Optimizing 3D Urban Modelling: Integrating Land Lot and Building Footprint Geometries in Dual-Iteration Morphometric Algorithms

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Abstract

The increasing demand for accurate 3D urban models is driven by rapid urbanization and the need for advanced geospatial tools in smart cities and digital twin applications. However, integrating Digital Terrain Models (DTMs) with 3D city models remains a persistent challenge due to misalignment between building footprints and terrain surfaces. Existing methodologies suffer from elevation discrepancies, inefficient interpolation techniques, and computational limitations, leading to inaccuracies in urban simulations, particularly for flood risk assessment and infrastructure planning. This study proposes a dual-iteration morphometric algorithm to enhance DTM-3D building integration, ensuring precise alignment of urban structures with real-world topography. The methodology involves node-based terrain adjustments, vertex and planar interpolation, and an iterative refinement process including land lot and building footprints geometry that improves elevation conformity. The algorithm was applied to a case study in Section 13, Petaling Jaya, Malaysia, using LiDAR-derived elevation data for validation. The results demonstrate a reduction in Root Mean Square Error (0.387 to 0.112) and a 75.8% decrease in Mean Absolute Error (0.219 to 0.053) compared to conventional DTM models, indicating significantly improved terrain adherence. Hydrodynamic simulations further reveal that the refined DTM reduces flood overestimation errors by 205.49%, capturing localized elevation variations more accurately. These improvements facilitate more reliable flood modelling, infrastructure planning, and urban resilience strategies. This research advances geospatial modelling for smart cities and digital twins, offering a scalable, high-accuracy framework for urban planning, disaster risk management, and climate adaptation. The proposed algorithm enhances urban simulation fidelity, ensuring more precise decision-making in sustainable city development.

1. Introduction

The rapid urbanization trend has led to an increasing demand for precise and reliable 3D urban models to support sustainable city planning, disaster resilience, and infrastructure development (Delval et al., 2020; Petrova-Antonova & Spasov, 2021). As cities expand, accurate spatial representation of the built environment becomes essential for managing urban growth, resource allocation, and climate adaptation strategies. 3D city models, particularly those incorporating Digital Terrain Models (DTMs), play a critical role in ensuring that planners and decision-makers have access to realistic and accurate geospatial data (Shirinyan & Petrova-Antonova, 2022). These models facilitate applications such as urban flood modelling, transportation planning, and infrastructure monitoring, allowing for better predictions and risk assessments (Al Kalbani & Rahman, 2021; De Morais et al., 2022). However, integrating 3D city models with DTMs remains a significant challenge, particularly in maintaining alignment with the earth's surface (Yan et al., 2019). Inconsistencies in terrain representation often lead to floating or sunken buildings, reducing the reliability of urban models for analysis and decision-making. The lack of standardized terrain integration methodologies further complicates the process, requiring innovative solutions to improve the accuracy of 3D urban simulations.

One of the primary challenges in urban 3D modelling is the misalignment between DTMs and building footprints, which results in inaccuracies in terrain representation (Yan et al., 2019). Traditional methods for integrating 3D buildings and terrain models suffer from multiple drawbacks, including varying data resolutions, ineffective interpolation techniques, and a lack of robust morphometric algorithms (Petrova-Antonova & Spasov, 2021). These issues affect the validity of urban simulations, particularly in flood risk assessment and climate resilience planning, where precise elevation models are crucial for hydrodynamic analysis. Furthermore, standard DTM-3D model integration approaches do not account for localized variations in elevation, leading to inconsistencies in terrain adjustments (Petrova-Antonova & Spasov, 2021). This problem becomes more pronounced in cities with complex topography, such as hilly urban environments, where elevation misrepresentation can impact infrastructure planning and flood mitigation strategies. Additionally, computational inefficiencies in existing integration techniques limit the feasibility of applying DTMs in real-time urban planning scenarios, restricting their usability in large-scale projects.

To address these challenges, this study aims to develop a dual-iteration morphometric algorithm that enhances DTM-building integration, ensuring accurate alignment of urban structures with real-world terrain through a refined morphometric approach, improved hydrodynamic stability for flood modelling by minimizing elevation discrepancies in urban water flow simulations, and efficient computational processing through optimized node-based terrain adjustments that balance precision and data storage efficiency. This research is significant in multiple ways, particularly in supporting urban sustainability and digital twin applications. By improving the accuracy of 3D urban modelling, this study contributes to smart city planning, enabling urban planners to design efficient infrastructure, optimize land use, and predict future urban expansion more effectively. It enhances disaster resilience and flood modelling by facilitating more accurate flood risk assessments, reducing uncertainties in hydrodynamic simulations, and improving urban flood mitigation strategies. Additionally, it supports digital twin implementation, ensuring seamless real-time urban monitoring and simulation. By addressing the limitations of existing urban terrain modelling methods, this study introduces a technical framework for more precise and scalable DTM-3D model integration, making it a valuable contribution to geospatial science, urban resilience planning, and digital infrastructure development.

2. Literature Review

2.1 3D Urban Modelling, Smart Cities and Digital Twins

The integration of 3D urban modelling in smart cities and digital twin applications has been widely recognized as a crucial component of sustainable urban development (Delval et al., 2020; El-Agamy et al., 2024). 3D city models offer detailed visual and analytical representations of the built environment, allowing policymakers, urban planners, and researchers to simulate various planning scenarios (Hu et al., 2020; Fricke et al., 2023). These models play a critical role in multiple urban applications, including land-use planning, infrastructure development, transportation analysis, and environmental impact assessments (Janečka, 2019; Kong et al., 2022; Mazzetto, 2024). The adoption of smart city and digital twin technologies, combined with accurate 3D models, supports decision-making processes by providing spatially accurate data for better resource allocation and real-time monitoring (Lafioune & St-Jacques, 2020; Lee et al., 2020; Liu et al., 2024).

However, the effectiveness of 3D city models depends on their alignment DTMs, which represent the underlying topographic surface of urban landscapes (Yan et al. 2019; Petrova-Antonova & Spasov, 2021). A precise DTM integration is essential to avoid inconsistencies in elevation representation, such as misaligned building footprints and incorrect terrain elevations. These issues impact various applications, particularly those related to hydrodynamic modelling, flood risk assessment, and climate adaptation planning (Petrova-Antonova & Spasov, 2021). Although several geospatial techniques have been developed to improve DTM integration, challenges remain in ensuring accuracy and computational efficiency in large-scale urban environments.

2.2 Challenges in Integrating DTMs and 3D Buildings

The integration of DTMs with 3D buildings presents numerous technical challenges, primarily due to variations in data resolution, interpolation inaccuracies, and computational constraints (Yan et al. 2019; Petrova-Antonova & Spasov, 2021). Traditional DTM integration methods often fail to account for local elevation variations, leading to errors in terrain adjustments. One of the most common issues is building floatation or subsidence, where structures appear elevated or buried within the terrain model due to poor alignment between elevation datasets (Rong et al., 2020). This problem is particularly pronounced in urban areas with complex topography, such as cities with diverse elevation gradients, underground structures, or varying land cover types.

2.3 Morphometric Structuring and Terrain Intersection Curve (TIC)

Morphometric structuring is a fundamental aspect of 3D urban modelling that enhances terrain representation by refining the alignment between building footprints and DTMs (Patel et al., 2023). The TIC technique is one of the most effective approaches for achieving seamless integration by ensuring that building footprints accurately conform to elevation contours (Shirinyan & Petrova-Antonova, 2022). TIC serves as a guiding framework for terrain adjustments, allowing urban models to achieve consistency in structural alignment while minimizing elevation discrepancies that could impact urban planning, infrastructure development, and hydrodynamic simulations.

The TIC approach involves systematically defining terrain intersection points along the building perimeters, and adjusting elevation values to fit smoothly within the terrain model (Shirinyan & Petrova-Antonova, 2022). This process ensures structural integrity, preventing floating or sunken buildings, which are common issues in urban models with poor DTM integration. Additionally, TIC-based refinements enable better flood simulation models, as buildings correctly positioned within the terrain provide more realistic water flow dynamics (Rong et al., 2020). The incorporation of dual-iteration morphometric algorithms in TIC-based structuring further optimizes the process by iteratively refining elevation values for greater accuracy. As a result, TIC-enhanced urban models improve the applicability of 3D city models in digital twin development, disaster resilience planning, and environmental impact assessments.

3. Methodology

3.1 Study Area and Data Sources

The study area selected for this research is Section 13 Petaling Jaya, Malaysia (Figure 1), an urban region with diverse topographical features (MBPJ, 2019), making it a suitable testbed for evaluating the effectiveness of the proposed methodology. The city is characterized by a combination of flat, hilly, and built-up areas, providing a complex environment for terrain and building integration (Haron, 2013; MBPJ, 2019). This variability makes it an ideal case study for assessing the challenges of DTM and 3D building model alignment.

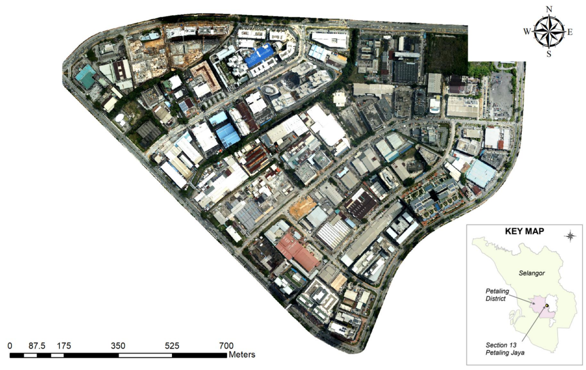

Figure 1. The study area in Section 13 Petaling Jaya.

To conduct this study, several datasets were utilized. LiDAR point clouds obtained from airborne LiDAR surveys provided high-resolution elevation data, serving as a ground truth reference for model validation (Hassan & Abdul Rahman, 2021). Additionally, government-supplied DTMs (DTMj) with 0.5-meter resolution were used as the baseline terrain representation, while a customized DTM (DTMc) with 0.5-meter resolution was generated using the proposed morphometric algorithm to optimize terrain accuracy and integration. The study also incorporated land lot and building footprint geometries, which define the spatial extent of urban structures and are essential for assessing alignment with the terrain.

3.2 Dual-Iteration Morphometric Algorithm

The proposed dual-iteration morphometric algorithm is designed to refine the integration between DTMs and 3D building models, ensuring accurate elevation alignment and hydrodynamic consistency. The methodology consists of three iterative steps.

Step 1: Node-Based Adjustments

The first step involves node-based adjustments, introducing additional control nodes at 0.25m intervals along building footprints to fine-tune elevation alignment. This process increases precision in terrain adherence while maintaining computational efficiency. The iterative nature of this adjustment ensures that buildings remain correctly positioned within the urban model, reducing vertical discrepancies that may affect hydrodynamic simulations. The enhanced building footprint was later developed into a Level-of-Details 1 (LoD1) 3D building model for validation purposes.

Step 2: Incorporating Vertex and Planar Interpolation with Land Lot Geometry for Perimeter Control in the First Iteration Process

In the first iteration of the multi-iteration morphometric algorithm, the integration of vertex interpolation and planar interpolation with land lot geometry plays a critical role in establishing perimeter control. This step ensures that building footprints are correctly aligned with the underlying terrain, preventing distortions in elevation representation that could lead to inaccuracies in 3D urban models. The vertex interpolation method is applied to sample and adjust elevation values at critical boundary points along the building footprint. Each vertex is anchored to the nearest elevation grid from DTM, ensuring that perimeter control is maintained and that each structure remains aligned with the local topographic conditions. This prevents misalignments such as floating or sunken buildings, which are common in models where perimeter constraints are not strictly enforced.

Following vertex adjustments, planar interpolation is implemented to refine the elevation transition within the footprint. This approach uses Triangular Irregular Network (TIN) surface fitting to generate a continuous elevation plane within each building lot, reducing discrepancies between internal elevation nodes. By applying this planar interpolation method, the algorithm ensures a smooth transition between the perimeter-controlled elevations and the internal building footprint, minimizing artificial elevation anomalies that could compromise hydrodynamic simulations and structural assessments. The integration of land lot geometry further enhances perimeter control by defining boundary constraints based on cadastral and zoning information (Soupios et al., 2007; Ou et al. 2023). By enforcing perimeter conformity to legal land lot boundaries, the algorithm ensures that buildings remain accurately positioned within their designated plots, reducing errors in land-use classification, urban zoning analysis, and hydrological modelling.

This first iteration process, incorporating vertex and planar interpolation with land lot geometry, sets the foundation for subsequent refinement steps. By accurately adjusting the building-terrain alignment at the initial stage, the multi-iteration approach builds upon a precise geometric foundation, leading to improved accuracy in urban morphology, flood modelling, and smart city planning.

Step 3: Incorporating Vertex and Planar Interpolation with Building Geometry for Localized Control in the Second Iteration Process

Following the initial perimeter control using land lot geometry, the second iteration focuses on localized adjustments within individual building footprints to refine their alignment with the DTM. This step ensures that the internal structure of each building footprint conforms more precisely to localized terrain variations, rather than relying solely on perimeter-controlled elevations from the first iteration. In this stage, vertex interpolation is applied directly to building footprint vertices, allowing each structure to be finely adjusted based on the localized terrain. Instead of relying on a single planar adjustment across the entire lot, this approach refines the terrain adherence at a granular level, ensuring that buildings do not experience internal elevation inconsistencies that could distort their representation in hydrodynamic models and digital urban simulations.

Following vertex interpolation, planar interpolation is applied within each building footprint. This step generates an optimized surface within the footprint boundary, ensuring that internal elevation values transition smoothly between terrain-adjusted footprint vertices. TIN modelling and planar interpolation techniques are used to achieve localized elevation consistency. This interpolation technique is particularly critical for complex terrain environments, where buildings may experience intra-footprint elevation variations that need localized correction. The importance of this second iteration lies in its ability to achieve building geometry-specific control. Unlike the first iteration, which ensures global perimeter alignment with cadastral constraints, the second iteration focuses on adjusting buildings individually based on their spatial position and terrain characteristics. This refinement process is essential for applications requiring high-precision hydrodynamic simulations, such as urban flood modelling, where even minor discrepancies in building-ground integration can significantly impact water flow predictions and flood risk assessments.

Additionally, incorporating building geometry for localized control in this iteration enhances the reliability of smart city

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models and digital twins. By refining elevation adjustments at the footprint level, urban planners and GIS analysts can ensure that 3D building models better represent real-world elevation conditions, improving their applicability in infrastructure planning, disaster management, and climate resilience strategies.

By integrating vertex and planar interpolation with building geometry in the second iteration, this methodology ensures that each structure is accurately adapted to localized terrain conditions, minimizing elevation distortion artefacts that often occur in conventional DTM-based urban modelling approaches. This step generated the 0.5-meter resolution DTMc with optimized terrain accuracy and integration.

3.3 Validation Approaches

The effectiveness of the product of the proposed methodology (DTMc) is evaluated through two validation techniques, each targeting a specific aspect of accuracy and applicability.

3.3.1 Statistical Accuracy Assessment: To quantify the accuracy of the DTMc, statistical metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are computed. RMSE measures the average deviation between DTMc and LiDAR-derived terrain elevations, providing an overall error assessment. MAE, on the other hand, evaluates the magnitude of elevation discrepancies, offering a direct measure of deviation severity. These statistical analyses help determine the degree of improvement achieved by the proposed morphometric structuring technique (Ying et al., 2020).

3.3.2 Hydrodynamic Simulation: To evaluate the practical impact of terrain adjustments, flood simulations are conducted by testing on the 3D city model developed based on the LoD1 and DTMc models. The primary goal is to analyze how DTMc influences water flow patterns and flood inundation areas. Hydrodynamic simulations are run under different DTM configurations to assess variations in water level predictions. The analysis focuses on understanding how the refined terrain alignment affects flood risk assessment, drainage modelling, and urban water management. The results of these simulations provide insight into the reliability of DTMc for urban flood risk management and smart city resilience planning.

By integrating statistical accuracy assessments, cross-section analyses, and hydrodynamic simulations, this methodology ensures that the dual-iteration morphometric algorithm is rigorously tested for accuracy, efficiency, and real-world applicability. These validation approaches reinforce the feasibility of the proposed technique for improving 3D urban modelling, smart city planning, and climate resilience strategies

4. Results and Discussion

Based on the dual-iteration process, the DTMc were developed. Figure 2 presents a comparison of the output morphometric algorithm design in the form of DTMj and DTMc models. Both models exhibit similar surface morphology patterns with nearly identical elevation variations across the study area. However, a closer examination reveals that the DTMj model (Figure 2a), serving as the reference model, demonstrates superior consistency in maintaining the accuracy of the original data. In contrast, the DTMc model (Figure 2b) appears more responsive to subtle elevation changes, as indicated by color gradation variations in hilly regions and areas with building structures. The DTMc model also captures additional detail in zones with minor topographic variations (highlighted in the red box), a result of the land lot geometry adjustment and interpolation techniques applied in this study. This refined DTMc will serve as the foundation for developing a multidimensional urban model and will undergo further evaluation using various methods to assess its accuracy and potential.

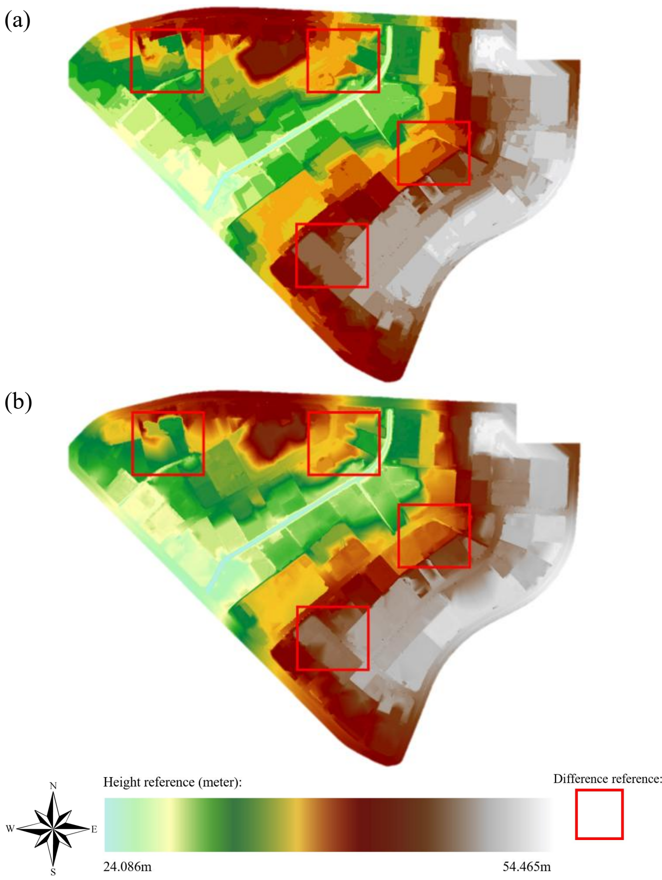

Figure 2: Comparison between (a) DTMj and (b) DTMc

4.1 Statistical Accuracy Assessment

The proposed dual-iteration morphometric algorithm significantly enhances DTM-building alignment, ensuring that building footprints are accurately draped onto the terrain without floating or subsidence issues. The statistical validation confirms that DTMc reduces elevation discrepancies by 71.0% in RMSE and 75.8% in MAE compared to the baseline DTMj. Specifically, RMSE for DTMc is 0.1121, while DTMj records a higher value of 0.3871, demonstrating the superior accuracy of the proposed approach. MAE follows a similar pattern, with DTMc achieving 0.053, compared to 0.2193 for DTMj, marking a substantial reduction in elevation discrepancies.

Metrics	DTMj	DTMc	Difference
RMSE	0.3871	0.1121	>71.0%
MAE	0.2193	0.053	>75.8%

Table 1. The RMSE and MAE results.

4.2 Hydrodynamic Simulation Testing

The hydrodynamic simulation results were visualized (Figure 3) before the quantitative elements were extracted and computed (Table 2). The difference in the average water surface elevation z-score between the multi-dimensional urban models based on

DTMj and DTMc is 0.338, where the DTMc-based model shows a negative mean value (-0.164) compared to the DTMj-based model, which is positive (0.174). In percentage terms, the DTMj-based model predicts an average water surface elevation that is 205.49% higher than that of DTMc-based modelling. This indicates that DTMj-based modelling tends to overestimate water surface elevations compared to DTMc. Furthermore, the DTMc-based model has a slightly higher standard deviation of 2.782 compared to 2.679 in the DTMj-based model. While the difference is relatively small (0.103), this represents an increase of approximately 3.84% in the standard deviation for the DTMc-based model. This suggests that DTMc-based modelling is more sensitive to variations in water surface elevation simulations, reflecting a more accurate representation of topographic complexity.

(a)

(b)

Figure 3: The hydrodynamic simulation results visualization, (a) DTMj-based and (b) DTMc-based Hydrodynamic Simulation

Table 2: The hydrodynamic simulation results analysis

Metrics	DTMj	DTMc
Water Surface Height Average (z-score)	0.174	-0.164
Standard deviation	2.679	2.782
Skewness	0.007	0.127
Kurtosis	2.842	3.671

From a skewness perspective, DTMc-based modelling records a skewness value of 0.127, whereas DTMj is nearly symmetrical at 0.007. The skewness of the DTMc-based model is approximately 1714.29% higher than that of DTMj. While this percentage may seem very high, the positive skewness indicates that DTMc-based modelling tends to have more areas with extreme water surface elevations (either very shallow or very deep) compared to the average, emphasizing its ability to capture deeper topographic variations. The kurtosis value for DTMc-based modeling is 3.671, whereas DTMj records a value of 2.842. The DTMc-based model exhibits a 29.17% increase in kurtosis, suggesting that DTMc-based data distribution is more prone to having longer tails, indicating areas with extreme water surface elevations. This means that DTMc is better at predicting high-risk flood-prone areas, as it captures more extreme topographic variations.

Through the addition of this percentage-based analysis, it becomes evident that DTMc-based modelling exhibits superior performance in capturing more precise and detailed water surface elevations than DTMj. With significant differences in mean water surface elevation, skewness, and kurtosis, DTMc demonstrates better capability in simulating topographic variations and flood risk assessment. This strengthens the argument that DTMc-based modelling is more suitable for digital twin studies and disaster management, where accuracy and topographic detail are critical for producing more realistic simulations.

4.3 Implications for Smart Cities, Digital Twins and Urban Planning

The findings of this study underscore the transformative impact of high-accuracy 3D urban models on smart city planning, disaster resilience, and infrastructure development. As urbanization accelerates, precise geospatial data is essential for effective governance and resource allocation. The integration of DTMc-based models into digital twin frameworks enhances spatial reliability, supporting applications such as interactive urban simulations, infrastructure risk assessment, and real-time digital twin environments. The capacity of DTMc models to capture fine-scale elevation variations significantly improves urban flood forecasting, stormwater management, and emergency response planning. In the context of flood resilience, DTMc's superior hydrodynamic modelling accuracy ensures that terrain-induced water flow behaviours are more accurately represented. Traditional DTMj-based flood models often fail to capture subtle variations in elevation, leading to overestimated flood extents and inefficient drainage infrastructure planning. By contrast, DTMc-based flood simulations enable municipal authorities to identify flood-prone areas with greater precision, facilitating the implementation of targeted flood mitigation measures, such as optimized storm drain placements and real-time urban water level monitoring systems.

The advancements presented in this study also contribute to sustainable urban development and climate resilience strategies. Cities adopting DTMc-enhanced urban models can leverage their improved terrain-conformity attributes for more effective land-use planning, especially in transportation network design and underground infrastructure mapping. Furthermore, the seamless DTMc integration with digital twin platforms provides policymakers with a robust tool for scenario-based analysis, enabling predictive assessments of future urban expansion and climate change impacts. In conclusion, the high-fidelity terrain representation achieved through DTMc-based models provides tangible benefits for urban governance, climate resilience, and infrastructure sustainability. The ability to accurately simulate flood dynamics, optimize drainage systems, and enhance digital twin functionalities ensures that urban planners and

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policymakers can make data-driven decisions for future-ready smart cities.

5. Conclusion

This study presents a dual-iteration morphometric algorithm that significantly enhances DTM-3D building model integration, reducing elevation errors, improving hydrodynamic stability, and maintaining computational efficiency. The 71.0% RMSE reduction and 75.8% MAE improvement confirm that DTMc outperforms conventional DTMj, making it a valuable tool for flood modelling, infrastructure planning, and urban resilience strategies. Beyond improving geometric accuracy, the dual-iteration refinement approach ensures more realistic digital representations of urban environments, reinforcing its applicability in high-precision urban planning and hydrodynamic simulations. The hydrodynamic improvements demonstrated in this study further emphasize the superior accuracy of DTMc in flood modelling applications. The DTMj-based model predicts an average water surface elevation that is 205.49% higher than that of DTMc, indicating that DTMj tends to overestimate flood levels. Additionally, the DTMc-based model exhibits a 3.84% increase in standard deviation, suggesting that it is more responsive to subtle variations in topography, thus capturing floodwater behaviour more accurately. The higher skewness (0.127) and kurtosis (3.671) values of DTMc indicate its ability to model more extreme elevation variations, improving its capability in identifying high-risk flood-prone areas. These refinements ensure that DTMc-based modelling provides more reliable flood predictions, making it particularly valuable for disaster risk management and climate resilience strategies.

The proposed method introduces a scalable geospatial framework for accurate DTM-3D model integration, supporting urban digital twins, climate adaptation strategies, and terrain-sensitive infrastructure design. The demonstrated hydrodynamic improvements reinforce its potential applications in disaster risk management and urban sustainability. By improving the accuracy of terrain representation, this method enables better-informed decision-making in stormwater management, transportation planning, and emergency response strategies. Furthermore, the ability to seamlessly integrate DTMc into digital twin platforms offers a significant advancement in real-time urban monitoring, helping cities predict and mitigate the effects of environmental and climate-related challenges. Overall, this research establishes a solid foundation for advancing DTM-3D building model integration and terrain-based hydrodynamic simulations, contributing to more accurate, efficient, and resilient smart city and digital twin implementations. The findings highlight the necessity of continued innovation in geospatial modelling techniques, pushing towards a future where digital urban environments more precisely reflect their real-world counterparts.

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Data availability statement

Raw data were generated at Universiti Kebangsaan Malaysia, Malaysia. Derived data supporting the findings of this study are available from the corresponding author [Khairul Nizam Abdul Maulud] on request.

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