ~44 km, from the city of Andernach (Germany) to the confluence with the river Sieg. An upstream boundary condition of a constant discharge of 10,000 m^3/s is implemented. Downstream a Qh-relation is implemented. Maximum water levels are compared at eight locations along the river branch and also the computation-time is logged.

2.1 Grid types

In total, four grids are considered: two hybrid (curvilinear-triangular) grids and two complete triangular grids. The coupled grids have a curvilinear grid in the summer bed of the river Rhine while the floodplains are discretized by triangles. Different resolutions of both grid types are considered to study the effect of resolution on model performance and computation time. The following grids are studied:

1. Hybrid grid high resolution: This grid has 16 grid cells in transverse direction of the summer bed to be able to include the bathymetry of the summer bed with high accuracy. The floodplains are discretized by triangles in which the size of the triangles is adjusted to the length of the curvilinear grid cells (Fig. 1). This results in relatively large triangles (a low resolution grid) in the floodplains.
2. Hybrid grid low resolution: This grid is identical to grid 1. Only the width of the curvilinear grid cells was increased with a factor 2, leading to eight grid cells in river cross direction. Note that the length of the grid cells remains the same as grid 1 and therefore also the resolution in the floodplains.
3. Triangular grid low resolution: The whole study area is discretized by triangles. The resolution in the floodplains is identical to the resolution of grid 1 and 2. This leads to a relatively low resolution in the river cross direction with only two till three triangles.
4. Triangular grid high resolution: The whole study area is discretized by triangles as in grid 3. However, the size of the triangles was decreased in order to get 8 to 12 grid cells in the width of the summer bed. The resolution was decreased towards the boarders of the model domain.

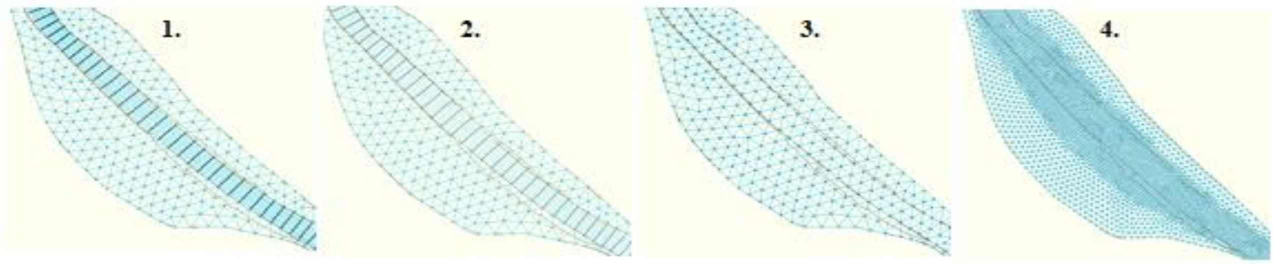

Figure 1: The four grid types studied, in which grid 1 and 2 represent the hybrid grid types and grid 3 and 4 the complete triangular grids.

2.2 D-Flow FM solver

Since there are no grid rows and columns present in case of an unstructured flexible mesh, there is also no ADI-solver possible (Deltares, 2016b). D-Flow FM solves the 2D shallow water equations on a staggered grid with the use of a finite volume solver. The grid needs to be orthogonal to be able to implement a staggered scheme. A grid is orthogonal when the circumcentre (i.e. intersection of the bisectors) of each cell lies within that cell, and the line segment that connects the circumcentres of two neighbouring cells should intersect orthogonally with the interface between them (Kernkamp et al., 2011). For more information about the D-Flow FM solver and orthogonality principle see Deltares (2016a) and Kernkamp et al. (2011).

3. Results

The results of the simulations are given in Table. 1. The locations represent the distance in km from the upstream boundary. The grids are compared based on water level since this parameter indicates if inundations will evolve. So, in order to model flood patterns correctly it is of great importance that water levels are modelled with sufficiently high accuracy. The water levels of each grid are compared with grid 1, since this grid has the highest resolution in the summer bed and therefore is expected to have the highest accuracy.

Table 1: Simulated water levels for the four different grid types.

	Grid 1	Grid 2		Grid 3		Grid 4	
Grid cells in summer bed	16	8		2-3		8-12	
Locations	*Water level [m]*	*Water level [m]*	*Diff. [m]*	*Water level [m]*	*Diff. [m]*	*Water level [m]*	*Diff. [m]*
Km 1	60,21	60,34	-0,13	60,63	0,42	60,06	-0,15
Km 9	58,5	58,56	-0,06	59,35	0,85	58,5	0

Km 16	57,34	57,41	-0,07	58,41	1,07	57,43	0,09
Km 22	55,94	56	-0,06	57,1	1,16	55,99	0,05
Km 28	54,99	54,95	0,04	55,66	0,67	54,98	-0,01
Km 32	54,16	54,08	0,08	54,66	0,5	54,36	0,2
Km 40	52,5	52,34	0,16	52,65	0,15	52,66	0,16
Average difference [m]			0,09		0,69		0,09

The results show that grid 3 has a high deviation of approximately 70 cm in water level compared to grid 1. This high deviation can be explained by the schematised geometry of the summer bed and therefore by the amount of grid cells in the river cross direction. More grid cells will lead to a schematization of higher accuracy. Only including 2 to 3 grid cells will lead to a unreliable representation of the geometry. Fig. 2 shows how the geometry of the summer bed is discretized inside D-Flow FM. This shows that only considering two grid cells in the transversal direction of the summer bed will lead to an underestimation of the cross section of the river and hence the capacity of the river. Consequently, higher water levels are simulated. It can therefore be concluded that the resolution of grid 3 is not sufficient to correctly predict water levels.

Grid 2 and 4 have equal performance. However, the size of the grid cells inside the summer bed influences the resolution in the floodplains. Therefore, grid 4 has a relatively high resolution in the floodplains (Fig. 1). This unnecessary high resolution has negative influence on computation time. Flow gradients in the channel length direction are often smaller than those in the channel cross direction (Kernkamp et al., 2011). Therefore, curvilinear grid cells are desirable since they are aligned with the flow direction. A curvilinear grid has less grid cells in longitudinal direction compared to a triangular grid, while having a higher resolution in the transversal direction (Kernkamp et al., 2011).

Although grid 1 has the highest resolution and therefore the highest accuracy, this grid is not preferred. The computation time of grids 2,3 and 4 were in the order of minutes. However, the increase of resolution of the summer bed in grid 1 resulted in a computation time in the order of hours. This is highly undesirable since the grid will be used to model historic floods of a much larger area, stretching from Andernach up to the Dutch deltaic areas. Considering the combined results on computation time and model performance, hybrid grid 2 is preferred to be used for 2DH hydraulic modelling.

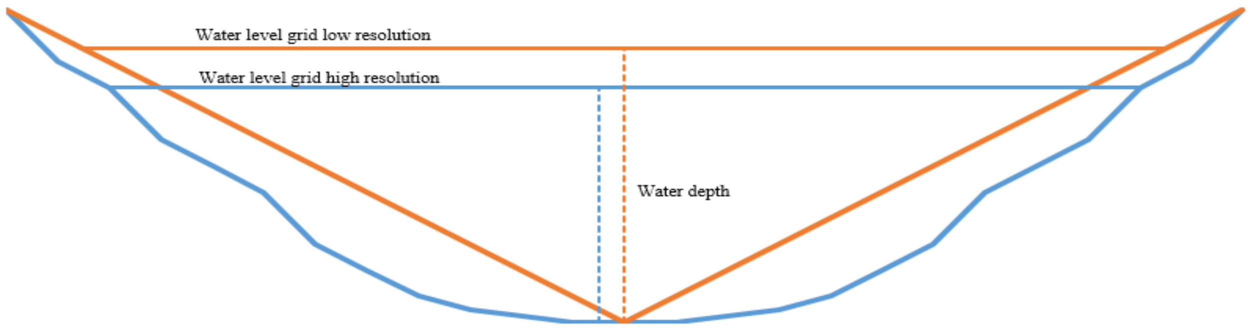

Figure 2: Example of discretization of the summer bed geometry for a grid with only two grid cells in the summer bed (orange) and a grid with a much finer resolution (blue).

5. Conclusions

In this study four different grid types are compared with the use of the model package D-Flow Flexible Mesh. The main focus was to maintain sufficiently high detail in the summer bed to be able to model the water levels accurately, while computation time must still be acceptable. From these criteria it can be concluded that a flexible mesh is a good alternative for the structured curvilinear grid. However, it is advised to keep a curvilinear grid in the summer bed of the river since this results in a relatively high resolution in the river cross direction while having a much lower resolution in the surrounding floodplains.

Although a high resolution in the summer bed is desired, too much detail will result in an extreme increase of computation time. Therefore, a balance should be found between model accuracy/resolution and computation time.

6. Acknowledgement

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