Proceedings of Engineering and Technology Innovation, vol. 28, 2024, pp. 55-66

Comparison of FLUMEN and HEC-RAS 2D Models for Flash Flood Inundation in Urban Landscape

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Received 28 May 2024; received in revised form 27 August 2024; accepted 28 August 2024

DOI: https://doi.org/10.46604/peti.2024.13794

Abstract

Flood inundation maps play a crucial role in preventing flood damage. Among various numerical models used to generate these maps, the fluvial modeling engine (FLUMEN) and the hydrologic engineering center's river analysis system (HEC-RAS 2D) are particularly effective for simulating urban floods, which are influenced by complex factors such as buildings and landscapes. This study aims to examine the differences in flood analysis results that may arise from using different numerical models. This study compares the performance of FLUMEN and HEC-RAS 2D in modeling urban flash floods, characterized by local velocity variations and complex geometries. The analysis focuses on their numerical characteristics and simulation accuracy. The simulation results show that HEC-RAS 2D outperforms FLUMEN in handling turbulence, numerical stability, and peak water level predictions. These findings provide insights into the strengths and limitations of each model for urban flood management.

Keywords: flash flood, FLUMEN, HEC-RAS 2D, numerical model

1. Introduction

Climate change has emerged as a primary factor in increasing the frequency and intensity of localized extreme rainfall events. These changes significantly heighten the risk of flash floods in urban areas, making them a critical concern for urban planning and management strategies. Urbanization transforms natural landscapes into impermeable surfaces such as asphalt and concrete, reducing the land's permeability and altering the terrain through the construction of infrastructure. This increase in impermeable surfaces and the narrowing of waterways leads to greater surface runoff, raising the likelihood of urban flooding. During rainfall, stormwater is rapidly channeled into urban river systems, causing a sudden rise in water levels. If rivers cannot handle this surge, overflows and levee breaches may occur, resulting in river flooding and urban inundation. This phenomenon can cause severe damage to infrastructure, residences, businesses, public facilities, and transportation systems, while also leading to significant casualties, economic losses, and social disruption.

As one of the non-structural countermeasures to prevent the damage caused by river flooding, flood inundation maps are provided to the public, as shown in Fig. 1. These maps illustrate the extent and depth of inundation expected when rivers overflow or levees breach, assessing the likelihood of river flooding and identifying areas at risk of inundation. Therefore, the accuracy of the information provided by flood inundation maps is crucial in flood mitigation and management practices [1]. Consequently, it is necessary to validate and verify the predictive capability of flood inundation maps through models, as the results may differ depending on their governing equation, numerical techniques, and input data formats [2].

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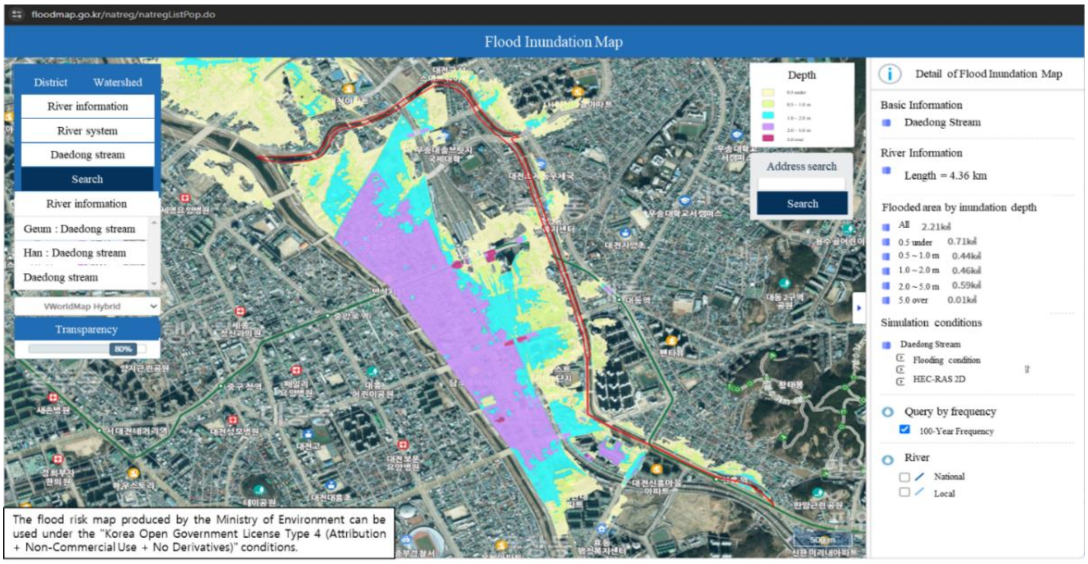
English language proofreader: Si Yu Lin



Detail of Flood Inundation Map

Basic Information
- Daedong Stream

River Information
- Length = 4.36 km

Flooded area by inundation depth
- All 2.21㎢
- 0.5 under 0.71㎢
- 0.5 ~ 1.0 m 0.44㎢
- 1.0 ~ 2.0 m 0.46㎢
- 2.0 ~ 5.0 m 0.59㎢
- 5.0 over 0.01㎢

Simulation conditions
- Daedong Stream
  - Flooding condition
  - HEC-RAS 2D

○ Query by frequency
☑ 100-Year Frequency

○ River
☐ National
☐ Local

The flood risk map produced by the Ministry of Environment can be used under the "Korea Open Government License Type 4 (Attribution + Non-Commercial Use + No Derivatives)" conditions.

Fig. 1 Flood inundation map presented in Korean by the Ministry of Environment, Korea [2]

In the process of interpreting urban floods, there is inevitable uncertainty that affects the accuracy of numerical simulations. This uncertainty arises from the numerical performance when analyzing the model, which can be addressed by appropriately selecting the discretization method or grid type used to solve the governing equations. It has been argued that these choices can resolve the uncertainties [3]. Given the diversity of flood analysis models, comparative and evaluative research on each model has been actively conducted.

Liu et al. [4] conducted a comparative analysis of the 1D and 2D modules of HEC-RAS and LISFLOOD-FP using a consistent 30 m grid, concluding that the 2D model yields more precise flood inundation results than the 1D model. Shustikova et al. [5] evaluated the HEC-RAS and LISFLOOD-FP models across various grid sizes, focusing on the accuracy and efficiency of the outputs. Willis et al. [6] examined the impact of variables such as grid size and the presence of buildings on the results of the LISFLOOD-FP model, finding that uncertainty is reduced in simpler terrains. However, they determined that numerical complexity is the primary source of uncertainty in complex fluid systems. Similarly, the HEC-RAS 2D model can successfully capture the flow process when compared to the coupled 1D/2D HEC-RAS models during high flow conditions. Therefore, it is concluded that the HEC-RAS 2D model would be more suitable for flash flood situations.

Horritt et al. [7] applied the one-dimensional hydrologic engineering center's river analysis system (HEC-RAS) and two-dimensional (TELEMAC-2D, LISFLOOD-FP) models for river flood prediction on the Severn River in the UK, adjusting roughness coefficients to assess the suitability of each model. Lee et al. [8] simulated river flooding using HEC-RAS 2D and FLUMEN models and compared the results regarding the inundation area. Furthermore, Lavoie and Mahdi [9] conducted an objective comparison of two river flooding models, sedimentation and river hydraulics – two-dimensional (SRH-2D) and Hydro_AS-2D, a two-dimensional hydrodynamic model, applying them to a dam break scenario and providing foundational data for selecting flood models. Dimas et al. [10] simulated mudflow using both the HEC-RAS model and FLO-2D, which is a two-dimensional flood routing model, and evaluated the applicability of each model.

These studies underscore the importance of selecting a flood model best suited to the specific characteristics of the area being studied. The appropriateness of the model can significantly influence the accuracy of flood inundation maps, highlighting the need for careful selection based on the unique hydrological and urban characteristics of each region. Park and Han [11] utilized the 1D dam-break flood forecasting model (DAMBRK) and the 2D FLO-2D model to develop evacuation maps during the creation of an emergency action plan (EAP). They found that the 2D model, which can incorporate detailed topographical features such as buildings and roads, is more appropriate for hydraulic analysis. When addressing the challenges of flood modeling following flash floods, it is important to acknowledge the essential role of 2D shallow water models. These models are particularly crucial in capturing the complex dynamics of floods when encountering low predictability [12]. The complexity of models applied in flood analysis ranges from simple interpolation methods to sophisticated and spatially detailed models that solve the water equations in two dimensions [13]. For these reasons, studies utilizing numerical models to develop flood maps have been continuously conducted in recent years [14].

Previous studies have shown that flood simulation outcomes can vary significantly, even when modeling the same geographic area, due to the use of different flood analysis models. Comparative analyses have clearly demonstrated these variations. However, the performance of these models can also be influenced by engineers' proficiency in the operation. Relying solely on metrics such as inundation area or depth to evaluate model superiority may hinder objective assessments.

Therefore, a comprehensive comparison of both the application processes and the results of these models is essential for a more holistic evaluation. Urban areas consist of diverse buildings and terrain, which can lead to varying flood simulation results depending on the model used. This study conducts a detailed comparative analysis of various models to identify the most suitable one for simulating floods in specific regions. By critically comparing the characteristics of each model, this study aims to help engineers select the most appropriate model for particular environmental conditions.

2. Methodology and Materials

This section outlines the methodology used to evaluate and compare the performance of FLUMEN and HEC-RAS 2D hydraulic models, as well as the materials used in the experimental studies. The following subsections describe the step-by-step process, from data collection to model validation, ensuring consistency and reliability in the results.

2.1. *Methodology*

This study aims to evaluate and compare the performance of two hydraulic models, FLUEMEN and HEC-RAS 2D, by simulating depth under controlled experimental conditions. Fig. 2 represents the methodology of this study. The study is conducted by constructing terrain data, configuring the models, and then comparing and analyzing the simulation results of each model. The data required for each model are collected based on the experimental study conducted by [15], with both FLUMEN and HEC-RAS 2D models configured to operate under identical conditions. The water depth observation results from the experimental study are used to validate both models, involving a comparison of the performance procedures and the simulation results of the two models.

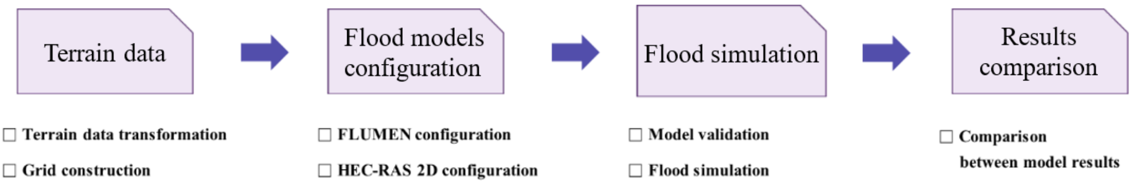


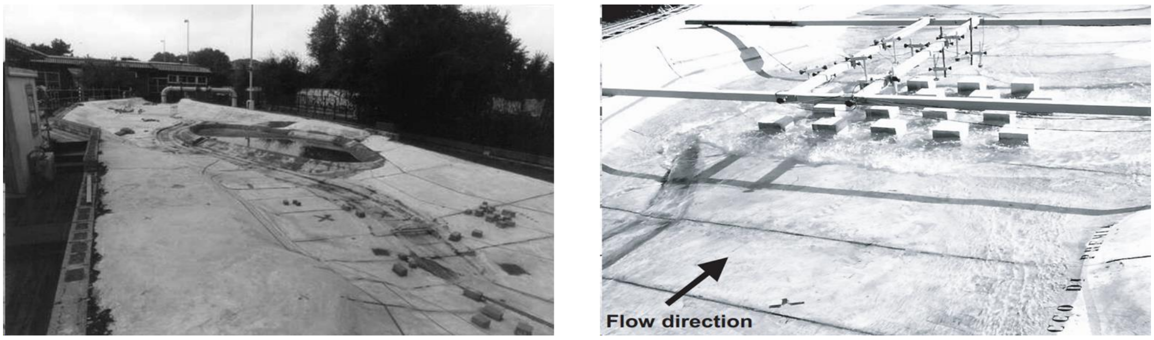
Fig. 2 Procedure of this study

2.2. *Experimental studies*

Testa et al. [15] conducted research to provide a dataset for studying flow characteristics in urban environments and assessing the accuracy of numerical models in reproducing these characteristics. This research is part of a broader study on flood propagation in urban areas, conducted under the European joint project called Investigation of extreme flood processes and uncertainty (IMPACT). This study utilizes the dataset from [15], which includes terrain data, boundary conditions, and roughness coefficients.

2.2.1. *Terrain data*

A digital terrain model (DTM) of the physical model of the Toce River valley in Italy is provided with 5 cm intervals. For the reported experiments, only an area of 5 m in length at the upstream end of the total 50 m in length is used. This corresponds to the original valley terrain of the actual Toce River valley, scaled down at a ratio of 1:100. The terrain data are provided in a scatter file format, with points spaced 5 cm apart. An overview of the experimental site is shown in Fig. 3.

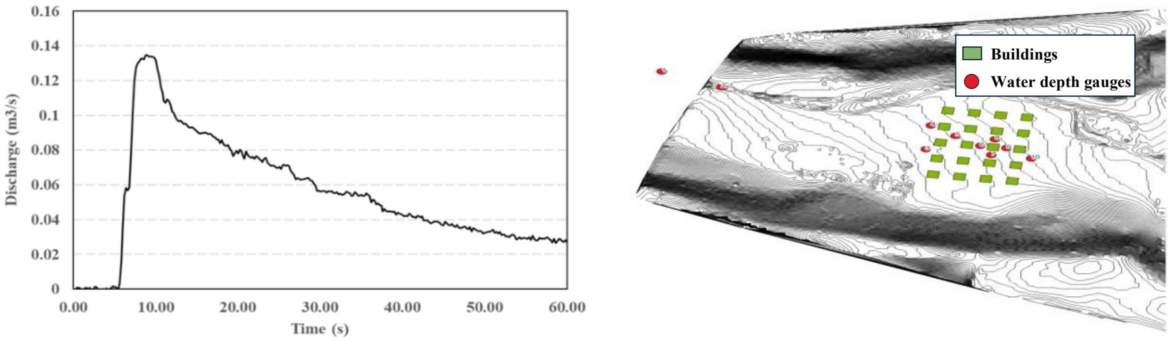


(a) Overview of Experimental Terrain (b) Conducting the Experiment

Fig. 3 General view of Toce River physical model looking upstream [15]

2.2.2. Flow data and observational data

In this experiment, Fig. 4. (a) shows the inflow hydrograph used in the experiment, and (b) indicates the water level measurement points. The experiment simulated an urban flash flood scenario, supplying valuable reference data for validating flood analysis models. A 5-meter-long concrete river model is constructed, with water depth measurements taken at ten specific locations. Depth variations over time are carefully recorded, providing essential comparative data for evaluating the performance of the flood models. These results are used to validate the accuracy of HEC-RAS 2D and FLUMEN models in replicating urban flood dynamics. The primary objective is to analyze flow characteristics in urban environments and assess the models' ability to accurately reproduce these dynamics, offering insights into their application for managing urban flood risks.1



(a) Inflow hydrograph (b) Location of water depth gauges

Fig. 4 Basic information of experimental study [15]

3. Overview of Numerical Models

This section provides an overview of the two numerical models, HEC-RAS 2D and FLUMEN, used in this study. Both models apply the finite volume method (FVM) to simulate hydrodynamic phenomena and handle complex boundary conditions in flood scenarios. The following subsections describe the numerical schematics and specific characteristics of each model.

3.1. Numerical schematic of two models

Both HEC-RAS 2D and FLUMEN models utilize the finite volume method (FVM), a numerical approach well suited for conserving mass and energy in fluid dynamics, to simulate hydrodynamic phenomena. This method discretizes the computational area into a finite number of control volumes and integrates the governing equations over each volume. In flood inundation modeling, the application of FVM enables precise representation of flow fields and water surface elevations, which are critical for predicting the extent and dynamics of floods. By employing this method, HEC-RAS 2D and FLUMEN models effectively handle complex boundary conditions, and irregular terrains often encountered in urban flood scenarios. The strength of FVM in managing shocks and discontinuities also enhances its applicability in modeling transient flood events.

FLUMEN employs the flux difference splitting (FDS) method, which is derived from Euler's equations and tailored for hyperbolic shallow water equations. This method helps reduce numerical oscillations, making it highly effective in simulations that involve fast-changing dynamics such as shock waves. HEC-RAS 2D uses the Saint Venant equations for its simulations, a set of shallow water equations suitable for flood analysis. The model is capable of incorporating turbulence terms which significantly enhance the accuracy of velocity component calculations in flood situations. This addition is crucial for more accurate predictions and analysis in complex flow scenarios.

3.2. FLUMEN (fluvial modelling engine) [16]

Developed by Beffa in Switzerland, the fluvial modeling engine (FLUMEN) model is used for flood analysis in countries such as Switzerland, Germany, and Austria. This two-dimensional model employs shallow water equations on an unstructured grid, making it highly effective for modeling hydrologically complex areas, including river bends and confluences. FLUMEN model uses the FDS, which significantly reduces numerical oscillations [17], evolved from the application of Euler's equations, and applies to hyperbolic shallow water equations [18]. It performs exceptionally well in simulating viscous flows and shock wave calculations [19].

The governing equations of the FLUMEN model are the depth-integrated nonlinear shallow water equations with hydrostatic pressure distribution, which can be represented in conservative form as Eq. (1):

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial G}{\partial y}+S=0 \tag{1}$$

In Eq. (1), the conservative variable vector U can be represented in terms of water depth h and specific discharge q and r, as shown in Eq. (2):

$$U=\begin{pmatrix} h \\ q \\ r \end{pmatrix} \tag{2}$$

Meanwhile, the flux vectors E, G along the x and y axes, and the source vector S are respectively presented, as shown in Eq. (3):

$$E=\begin{pmatrix} q \\ \dfrac{q^2}{h}+\dfrac{g}{2}h^2 \\ \dfrac{qr}{h} \end{pmatrix}, G=\begin{pmatrix} r \\ \dfrac{qr}{h} \\ \dfrac{r^2}{h}+\dfrac{g}{2}h^2 \end{pmatrix}, S=\begin{pmatrix} 0 \\ gh\dfrac{\partial z_b}{\partial x}+\dfrac{\tau_{bx}}{\rho} \\ gh\dfrac{\partial z_b}{\partial y}+\dfrac{\tau_{by}}{\rho} \end{pmatrix} \tag{3}$$

In Eq. (3), g is the gravitational acceleration, ρ is the density of the fluid, z_b is the bed elevation, and τ_b is the bed shear stress.

3.3. HEC-RAS 2D (Hydrologic Engineering Center River Analysis System 2D) [20]

HEC-RAS is a freely available software developed by the U.S. Army Corps of Engineers, capable of simulating 1D, 2D, and combined unsteady flows (1D-2D). It is also one of the most widely used hydrodynamic models for result visualization, offering gridded data outputs such as velocity, depth, and water surface elevation. Although it can select either the full Saint-Venant Equation or the 2D diffusion wave equation for simulations, this study employs the Saint-Venant Equation, which is deemed more suitable for flood analysis simulations.

The governing equations of HEC-RAS 2D are the mass conservation equation and the momentum conservation equation. Assuming the flow is incompressible and the vertical velocity differences are neglected, the unsteady differential mass conservation is given as Eqs. (4)-(6):

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0 \tag{4}$$

Additionally, the momentum conservation equation is provided as follows:

$$\frac{\partial (hu)}{\partial t}+\frac{\partial (hu^2)}{\partial x}+\frac{\partial (huv)}{\partial y}+gh\frac{\partial h}{\partial x}=\nu_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-C_f u+fv \tag{5}$$

$$\frac{\partial (hv)}{\partial t}+\frac{\partial (huv)}{\partial x}+\frac{\partial (hv^2)}{\partial y}+gh\frac{\partial h}{\partial y}=\nu_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-C_f v+fu \tag{6}$$

where h is the water depth, u is the velocity in the x-direction, v is the velocity in the y-direction, and g is the gravitational acceleration. Additionally, q is the source-sink flux term, ν_t is the eddy viscosity, C_f is the bottom friction, f is the Coriolis parameter. In this study, the values of the eddy viscosity coefficient are set to 0.3 and 0.1 for the longitudinal and transverse directions, respectively.

Both models use the shallow water equations as their governing equations. However, unlike FLUMEN, HEC-RAS 2D incorporates turbulence terms, enabling it to perform more accurate calculations of velocity components in flood situations.

4. Terrain Data

To properly input the terrain data provided by previous studies into both models, the data must be converted into a format suitable for each model. Therefore, terrain data in scatter format at 5 cm intervals are converted into mesh format (2dm) for the FLUMEN model and raster format (tiff) for the HEC-RAS 2D model. Fig. 5, (a) shows the grid structure in the FLUMEN model, and (b) presents the grid structure in the HEC-RAS 2D model.

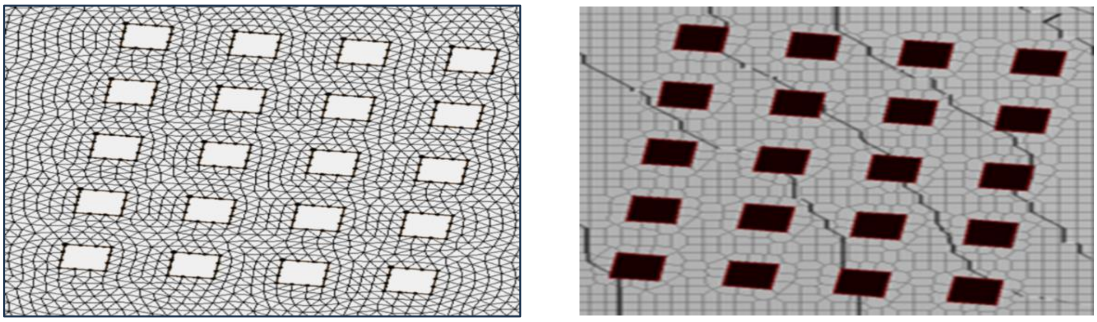

(a) Grid in the FLUMEN model (b) Grid in the HEC-RAS 2D model

Fig. 5 Grid system in both models

A key difference between the models is the subgrid approach of HEC-RAS 2D. This subgrid involves incorporating smaller grids within a larger grid to perform calculations at a higher resolution in certain areas. These smaller grids can represent detailed data and terrain features much more accurately than the larger grid, thus enhancing the overall precision of the model.

4.1. Scatter to mesh

To facilitate the input of terrain data into the FLUMEN model, the provided scatter data are converted into a mesh format and subsequently saved in a 2dm file format utilizing the surface-water modeling system (SMS), an advanced software package used by hydrologists and engineers to process terrain data and construct surface water models. This system supports users in analyzing terrain data, generating meshes, and applying various hydrological and hydrodynamic models. Using the SMS terrain processing program, nodes and polygons are created to fit the simulation range, and then elevation data entered in the scatter data are linearly interpolated and input into the mesh.

Using this method, the files in mesh format are converted and applied as terrain data in the FLUMEN model. The grid system in the FLUMEN model is implemented as an unstructured triangular mesh. Considering the resolution of the given terrain data, the grid spacing is also set to 5 cm, minimizing distortion to the given terrain data. Implementing building information, set in the experimental terrain directly into the grid could result in errors in the terrain around the buildings due to abrupt changes in elevation. Therefore, by removing the grids where buildings are located from the terrain data, the model reflects the impact of buildings on the flow. This involves excluding the space occupied by buildings in the model, which can obstruct and alter the direction of the flow.

4.2. Scatter to raster

To input terrain data into the HEC-RAS 2D model, the provided scatter data are converted into a raster format. This conversion is accomplished using a quantum geographic information system (QGIS), and the data are subsequently saved in TIFF format. QGIS is an open-source geographic information system (GIS) software that is highly compatible with other terrain modeling software. This software supports various data formats and provides powerful visualization and data processing capabilities, which enhances versatility and flexibility in the GIS field.

Using the QGIS terrain processing program, scatter data are linearly interpolated and directly converted into a raster file. Compared to the FLUMEN model, the converted terrain data are relatively straightforward. Unlike the FLUMEN model, the grid system in HEC-RAS 2D is implemented as an unstructured rectangular mesh. The grid spacing is set to 5 cm to construct a terrain as similar as possible to that of the FLUMEN model. In the HEC-RAS 2D model, unlike FLUMEN, grids cannot be deleted, and building information can be directly added to the terrain. Therefore, building information is directly added to the terrain data, implementing the presence of buildings in the model. Raster data consists of a grid of pixels, each storing specific spatial values, and is typically saved in TIFF format.

This format is resolution-dependent, with smaller pixel sizes offering higher accuracy but resulting in larger file sizes. In contrast, mesh data comprise a network of nodes, edges, and faces, which allow for the precise modeling of more complex terrains. Mesh data can accurately represent irregular terrains, and the arrangement of elements can be adjusted as needed to enhance calculation accuracy.

5. Numerical Stability (CFL number)

The CFL number is a dimensionless value that represents the stability condition required for calculations in numerical analysis. Initially aligned the calculation times of HEC-RAS 2D and FLUMEN models by adjusting the Courant-Friedrichs-Lewy (CFL) number. This adjustment serves as a critical factor in controlling the calculation times for each model. In the FLUMEN model, specific CFL numbers can be directly set, while in the HEC-RAS 2D model, the calculation times are adjusted by specifying a range for the CFL number. Eq. (7) and (8) define the CFL number for each model.

$$HEC-RAS\,2D: CFL = \frac{V\Delta t}{\Delta x} \tag{7}$$

$$FLUMEN: CFL = (V + \sqrt{gh})\frac{\Delta t}{\Delta x} \tag{8}$$

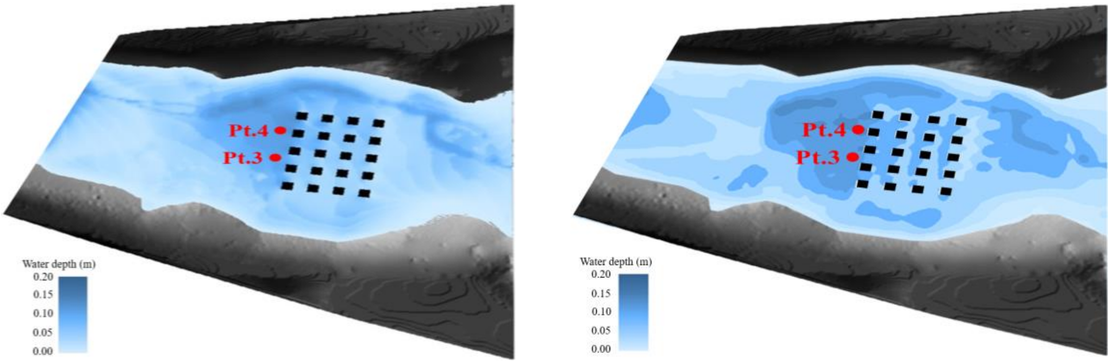
where V is the grid velocity, Δt is the time step, Δx is the cell size, h is the water depth, and g is the gravitational acceleration.

In scenarios with high-velocity variability, such as flash floods, setting a range for the CFL number has been shown to be beneficial. Initially, for the HEC-RAS 2D model, the CFL number is set between 0.029 and 0.060, and for the FLUMEN model, it is set to 0.060. To equalize the calculation times, the CFL number for the HEC-RAS 2D model is adjusted to 0.040.

This alignment allows both models to operate within consistent calculation times, ensuring stable and efficient analytical outcomes. Such synchronization not only standardizes computational methods across the models but also enhances modeling accuracy for various hydrological events. A very small CFL number can lead to numerical diffusion in shallow water simulations [21]. However, in this study, it is necessary to simulate situations where the velocity changes rapidly within a short period of time. In flash flood scenarios with significant variations in velocity, a high CFL number could cause numerical instability in the simulation. Therefore, maintaining a small CFL value is essential for obtaining stable and accurate results.

6. Flash Flood Simulation

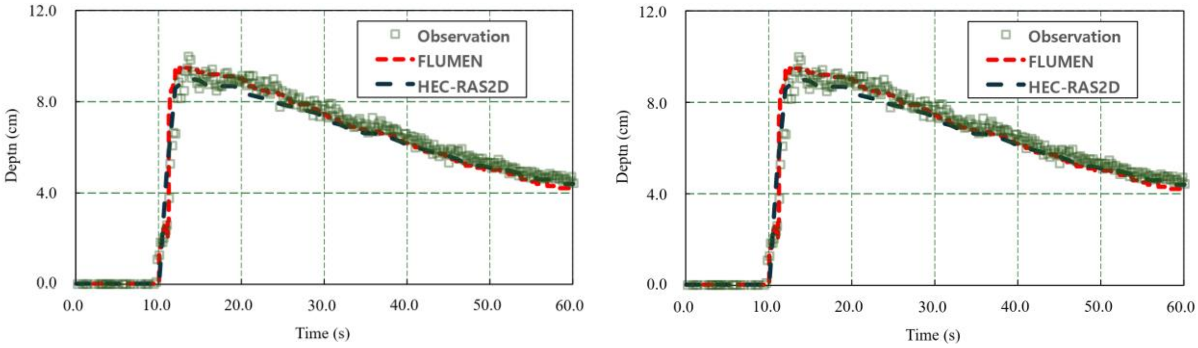
The initial condition of the model is set to dry, considering the experimental environment. The upstream boundary condition utilizes flow data presented in previous studies, while the downstream boundary condition is set to normal depth. Considering that the riverbed is composed of concrete, the roughness coefficient is set to n = 0.0162. The model validation is performed by comparing the simulated results with the water depth observation data measured at eight locations during the experiment. Figs. 6 (a) shows the simulation results of the HEC-RAS 2D model, and (b) presents the simulation results of the FLUMEN model.



(a) Water depth result of HEC-RAS 2D (b) Water depth result of FLUMEN

Fig. 6 Comparison of water depth result from the two models

Figs. 7 (a) and (b) provide the water level prediction results at points 3 and 4, respectively, and both the FLUMEN model and the HEC-RAS 2D model exhibited patterns similar to the observed values from the experiment.



(a) Water depth at probe points #3 (b) Water depth at probe points #4

Fig. 7 Observed and simulated water depth at probe points

7. Comparison of Simulation Results

This section compares the simulation results of the HEC-RAS 2D and FLUMEN models. The accuracy of both models is evaluated using performance metrics such as R^2 and RMSE, with FLUMEN generally showing higher overall accuracy. However, HEC-RAS 2D performed better in predicting peak water levels. Both models showed decreased accuracy when analyzing the flow between buildings. These comparative results highlight the strengths and weaknesses of each model, providing important insights for selecting models in flood risk management.

7.1. Comparisons with performance

To effectively evaluate and compare the simulation results of the two hydraulic models, widely recognized statistical evaluation metrics are employed. These include R-squared (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean error (ME), with their mathematical definitions provided in Eqs. (9)-(12), respectively. The calculated values of these performance metrics for both models are comprehensively displayed in Table 1.

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(P_i - \bar{P}\right)^2}} \right)^2 \tag{9}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right)^2} \tag{10}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|O_i - P_i\right| \tag{11}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right) \tag{12}$$

where O and P represent the observed values and simulated results, respectively.

Table 1 Performance of FLUMEN and HEC-RAS 2D

Stations		Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Average
R^2	HEC-RAS 2D	0.97	0.95	0.85	0.85	0.94	0.81	0.83	0.89
	FLUMEN	0.98	0.96	0.94	0.93	0.86	0.86	0.83	0.91
RMSE	HEC-RAS 2D	0.52	0.74	0.92	0.85	0.58	1.08	0.69	0.77
	FLUMEN	0.43	0.65	0.48	0.50	0.81	0.85	0.53	0.61
MAE	HEC-RAS 2D	0.33	0.50	0.77	0.66	0.36	0.94	0.48	0.58
	FLUMEN	0.27	0.39	0.35	0.37	0.61	0.72	0.41	0.45
ME	HEC-RAS 2D	-0.16	-0.13	0.69	0.61	-0.11	0.92	0.22	0.29
	FLUMEN	-0.09	-0.09	0.21	0.11	-0.59	0.66	-0.40	-0.03

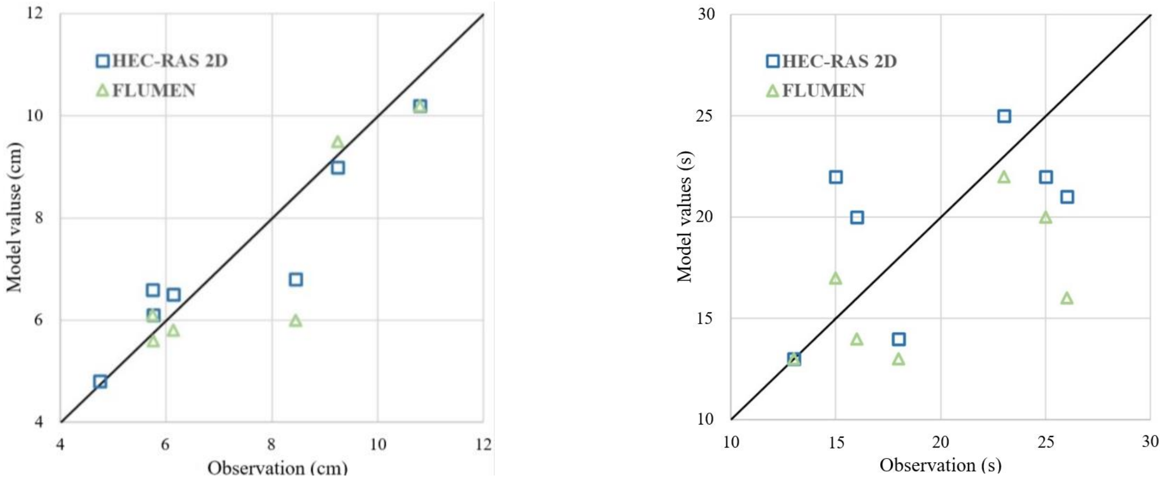
The most frequently used statistic for evaluating the goodness of fit of a model is likely the coefficient of determination, R^2 [22]. R^2 indicates the proportion of variance that is predictable from the predictors, with values closer to 1 being preferred. This demonstrates a high level of correlation, thus indicating effective model performance. RMSE and MAE measure the average magnitude of errors in predictions. Lower values are desirable as they suggest that the model's predictions are closer to observed data, reflecting better accuracy. ME, the average of prediction errors, is optimal when near zero, indicating no consistent bias in overestimating or underestimating observed values. Table 1 shows that at Point 3, the R^2 values for both models are 0.97 and 0.98, respectively, but at the final location, Point 9, both models display a relatively lower value of 0.83. It is observed that both models provide fairly accurate values in front of buildings; however, as they pass between buildings, the values become less accurate. 2D models focus on horizontal flow and find it difficult to account for vertical flow variations. Vertical turbulence can occur in the flow between buildings, and because it is challenging to consider this in the model, the accuracy of the model is likely reduced.

This indicates that there are still limitations in accurately analyzing flow between buildings using two-dimensional flood analysis models, suggesting potential areas for improvement in both models. The comparative analysis is meticulously conducted by focusing on the results of these evaluation metrics at predetermined specific locations, which are critical for understanding the models' performance in real-world scenarios. This methodical approach ensures a thorough and objective comparison of the models' accuracy. The analysis shows that, overall, the FLUMEN model slightly outperforms the HEC-RAS 2D model in terms of agreement with observed data, suggesting that it may provide a more reliable prediction under similar conditions. Such insights are crucial for model selection and further refinement in the field of flood risk management and hydraulic simulation.

7.2. Comparison of peak value

In flood inundation modeling, assessing the accuracy and reliability of different models is essential for effective planning and response. Not only is the comparison of overall values important, but the analysis of peak water levels and the timing of these peaks is also crucial for understanding the potential impact of flood events. The comparison of peak water levels between the models shows that, although both models present similar values, the HEC-RAS 2D model, on average, exhibits a closer match by approximately 8%. This suggests that the HEC-RAS 2D model may provide more precise predictions in scenarios where peak water levels are critical for flood risk management. Such findings are invaluable for enhancing the predictive capabilities of flood models and improving the strategies used in flood mitigation and emergency response planning.

Fig. 8 presents a direct comparison graph of experimental and modeled data to evaluate the accuracy of the two models. Fig. 8(a) compares the peak water levels, while Fig. 8(b) compares the timing of these peaks. When comparing peak water levels between the HEC-RAS 2D model and the observed values, a discrepancy of up to 19% is observed. In contrast, the discrepancy for the FLUMEN model reaches up to 29%, which is 10% higher than that observed with the HEC-RAS 2D model. From these graphs, it can be concluded that the HEC-RAS 2D model aligns more closely with the experimental results.



(a) Comparison of peak water level values (b) Comparison of peak water level occurrence time

Fig. 8 Comparison of peak water level and time between the two models

7.3. Comparison of features

Table 2 demonstrates superior features between models. For instance, HEC-RAS 2D is capable of considering turbulence terms, while FLUMEN cannot. Although both models exhibit satisfactory performance and results in other aspects, the model displaying superior capabilities compared to others is labeled as 'better'. HEC-RAS 2D shows more excellent results in numerical stability and peak water level prediction, whereas FLUMEN excels in stable grid construction and overall water level prediction.

Table 2 Comparison results of HEC-RAS 2D and FLUMEN

models	process			results	
	turbulence	grid construction	numerical stability	overall	peak
HEC-RAS 2D	good	good	better	good	better
FLUMEN	N/A	better	good	better	good

8. Conclusions

In this study, to identify the strengths and limitations under different flood scenarios, the performance of the HEC-RAS 2D and FLUMEN models for flood inundation analysis is thoroughly evaluated. This study presents the most suitable model for various flood conditions and provides practical applications based on their accuracy and performance. The main findings are summarized as:

(1) HEC-RAS 2D demonstrated superior capabilities in river flood analysis, especially in floodplain inundation and water flow pattern prediction. Its flexibility in adjusting the CFL number and handling turbulence provided reliable simulations. It is approximately 8% more accurate in predicting peak water levels than FLUMEN, enabling it to render more suitable for precise hydrodynamic analyses in riverine environments.

(2) FLUMEN, on the other hand, excelled in urban environments where detailed modeling of complex structures, such as buildings and infrastructure is crucial. While slightly less accurate in peak water level prediction, it generally performed better under typical conditions and provided a more precise interaction between floodwaters and urban elements, validating the effectiveness of urban flood prediction.

These findings highlight the necessity of selecting a model that aligns with the specific characteristics of the study area, as the choice of model can significantly affect the accuracy of flood maps. Future research should expand to include other 2D flood analysis models and variables such as temporally varied flood areas to enhance flood risk analysis and mitigation strategies.

Acknowledgment

This work is supported by the Korea Environment Industry & Technology Institute (KEITI) through the R&D Program for Innovative Flood Protection Technologies against Climate Crisis, funded by the Korea Ministry of Environment (MOE) (2022003470001)

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] R. B. Mudashiru, N. Sabtu, I. Abustan, and W. Balogun, “Flood Hazard Mapping Methods: A Review,” Journal of Hydrology, vol. 603, Part A, article no. 126846, December 2021.

[2] Han River Flood Control Office, “River Flood Map,” https://floodmap.go.kr/, April 1, 2024

[3] P. Luo, M. Luo, F. Li, X. Qi, A. Huo, Z. Wang, Y. Wang, et al., “Urban Flood Numerical Simulation: Research, Methods, and Future Perspectives,” Environmental Modelling & Software, vol. 156, article no. 105478, October 2022.

[4] Z. Liu, V. Merwade, and K. Jafarzadegan, “Investigating the Role of Model Structure and Surface Roughness in Generating Flood Inundation Extents Using One- and Two-Dimensional Hydraulic Models,” Journal of Flood Risk Management, vol. 12, no. 1, pp. 1-19, March 2019.

[5] I. Shustikova, A. Domeneghetti, J. C. Neal, P. Bates, and A. Castellarin, “Comparing 2D Capabilities of HEC-RAS and LISFLOOD-FP on Complex Topography,” Hydrological Sciences Journal, vol. 64, no.14, pp. 1769-1782, 2019.

[6] T. Willis, N. Wright, and A. Sleigh, “Systematic Analysis of Uncertainty in 2D Flood Inundation Models,” Environmental Modelling & Software, vol. 122, article no. 104520, December 2019.

[7] M. S. Horritt and P. D. Bates, “Evaluation of 1D and 2D Numerical Models for Predicting River Flood Inundation,” Journal of Hydrology, vol. 268, no. 1-4, pp. 87-99, November 2002.

[8] C. H. Lee and T. G. Lee, “Evaluation of an Applicability of HEC-RAS 5.0 for 2-D Flood Inundation Analysis,” Journal of the Korea Academia-Industrial Cooperation Society, vol. 17, no.4, pp. 726-733, April 2016. (In Korean)

[9] B. Lavoie and T. F. Mahdi, “Comparison of Two-Dimensional Flood Propagation Models: SRH-2D and Hydro_AS-2D,” Natural Hazards, vol. 86, pp. 1207-1222, 2004.

[10] K. Vashist and K. K. Singh, “HEC-RAS 2D Modeling for Flood Inundation Mapping: a Case Study of the Krishna River Basin,” Water Practice & Technology, vol. 18, no. 4, pp. 831-844, April 2023.

[11] J. H. Park and K. Y. Han, “Applicability Analysis of 2-D Model for Evacuation Map to Establish Dam Emergency Action Plan,” Journal of The Korean Society of Hazard Mitigation, vol. 20, no. 2, pp. 47-59, April 2020.

[12] A. Ferrari, R. Vacondio, and P. Mignosa, “High-Resolution 2D Shallow Water Modelling of Dam Failure Floods for Emergency Action Plans,” Journal of Hydrology, vol. 618, article no. 129192, March 2023.

[13] Z. Naiji, O. Mostafa, N. Amarjouf, and H. Rezqi, “Application of Two-Dimensional Hydraulic Modelling in Flood Risk Mapping: A Case of the Urban Area of Zaio, Morocco,” Geocarto International, vol. 36. no. 2, pp. 180-196, 2021.

[14] P. Dimas, G. Pouliasis, P. Dimitriadis, P. Papanicolaou, S. Lazaridou, and S. Michas, “Comparison of Mudflow Simulation Models in an Ephemeral Mountainous Stream in Western Greece Using HEC-RAS and FLO-2D,” Euro-Mediterranean Journal for Environmental Integration, vol. 8, no.4, pp. 919-933, December 2023.

[15] G. Testa, D. Zuccala, F. Alcrudo, J. Mulet, and S. Soares-Frazão, “Flash Flood Flow Experiment in a Simplified Urban District,” Journal of Hydraulic Research, vol.45, no. 1, pp. 37-44, 2007.

[16] User’s Guide: FLUMEN, Vers. 1.0, Fluvial.ch, 2003.

[17] P. L. Roe, “Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes,” Journal of Computational Physics, vol. 135, no. 2, pp. 250-258, August 1997.

[18] P. Glaister, “An approximate Linearised Riemann Solver for the Euler Equations for Real Gases,” Journal of Computational Physics, vol. 74, no. 2, pp. 382-408, February 1988.

[19] B. V. Leer, J. L. Thomas, P. L. Roe, and R. W. Newsome, “A Comparison of Numerical Flux Formulas for the Euler and Navier-Stokes Equations,” 8th Computational Fluid Dynamics Conference, pp. 87-1104, June 1987.

[20] User’s Guide: HEC-RAS River Analysis System, Vers. 5.0, US Army Corps of Engineers Hydrologic Engineering Center (HEC), 2016.

[21] R. J. LeVeque, Finite Volume Methods for Hyperbolic Problems, Cambridgeshire: Cambridge University Press, 2002.

[22] A. Y. J. Akossou and R. Palm, “Impact of Data Structure on the Estimators R-Square and Adjusted R-Square in Linear Regression,” International Journal of Mathematics and Computation, vol. 20, no. 3, pp. 84-93, 2013.