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Evaluation of DEM Accuracy and Mesh Resolution in 2D Hydraulic Flood Modeling

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Abstract

This study investigates the influence of Digital Elevation Model (DEM) accuracy and mesh resolution on flood inundation modeling using a two-dimensional (2D) hydraulic approach. The assessment of mesh independence and DEM sensitivity was carried out by examining key parameters, including computational time, extent of inundated area, maximum water depth, and average flow velocity across the floodplain domain. The findings indicate that enhancing DEM resolution not only improves the spatial accuracy of topographic representation but also contributes to reduced computational time through optimized mesh generation, fewer numerical corrections, and greater numerical stability. Conversely, while a reduction in mesh size leads to more detailed hydraulic results and improved accuracy in representing flow patterns, it simultaneously imposes a substantial increase in computation time. A mesh size of 25 meters was identified as an effective compromise between numerical precision and computational efficiency. Overall, selecting an appropriate combination of DEM resolution and mesh size plays a crucial role in ensuring both the reliability and practicality of flood inundation simulations.

Keywords: Accuracy Analysis, Digital Elevation Model (DEM), Computational Mesh, 2D Hydraulic Model, Flood

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1. Introduction

Flood zoning is a fundamental strategy for managing and mitigating risks associated with inundation. It involves the identification, analysis, and classification of areas based on their susceptibility to flooding, with the overarching goals of minimizing human and economic losses, safeguarding natural resources, supporting sustainable development, and enhancing quality of life. By preventing construction in high-risk zones, informing the design of resilient infrastructure, and guiding the implementation of effective management plans, flood zoning plays a pivotal role in reducing vulnerability.

Achieving these objectives requires accurate data, advanced modeling techniques, and close collaboration among communities, policymakers, and technical institutions. Numerical and hydrological models have therefore become indispensable tools in flood zoning, as they enable the simulation of flood dynamics and the prediction of potential impacts. Depending on their dimensionality, flood models are generally categorized as one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D). Each of these approaches provides unique advantages and limitations, with 2D models widely regarded as the most practical balance between computational efficiency and hydraulic accuracy for floodplain mapping and risk assessment.

Building on this foundation, the present study employs a high-resolution digital elevation model (DEM) with a 20 cm grid size, together with the MIKE 21 two-dimensional hydraulic model, to simulate river floodplain hydraulics. By systematically evaluating mesh resolution and DEM accuracy, the study aims to establish optimal conditions for effective flood zoning.

2. Literature Review

Flood modeling techniques have advanced considerably, with numerical models applying the governing equations of fluid dynamics to capture flow behavior and inform decision-making. One-dimensional models, such as HEC-RAS, are widely used for simplified analyses of channel hydraulics but struggle to capture lateral flow distribution and floodplain complexity. In contrast, two-dimensional models resolve flow in both longitudinal and lateral directions, providing greater accuracy in representing surface flow patterns and inundation extents. Tools such as HEC-RAS 2D and MIKE 21 have demonstrated a strong capacity to model multidirectional flow interactions in heterogeneous floodplains. Although three-dimensional models extend this further by accounting for vertical flow structures and turbulence, their data requirements and computational intensity often restrict their large-scale applicability.

A key factor influencing the accuracy of flood modeling is the quality of digital elevation models (DEMs). Bentivoglio et al. (2022) highlighted the promise of deep learning methods for improving flood mapping precision, while Ahmad et al. (2025) demonstrated the importance of careful DEM selection and correction—particularly when using datasets such as

ALOS—in improving HEC-RAS simulations. Xu et al. (2021) showed that statistical corrections like the Dixon criterion enhance the reliability of open-access DEMs in Shanghai. Similarly, Aristizábal et al. (2024) demonstrated that lidar-derived DEMs from the U.S. 3D Elevation Program (3DEP) substantially improve catchment analyses, though computational demands rise with higher resolution. Complementing these efforts, Zheng et al. (2024) introduced a globally consistent DEM-based floodplain delineation framework, achieving accuracy levels above 0.85 when compared to hydrodynamic models.

Comparative studies have further explored the strengths and limitations of 2D models. MIKE 21 has been recognized for its flexibility in applying mesh networks, offering precise delineation of flood-prone areas, while HEC-RAS provides broader applicability for practical zoning (Ansarifard et al., 2024). Shrestha et al. (2020) emphasized that HEC-RAS is advantageous for simpler, faster preprocessing, whereas MIKE 21 yields more realistic results by capturing wind effects and viscosity in flood propagation. MIKE FLOOD has also proven effective in urban and deltaic contexts, with studies by Hong et al. (2016), Patro et al. (2009), and Tuan et al. (2024) demonstrating its utility in flood prediction, urban planning, and damage reduction.

Overall, the literature highlights the widespread reliance on two-dimensional models due to their ability to balance accuracy with computational cost. Accuracy generally increases with mesh refinement, but this necessitates mesh independence analyses to prevent excessive computational demands (Ahn et al., 2019). Furthermore, the precision of flood simulations depends heavily on input data quality, including elevation models, channel geometry, and rainfall inputs (Hong et al., 2016). These insights underline the importance of systematically evaluating DEM accuracy and mesh resolution to ensure reliable and efficient flood zoning applications.

3. Methodology

3.1. Case Study

The study area selected for this research is the Jajrood River, one of the major rivers in Tehran Province. The river originates from the Kolon Bastak mountains, located north of Darbandsar village, and flows into the Latian Dam reservoir before continuing southward through the city of Jajrood and eventually joining the Karaj River. Owing to its role in supplying agricultural and drinking water, as well as its ecological and recreational importance, the Jajrood River represents a critical natural resource within the province.

The river corridor also provides habitats for diverse plant and animal species, while its scenic surroundings make it a popular destination for tourism and nature-based activities. These hydrological, ecological, and socio-economic characteristics underscore the relevance of Jajrood as a case for floodplain analysis.

For this study, a reach of approximately 8.5 kilometers was selected, extending from upstream of Shemiran to the vicinity of Lavasan (Figure 1). This section was chosen because of its hydraulic significance and environmental sensitivity, making it well-suited for testing the performance of high-resolution DEM data and two-dimensional hydraulic modeling in flood zoning applications.

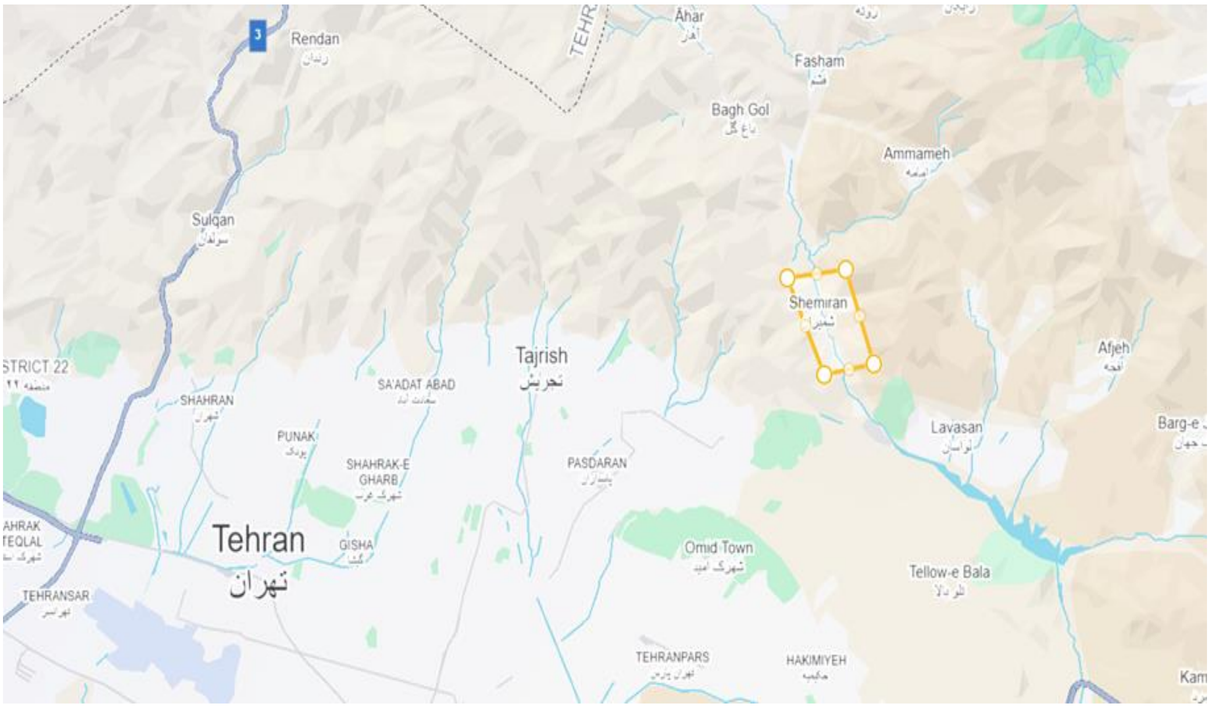

Figure 1. The reach of the Jajrood River selected for flood modeling

3.2. Governing Equations

Two-dimensional flood modeling is typically based on the shallow water equations. These equations simplify the Navier-Stokes equations for flows with depths much smaller than their length and width, and include the continuity equation (mass conservation) and the momentum equations.

3.2.1. Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \quad (1)$$

3.2.2. Momentum Equation

The X-component:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = fv - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz + F_u + \frac{\partial}{\partial z}(\nu_t \frac{\partial u}{\partial z}) + u_s S \quad (2)$$

The Y-component:

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = -fu - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz + F_v + \frac{\partial}{\partial z}(\nu_t \frac{\partial v}{\partial z}) + v_s S \quad (3)$$

In these equations, x, y, z are the Cartesian coordinates. u, y, w are the flow velocity components in the x, y, z directions, S is the general source term, ρ is the fluid density, P is the pressure, η is the free surface elevation, f is the Coriolis parameter, g is the gravitational acceleration and ν is the viscosity coefficient.

3.3. 2D Hydraulic Model

For flood zoning of the floodplain, MIKE 21 FM was employed (DHI, 2017). It is a powerful software for modeling two-dimensional water flows, developed by DHI, with applications in hydrodynamic engineering and environmental studies. The software utilizes unstructured grids, allowing precise adjustment of mesh size and density in complex regions, thereby enhancing computational accuracy. The MIKE21 uses an implicit solution method known as ADI (Alternating Direction Implicit) to solve the algebraic system resulting from the discretization of the continuity and momentum equations. In this method, the resulting equation matrix is solved in each direction using a double-sweep algorithm. In this scheme, the system of linear algebraic equations derived from the discretization is solved separately in the x and y directions using the Thomas algorithm, which is an efficient solver for tridiagonal matrices (DHI, 2017). The software is widely applied in flood studies, water resources management, coastal engineering, environmental assessments, and tidal predictions. Its high accuracy, capability to model complex environments, and extensive features for simulating coupled processes make MIKE 21 FM a valuable tool in scientific research, engineering, and natural resource management.

3.4. Model Setup

Modeling domain in MIKE 21, which is shown in Figure 2, was performed using the DEM of the study area with a resolution of 0.076 meters and a 24-hour observed hydrograph, as shown in Figure 3. Boundary conditions were considered fixed. A Manning's roughness coefficient of 0.05 was used; triangular meshes were applied, and time steps ranged from 0.01 to 1 second. The critical CFL number was set to 0.8. The CFL number is a key stability criterion for numerical solutions of partial differential equations (PDEs) employed in numerical methods such as the finite volume method (FVM). Other software settings were kept at their default values.

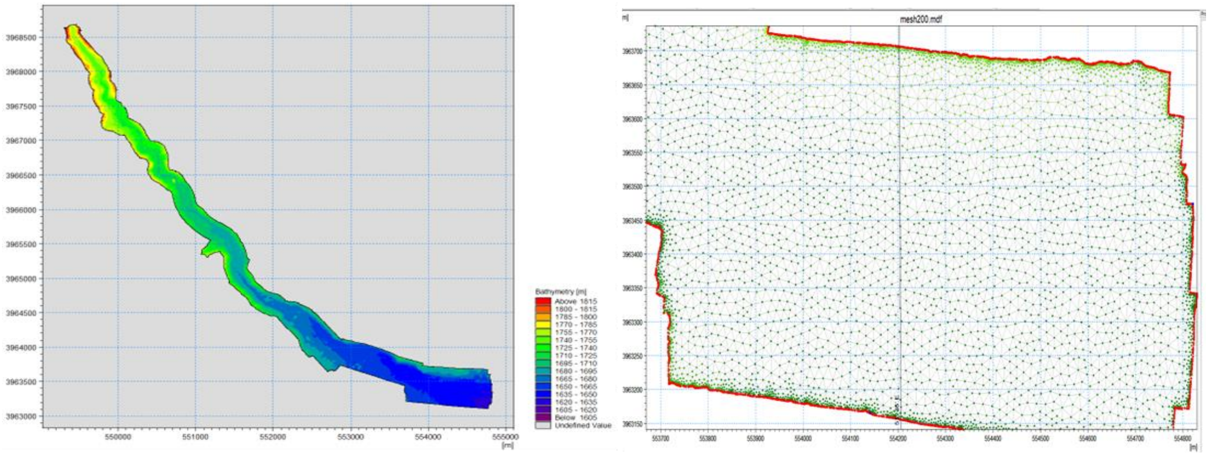

Figure 2. A) Modeling Jujrood River floodplain in MIKE 21 FM, B) Unstructured mesh generated in MIKE 21 FM

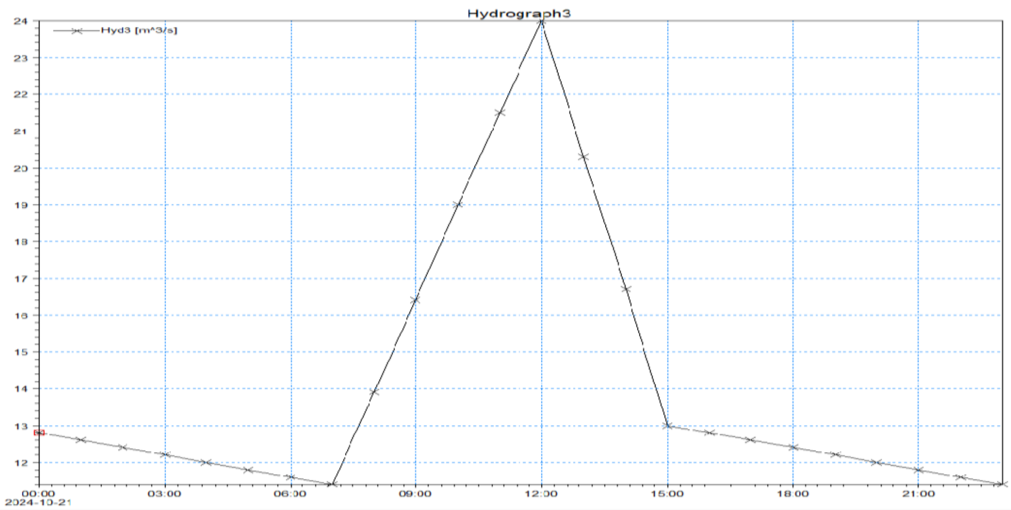

Figure 3. Considered the inflow hydrograph to the hydraulic model as the upstream boundary condition (from an event)

4. Model Implementation and Result Analysis

4.1. Modeling Scenarios and Comparing Results

Mesh independence analysis and DEM evaluation were carried out using parameters such as computation time, flood extent area, maximum depth, average maximum depth, and average flow velocity. To compare the results, the percentage error relative to the most accurate result was calculated:

$$percent\ error(\%) = \frac{(E - T)}{T} \times 100\% \tag{4}$$

In this equation, E represents the computed result and T denotes the most accurate result obtained.

4.2. Mesh Independence Analysis

The mesh independence analysis was conducted using a fixed DEM with a resolution of 0.076 meters and mesh sizes of 200, 100, 75, 45, 25, and 15 meters. The results are presented in Table 1. Table 1 includes the outcomes corresponding to different mesh sizes along with the percentage difference relative to the most accurate (finest) mesh. Additionally, part of the floodplains generated using various mesh sizes are illustrated in Figure 4.

Table 1. Mesh independence results

Mesh	Time(s)	Area(m2)	%diff	Max Depth (m)	%diff	Avg Max Depth (m)	%diff	Avg speed(m/s)	%diff
200	6006	473844	-0.66	10.56	16.27	1.07	-37.36	10.28	1198.26
100	8258	444029	-6.91	6.78	-25.4	1.14	-33.35	0.87	10.32
75	6679	463866	-2.75	8.25	-9.17	1.18	-30.99	0.84	6.39
45	8514	489419	2.61	8.99	-1.011	1.59	-7.02	0.78	-1.53
25	9499	473903	-0.64	9.05	-0.36	1.68	-1.82	0.79	0.37
15	12287	476976		9.08		1.71		0.79	

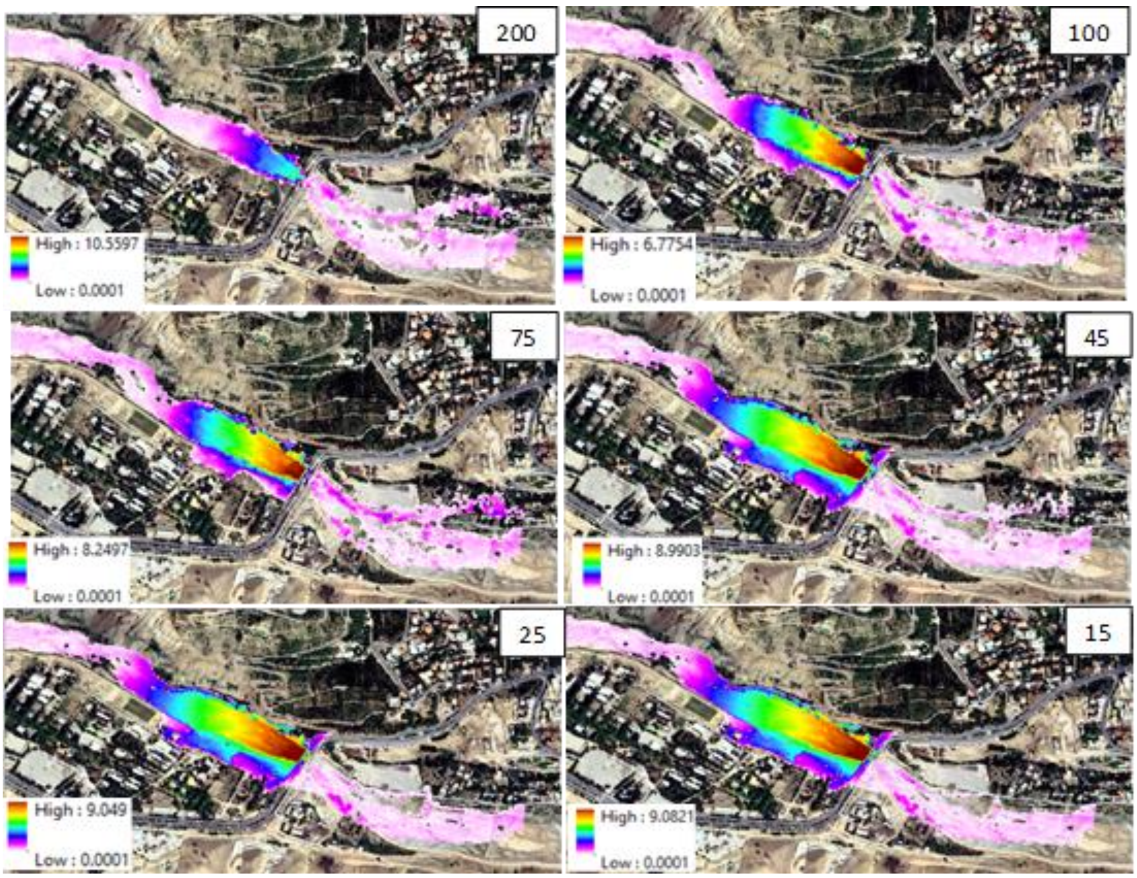

Figure 4. Flood zoning using different mesh sizes

Several points (Figure 5) were randomly selected within the floodplains, and the flood hydrographs at these locations are presented in Figure 6.

Figure 5. Selected points for comparing the flood depth in different mesh sizes

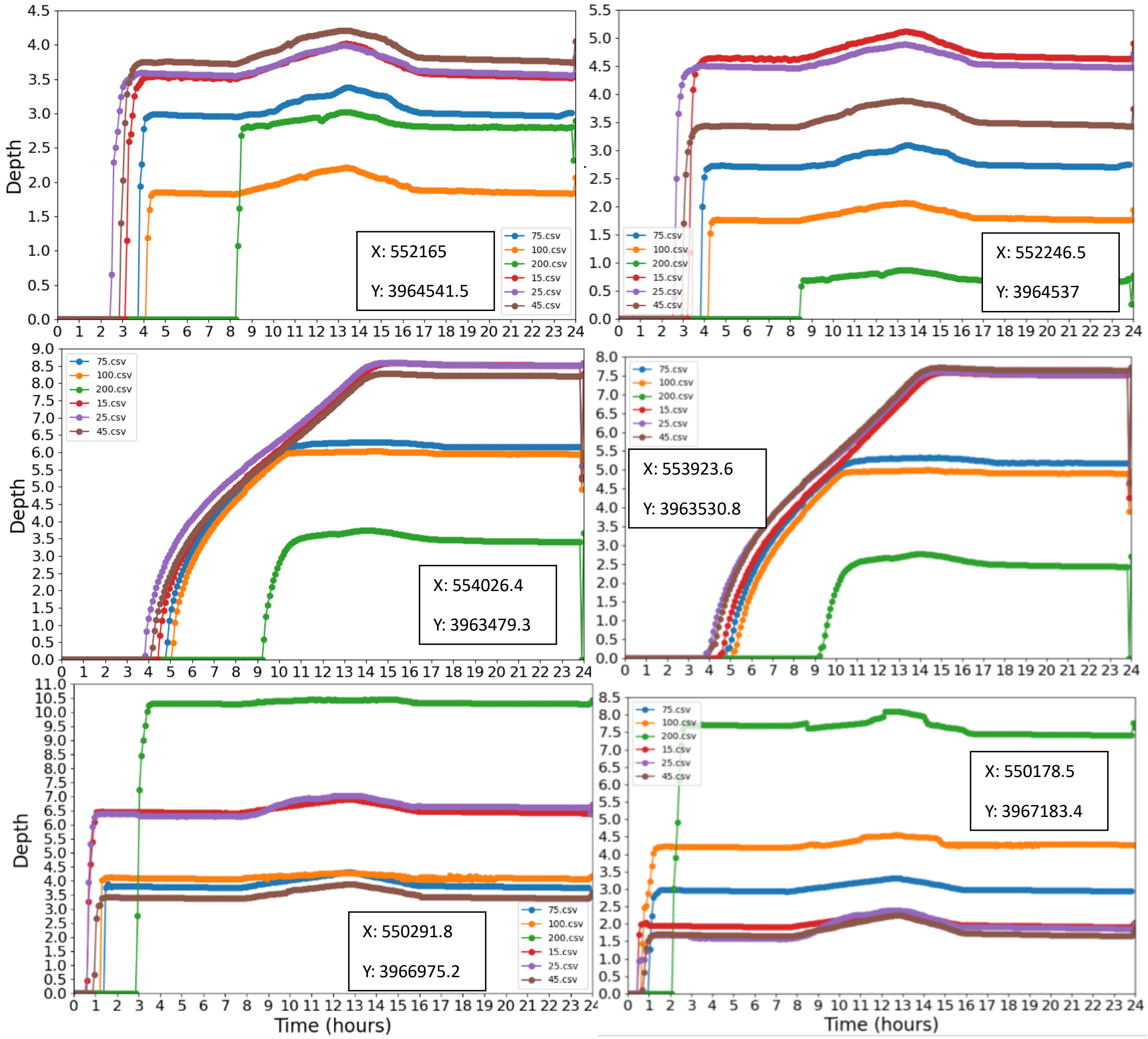

Figure 6. Hydrographs arrived at the selected points

4.3. Digital Elevation Model Analysis

The digital elevation model analysis was performed using a fixed mesh size of 25 meters and DEM resolutions of 100, 50, 25, 10, 5, and 0.076 meters. The results are presented in Table 2. Table 2 includes the outcomes for different DEM resolutions along with the percentage differences relative to the most accurate (finest) DEM. In addition, part of the floodplains corresponding to each resolution of the DEM are illustrated in Figure 7.

The results indicate that increasing mesh resolution leads to longer computation times; however, it also improves the accuracy of the results. By comparing the data presented in Table 1, it can be concluded that the 25-meter mesh offers acceptable accuracy, with a maximum error of 1.8% compared to the 15-meter mesh—this difference pertains to the average maximum depth—while requiring approximately 22% less computation time. The flood hydrographs at various points (Figure 6) further support this conclusion. Although larger mesh sizes result in shorter computation times, they fail to provide sufficient accuracy. For instance, the maximum error in average maximum depth was 7% for the 45-meter mesh, 31% for the 75-meter mesh, 33% for the 100-meter mesh, and 37% for the 200-meter mesh. These inaccuracies are also evident in the hydrographs shown in Figure 6, confirming that coarser meshes yield lower reliability.

In terms of flood extent mapping, nearly all mesh sizes produced acceptable results, with the largest discrepancy being about 7% for the 100-meter mesh, and even lower for the others. Ultimately, based on these evaluations, the 25-meter mesh was selected for the subsequent analysis of the digital elevation model.

Table 2. DEM resolution analysis results

DEM	Time(s)	Area(m2)	%diff	Max Depth(m)	%diff	Avg Max Depth(m)	%diff	Avg Speed (m/s)	%diff
100	53622	314568	-33.62	15.47	70.97	5.60	232.94	0.63	-20.29
50	52812	315094	-33.51	13.16	45.41	3.83	128.02	0.59	-26.34
25	18820	488465	3.07	8.59	-5.09	1.31	-22.25	0.74	-6.73
10	12778	473675	-0.048	11.47	26.71	1.40	-16.75	0.76	-4.43
5	97523	481598	1.62	8.73	-3.56	1.54	-8.189	0.79	-0.98
0.076	9499	473903		9.05		1.68		0.79	

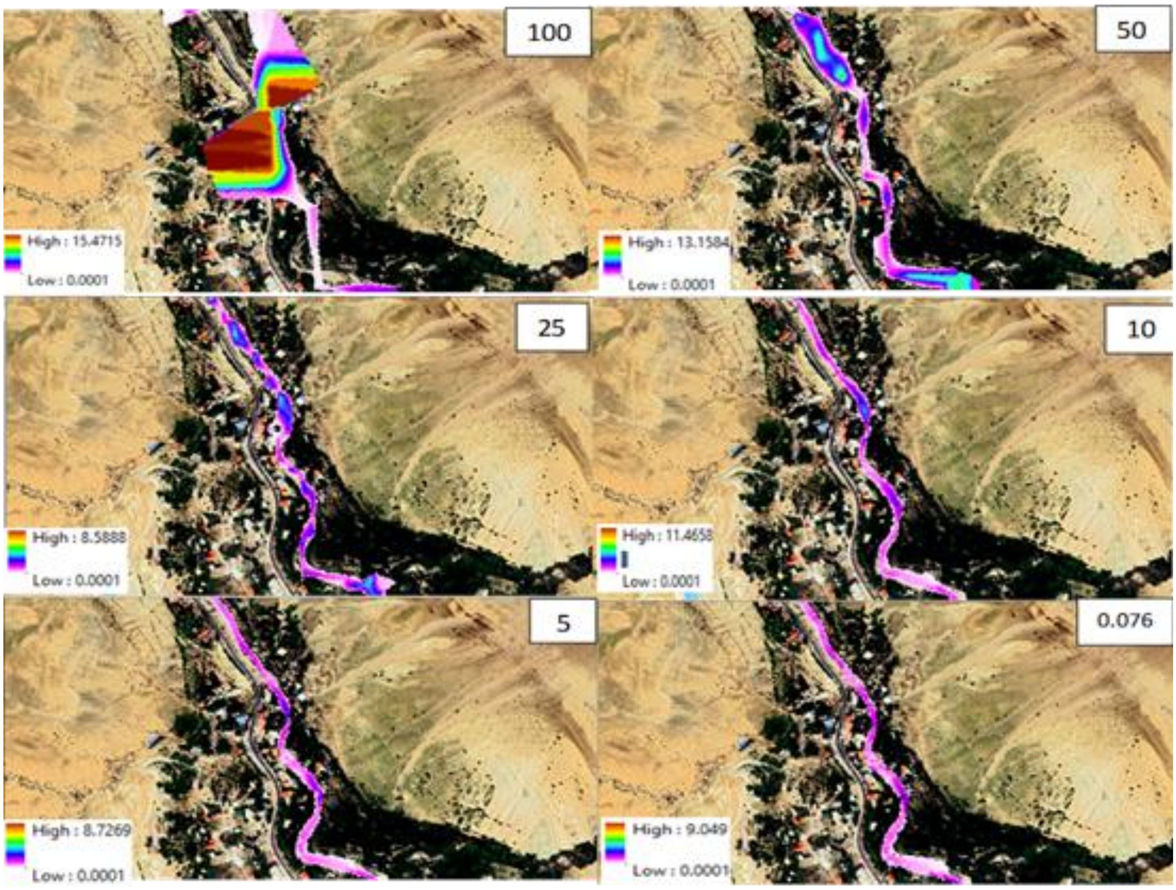

Figure 7. DEM analysis results using different DEM resolutions

Several points (Figure 8) were randomly selected within the floodplain, and the flood hydrographs at these locations are presented in Figure 9.

The results of DEM analysis differ notably from those of the mesh resolution analysis. In contrast to mesh analysis, increasing DEM resolution led to a decrease in computation time. Higher DEM accuracy in Flexible Mesh (FM) models can have multiple effects in reducing computational time. One of the most significant reasons is the optimization of mesh generation. A more accurate DEM leads to a more uniform and efficient mesh, reducing the number of irregular and unnecessary cells, which in turn accelerates processing. Additionally, fewer numerical corrections are required. When using a low-resolution DEM, the model must perform more corrections to adjust cell elevations, which increases computation time. A more precise DEM minimizes the need for such corrections, thereby speeding up the solution of equations.

Figure 8. Selected points for comparing the flood depth in different DEM sizes

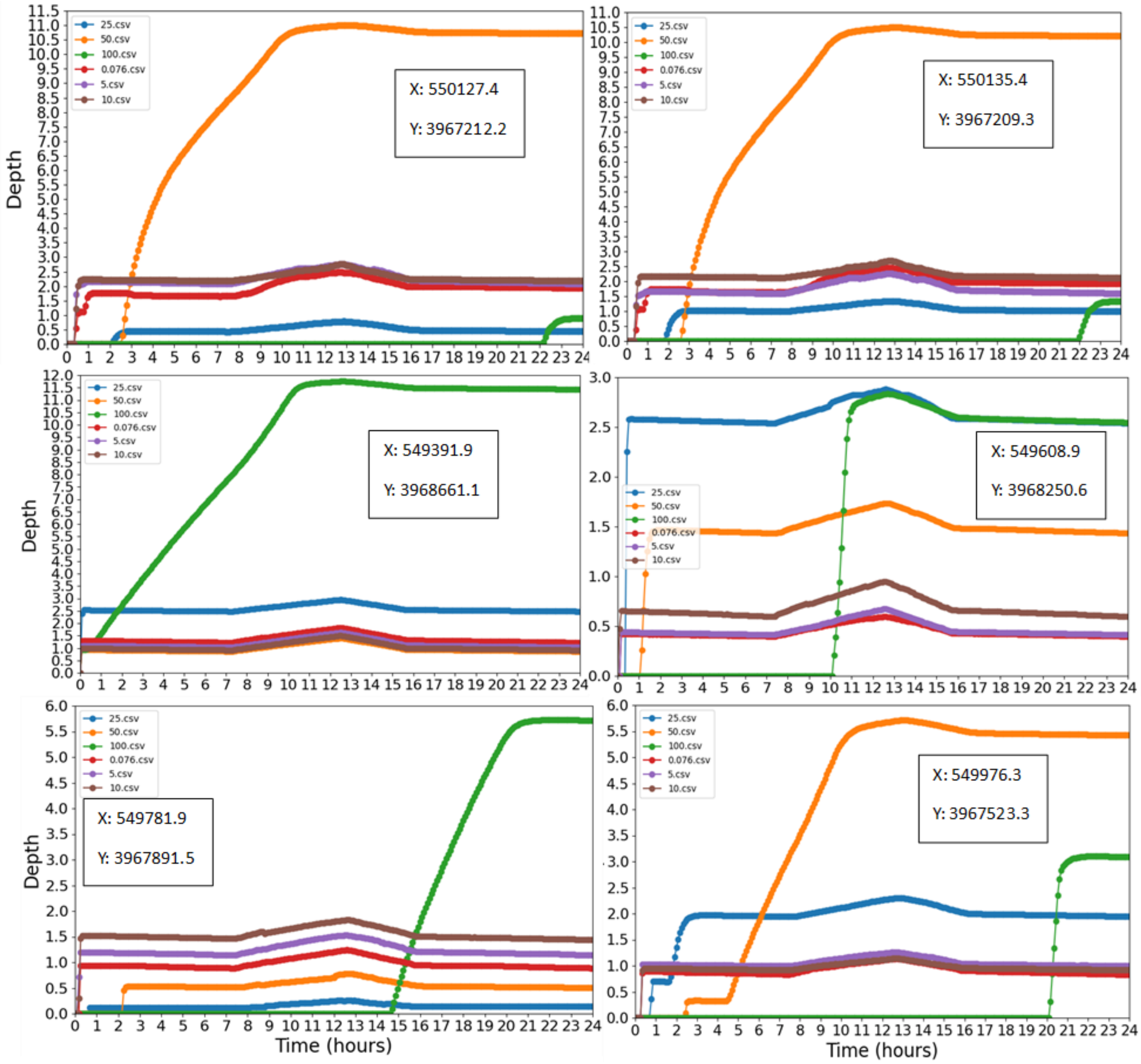

Figure 9. Hydrographs arrived at the selected points

Another important factor is the improvement in numerical stability. A low-accuracy DEM can introduce instabilities in the model, resulting in reduced time steps or an increased number of solver iterations. Conversely, a high-resolution DEM provides a better distribution of slopes and flows, enhancing numerical stability and speeding up computations. Furthermore, reducing the volume of unnecessary data can also significantly lower computation time. Low-resolution DEMs often contain noise or irrelevant information, the processing of which is time-consuming. A high-resolution DEM reduces such redundant data, making the model run more efficiently.

Nevertheless, high-resolution DEMs are not always readily available. Based on the results shown in Table 2, DEMs with resolutions finer than 25 meters provided satisfactory outcomes for floodplain mapping. The 25-meter DEM had a 3% error, the 10-meter DEM 0.04%, and the 5-meter DEM 1.6%. For other parameters, the 5-meter DEM was found to be the most suitable, with a maximum error of 8% in the average maximum depth. The point-based flood hydrograph results presented in Figure 9 also support these findings. The results were obtained using an Nvidia GTX 1080Ti graphics card and 96 GB of RAM.

5. Conclusion

The results of this study demonstrate that increasing the accuracy of the digital DEM in Flexible Mesh models can significantly influence both the accuracy and computational time of flood modeling. Contrary to the initial expectation that higher resolution typically leads to longer computation times, it was observed that a more accurate DEM actually reduced computation time. This reduction is primarily attributed to several factors, including optimized mesh generation, reduced need for numerical corrections, improved numerical stability, and the elimination of unnecessary data. A higher-resolution DEM produces a more uniform and optimized mesh, which reduces the number of unnecessary cells and enhances model convergence. Additionally, a low-resolution DEM may introduce numerical instabilities and require smaller time steps, while a more precise DEM enables better slope and flow distribution, leading to faster equation solving.

On the other hand, appropriate meshing also plays a critical role in model accuracy and efficiency. The results showed that decreasing mesh size increases model accuracy, though at the cost of longer computation times. The mesh independence analysis indicated that a 25-meter mesh provides acceptable accuracy, with only a 1.8% error in average maximum depth compared to the 15-meter mesh, and even smaller errors for other parameters, while reducing computation time by approximately 22%. This highlights the need to balance accuracy and computational efficiency to keep the model cost-effective.

Finally, the DEM accuracy assessment revealed that for floodplain mapping, DEMs with resolutions finer than 25 meters still provide reliable results. However, for parameters such as average maximum depth, a 5-meter DEM yields better performance. These findings underscore the importance of selecting an optimal DEM resolution and mesh size to achieve a flood model that is both accurate and computationally cost-effective. Therefore, decisions regarding DEM resolution and mesh size should be based on the specific modeling application, required accuracy, and available computational resources.

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