Evaluating the effect of mesh resolution on hydraulic modeling results under various discharge levels

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ABSTRACT: Accurate predictions in river flow modeling are essential for effective river management to support flood and low flow risk assessment. This research examines how mesh resolution and topographic data variability affect predictions in a 2DH finite volume river flow model. Various upstream boundary conditions ranging from low to high flows are considered. By comparing simulated water levels across various cross sections, mesh resolutions, and discharges, we explore potential patterns and trends that illustrate the influence of mesh resolution on model accuracy. This research employs a systematic approach to investigate hydraulic characteristics by simulating hypothetical rivers, which are derived from real-world data. Steady-state simulations are performed with a uniform roughness in the main channel and floodplains, allowing for a focused assessment of the influence of mesh resolution on the results for low, middle and high discharges. The differences in results between coarser and finer mesh resolutions vary notably with discharge levels, particularly for moderate discharges where water levels occur on the banks of the main channel having steep gradients. The river's bathymetry significantly influences the effect of mesh resolution on model output.

1 INTRODUCTION

Accurately simulating water levels in rivers is crucial for managing the environment and water resources. It helps with tasks like predicting floods, river management and planning, and designing infrastructure. Using 2DH hydraulic modeling is a popular method for simulating water levels in rivers. Unlike 1D models that represent the flow as a stream line, 2D models use a continuous mesh to accurately describe the shape of the riverbed (Bomers et al., 2019; Liu et al., 2019). The configuration of the mesh involves two main components: cell shape and cell size. Modelers decide on cell shape based on their priorities or software constraints, aiming to cover the entire river model area (Caviedes et al., 2012). An essential consideration for cell shape is aligning it with the primary direction of the river's channel (Yossef et al., 2018). In contrast, the size of the cells should be in alignment with the input data describing the river's topographical features (Gustard et al., 2009). Horritt et al. (2006) investigated how a 2D river flow model responded to changes in mesh resolution and the quality of topographic data. The findings show that the model is more sensitive to mesh resolution than the accuracy of topographic data. This sensitivity affects hydraulic results like simulated water level (Warmink et al., 2011).

In hydraulic modeling, using high-resolution meshes offers detailed simulations and most of the times increases the accuracy but requires significant computational resources, leading to slower processing times. Low-resolution meshes provide faster runs and lower resource demands, but can compromise the accuracy and quality of predictions. Finding the optimal balance between the two is crucial for effective river management and forecasting (Caviedes et al., 2012, Hardy et al., 1999). A lower mesh resolution leads to lower average flow velocities and, as a result, higher water depths compared to higher resolution and actual measurements. This difference is more noticeable at higher discharge rates (Bilgili et al., 2023). Bomers et al. (2019) emphasized the vital role of mesh selection in hydraulic modeling, particularly in simulating water levels in the Waal River in the Netherlands. Their study recommended hybrid grids with curvilinear cells in the main channel and triangular cells in floodplains as a balanced compromise between computational efficiency and predictive accuracy. This highlights the significant impact of grid size on the overall performance of the model (Bomers et al., 2019).

While previous research has thoroughly investigated the impact of mesh resolution along with other hydraulic parameters on simulation outcomes in hydraulic models, there exists a notable gap in studying the precise influence of mesh resolution on simulation results across different discharges. This type of investigation is essential for understanding how changes in mesh resolution impact simulation accuracy in various discharge scenarios, especially concerning systematic errors that may arise from mesh coarsening. This paper seeks to fill the identified research gap by systematically investigating how mesh resolution interacts with various discharge conditions influencing simulation results. The ultimate goal is to offer valuable insights and recommendations for optimizing mesh resolution in the context of diverse discharge scenarios, ultimately enhancing the accuracy and reliability of hydraulic modeling outcomes.

The methodology includes creating four hypothetical rivers to specifically examine the impact of mesh resolution on hydraulic simulation outputs, isolating it from other uncertainties and complexities. The inclusion of four distinct river bathymetries serves the purpose of exploring whether the shape of the river cross section influences the effects of mesh coarsening. Subsequently, simulations are conducted for various discharges using both high-resolution and low-resolution mesh setups.

2 MATERIAL AND METHOD

2.1 *Hypothetical rivers*

Four different hypothetical rivers are designed for this research. Three of them feature uniform bathymetry, achieved by duplicating a single cross section along the river (single cross section hypothetical river). The last one has a gradually changing bathymetry, resembling a real river more closely. This bathymetry is a combination of cross sections used in the single rivers (combined cross sections hypothetical river). The hydraulic properties of these hypothetical rivers were established using the physical information from the Waal River in the Netherlands. Figure 1 presents the used cross sections. Figure 2 presents one of the single cross section rivers (a) and the combined cross sections one (b).

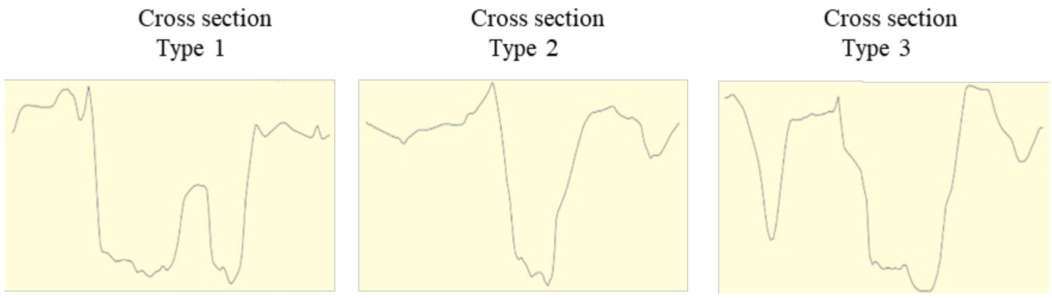
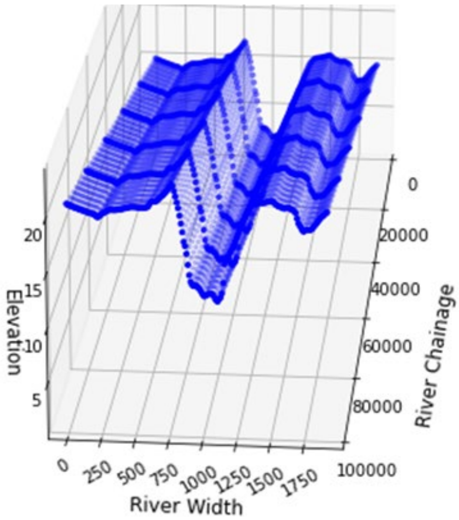


Figure 1. Different type of used cross sections



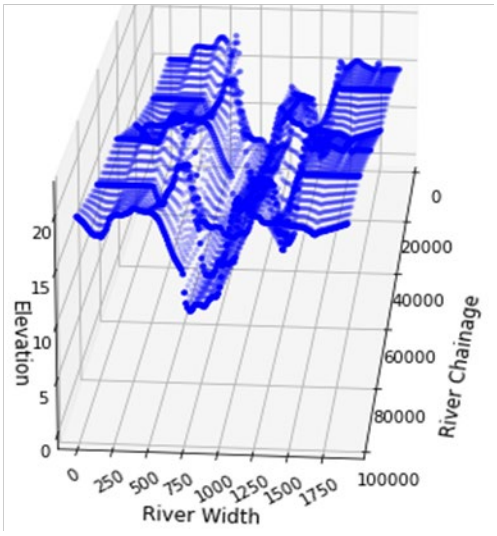


Figure 2. Hypothetical river with a) single cross section and c) combined cross sections.

2.2 *2D hydraulic simulations*

The simulation of flow dynamics and prediction of water levels were conducted using the D-Flow-FM software. D-Flow-FM is advanced modeling software designed to solve the 2D shallow water equations, encompassing the depth-averaged continuity and momentum equations in both the x- and y-directions.

To maintain consistency in the output, the roughness coefficient, a critical parameter in river modeling, was kept constant throughout this research. Various constant discharge values were simulated for the upstream boundary, while the corresponding water level was selected for the downstream boundary.

The choice of upstream discharges is determined by historical discharge data recorded in the Waal River. These selected discharges are classified as low (600 m^3/s), moderate-1 (1000 m^3/s), moderate-2 (2000 m^3/s), moderate-3 (3000 m^3/s), high-1 (5000 m^3/s), high-2 (7600 m^3/s), and, lastly, as an extreme event near the design discharge, high-3 (10000 m^3/s). The simulation was done using two different mesh setups: one with high resolution, consisting of 10m x 10m rectangular uniform cells, and another with relatively low resolution, consisting of 40m x 40m rectangular uniform meshes. Figure 3 presents a part of both meshes. A total of 56 simulations were conducted for this research, with the various combinations outlined in Table 1.

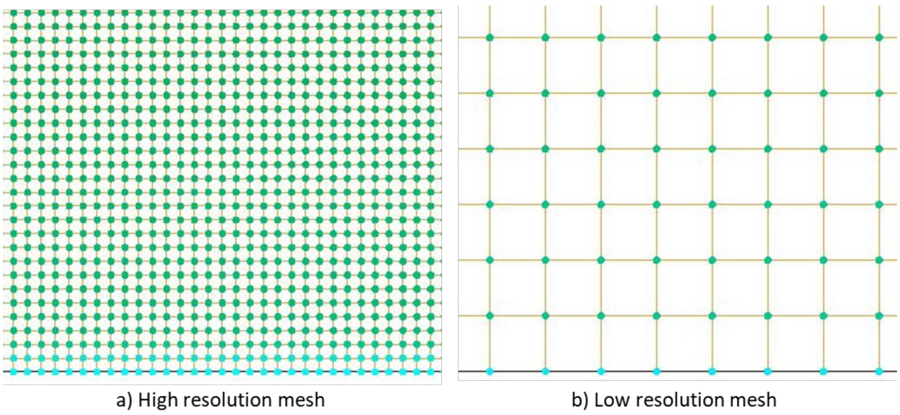


Figure 3. Different type of mesh set up used in the simulations.

Table 1. Simulation design for comparing high-resolution and low-resolution mesh set ups in D-Flow-FM model.

Bathymetry	Mesh setup	Upstream boundary condition
Single 1	High-resolution	Low
Single 2	Low-resolution	Moderate-1
Single 3		Moderate-2
Combined		Moderate-3
		High-1
		High-2
		High-3

2.3 *Output variables*

The output variables selected for assessment in this research are those involved in the commonly used equations for open channel flow, the Manning equation. The Manning equation is an empirical equation applicable to uniform flow in open channels, relying on the channel velocity, flow area, Manning's roughness coefficient, and channel slope as key factors. D-Flow-FM generates numerous flow characteristics as outputs from the hydraulic simulations, and among them, three variables, water level, cross-section velocity and cross-section area, are selected for detailed examination.

3 RESULTS

In this section, the model results from the 56 hydraulic simulations are presented. The plots depicted in Figure 4 illustrate the average differences in output variables between the high-resolution and low-resolution mesh setups. For all variables, the values for the river with single cross sections remain constant along the river since the bathymetry is constant. However, for the river with combined cross sections, the values are not constant due to the changing bathymetry along the river. Therefore, in addition to the average value for each variable, the accompanying lines depict the 95% confidence intervals.

Figure 4a illustrates the differences in water levels for two different mesh setups. The initial observation highlights that the differences are highly dependent on the geometry of the river. Another initial observation is that in the simulated rivers, the water level is generally higher in the low-resolution mesh model compared to the high-resolution mesh model for most discharge scenarios. The abrupt changes observed in river types 2 and 3 for a discharge of 5000 m^3/s and in river type 1 for a discharge of 2000 m^3/s occur in areas where the side channels are inundated. Apart from the sudden changes that occur with increasing discharge, the impact of coarsening the mesh on the water level diminishes.

Figure 4b illustrates the differences in cross section velocity for two different mesh setups. The velocity across the entire cross section fluctuates with varying discharges, even within a single river cross-section. Cross-section velocity for coarser meshes is lower than the high resolution mesh; however, as the discharge increases, the difference becomes less noticeable. This suggests that during high discharges, the impact of resolution on calculated cross-section velocity is relatively minimal. It is intriguing to observe significant fluctuations in velocity differences, especially for the lowest discharge in the combined cross-sections river. Figure 4c shows the differences in flow area between the high-resolution and low-resolution mesh setups. The results show that area in low-resolution models are generally overestimated. This overestimation is particularly pronounced in cross section Type2 with steep side banks in cross section.

Using high-resolution meshes provides greater accuracy, but this approach can be impractical for large-scale river modeling due to significant computational and resource demands. In contrast, low-resolution meshes offer a much faster simulation time of around 20 minutes compared to around 3 days with high-resolution meshes. This trade-off emphasizes the need for a careful balance between efficiency and accuracy in hydraulic modeling.

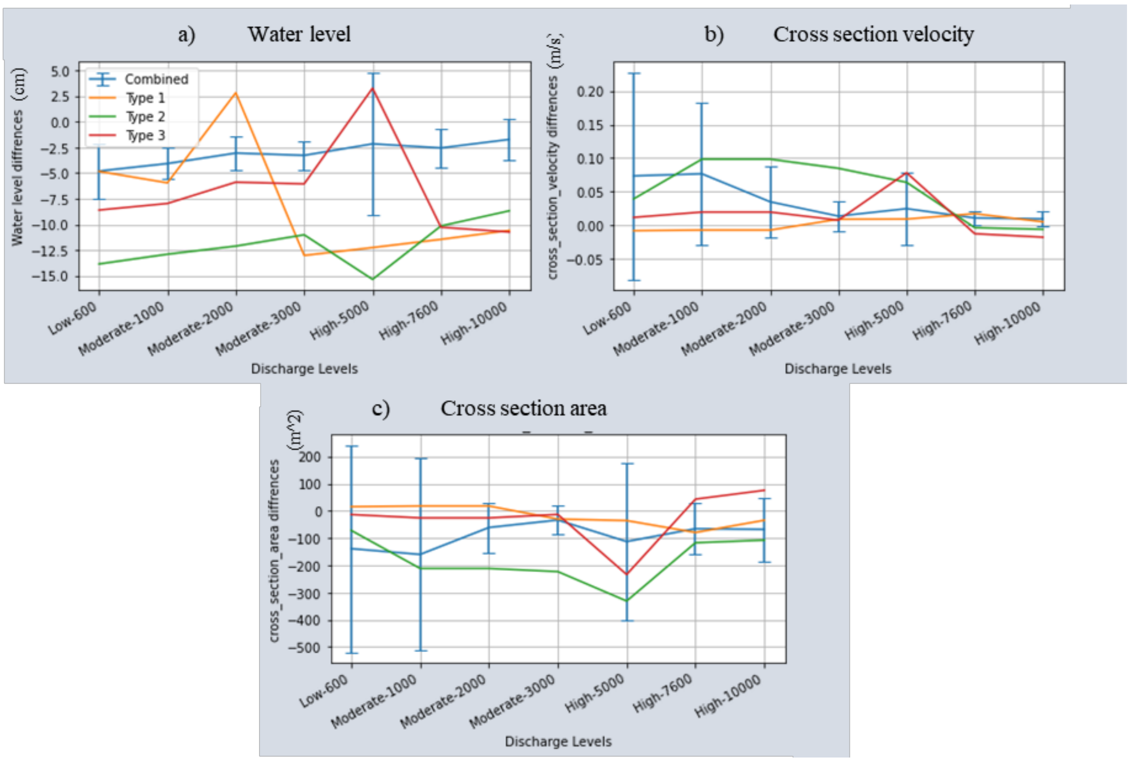


Figure 4.Differences between out puts of high resolution mesh and low resolution mesh (”High” – “Low”) a) Water level differences , b) Cross section velocity differences and c) Cross section area differences simulated by the high-resolution mesh and the low-resolution mesh, for different hypothetical rivers.

4 CONCLUSION

The study focused on assessing the impact of varying mesh resolution and different topographic river shapes on hydraulic simulations. Using the D-Flow-FM software, simulations were conducted for hypothetical rivers with high and low-resolution mesh setups across different discharge levels. Water levels are most important for effective river management. Unlike velocity and area, which are directly calculated from input information such as bathymetry, discharge, and Manning roughness coefficient, water level is derived from the velocity and the area. As observed in the results section, variations in area values exhibit a consistent trend across different discharges, mirroring the patterns observed in water level differences. Therefore, to improve the simulation of water levels, improving the area of the low-resolution mesh setup to be closer to the area of the high-resolution mesh setup is recommended.

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