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Analysis of Fixed-Time Synchronization by Rainfall Runoff Method

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Abstract

Due to climate change, the frequency and intensity of torrential rainfall in urban areas are increasing, resulting in frequent flood damage. Despite the wide usage of the dual-drainage model—which relies on minimum time-step synchronization for accurate flood analysis—computational speed remains a major challenge. This study employs the Hyper-Connected Solution for Urban Floods (HC-SURF) model to conduct a sensitivity analysis of fixed time-step flow synchronization for different rainfall runoff approaches(lumped and distributed). Laboratory experiments and real-world urban watershed simulations were used to evaluate the accuracy and efficiency of each approach. While some accuracy loss may occur due to the choice of rainfall runoff method, overall performance in terms of mass balance and maximum inundation area remained excellent. These findings highlight HC-SURF's potential for rapid and precise urban flood modeling, offering a balanced perspective on computational efficiency and model accuracy.

Highlights

- Demonstrates feasibility of fixed time-step flow synchronization in HC-SURF for urban flood modeling.
- Compares lumped and distributed runoff methods, revealing minimal accuracy loss under varied conditions.
- Balances enhanced computational speed with consistent flood prediction precision.

Introduction

With climate change causing global warming and altering rainfall amounts and durations, along with rapid urbanization leading to a sharp increase in impervious areas, urban flood damage is becoming increasingly severe. In particular, in regions where urbanization has progressed rapidly, surface flow and the effects of sewer flow interact in complex ways, necessitating a sophisticated and comprehensive approach to flood analysis. To address such flood risks, the development of flood analysis models and related research has been actively pursued. Recently, for more accurate urban flood simulations, the dual-drainage model—which integrates surface flow and sewer flow—has been widely used. However, this model requires the synchronization of the minimum time step for both surface and pipe flows, resulting in significantly higher computational costs.

To overcome these limitations, improvements in the model structure and the introduction of more efficient algorithms are necessary. Ultimately, the development of an analytical method capable of providing rapid and accurate flood forecasting, even in complex urban environments, is required.

Against this backdrop, this study applies the Hyper-Connected Solution for Urban Floods (HC-SURF) model to propose a method for effectively integrating complex urban drainage systems with surface flow. In particular, by examining the structural characteristics of the HC-SURF model and exploring the analytical features related to fixed time-step flow synchronization and types of rainfall-runoff (lumped vs. distributed), we seek an approach that achieves both efficiency and accuracy in urban flood analysis. It is anticipated that this will lay an important foundation for preventing urban flood damage and establishing a real-time disaster response system.

Methodology

HC-SURF Model

In this study, urban flooding was analyzed using the HC-SURF (Hyper Connected Solution for Urban Flood) model, which was developed to simultaneously handle flows in stormwater sewer networks and overland surfaces. For the stormwater network flow analysis, the source code of SWMM 5.2—widely recognized as one of the most common versions—was utilized, while the surface water flow analysis was performed using an in-house code that discretizes the two-dimensional shallow water equations via the finite volume method. The SWMM model is written in C, and the surface flow component is developed in Fortran. These were configured as a single project within Visual Studio so that they could exchange information, and then compiled into a single executable file.

HC-SURF applies the finite volume method to discretize the continuity equation and the diffusion wave form of the momentum equation, as shown in Equations (1)–(3), in order to analyze overland flow in urban flooding.

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=R+E \qquad (1)$$

$$\frac{\partial (hu)}{\partial t}+g\frac{\partial (h+z)}{\partial x}=S_{fx} \quad (2)$$

$$\frac{\partial (hv)h}{\partial t}+g\frac{\partial (h+z)}{\partial x}=S_{fy} \quad (3)$$

Here, h denotes the water depth, and u and v are the velocity components in the x and y-directions, respectively. The term S_f represents the Manning bed friction, which can be expressed using the Manning equation. In the continuity equation (1), R on the right-hand side represents the rainfall intensity, while E signifies the inflow/excess flow exchanged with the stormwater sewer network. To simulate changes in flow, the unit discharge at the boundaries of the computational grid was calculated using Equations (2) and (3), and then applied to Equation (1) to determine changes in water depth.

Rainfall Runoff Method

In urban flood analysis, rainfall runoff methods can be broadly divided into two types. The first method directly simulates surface flow. This method simulates surface flow after rainfall runs off the surface and models the process of water entering or exiting manholes. This method allows for precise analysis of interactions between surface water and the sewer system by reflecting the actual runoff paths and hydrological conditions.

The second method uses the RUNOFF block of EPA-SWMM. This method assumes that all effective rainfall from the manhole catchment area is collected and calculates the amount of water discharged through the manhole, using it as input data for surface flow simulation. This method effectively simulates the flow in sewer systems and is widely used in urban environments for rainfall runoff analysis. In the first method, surface flow only occurs if the manhole exceeds its capacity, so surface flow does not occur in areas where manhole flooding does not occur. In contrast, the second method simulates rainfall runoff across all surfaces and performs flow exchange between surface flow and manholes, allowing for a more detailed analysis. However, it requires a longer computation time, and various factors such as the resolution of the surface grid and building density affect the surface flow analysis, making the accuracy of the initial data crucial. This study aims to perform dual-drainage simulations using both of the rainfall treatment methods and evaluate the flood analysis capabilities of each method under simplified sewer networks (Figure 1).

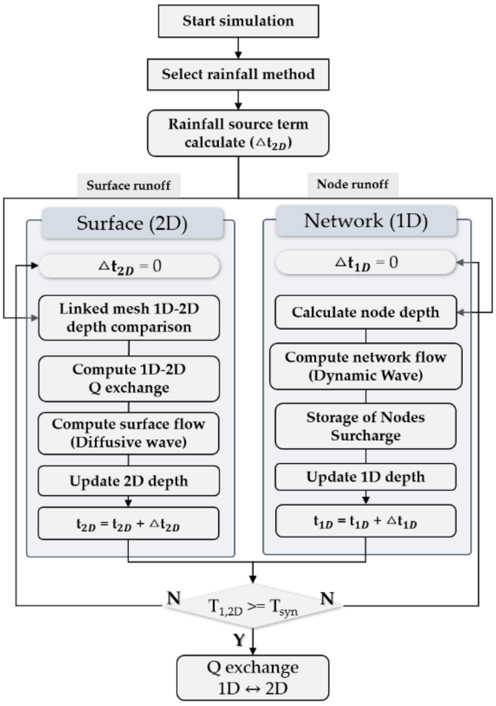

Figure 1. Rainfall Runoff Method

Fixed Time Synchronization

In the dual-drainage model, there are two methods of time synchronization: (1) using the minimum Δt (CFL condition) of the pipe (1D) and surface (2D) as is, and (2) periodically exchanging at a fixed time(Δt_{fixed}) specified in advance by the user (Fig. 2). The minimum Δt method is simple in terms of algorithm, but when the Δt_{2D} becomes as small as microseconds, the computational load increases significantly. Therefore, this study adopts a Δt_{fixed} and repeats the following procedure to achieve precision similar to the actual minimum Δt method.

1) Storage – Record the inflow, outflow, and water level of each 1D node at each user-defined Δt_{fixed}.
2) Transfer and interpolation – Transfer the recorded values to 2D and linearly interpolate the previous and current water levels to reflect changes within the fixed interval.
3) Calculate and feedback – Develop the 2D surface flow up to Δt_{fixed}, accumulate the flood/drainage volume, return it to 1D, and move on to the next cycle.

In this study, we set fixed times to 1, 10, 30, 60, 120, 180 and 300 seconds and compared simulation results with different rainfall runoff methods for each fixed time to perform a sensitivity analysis on computational accuracy and computational time.

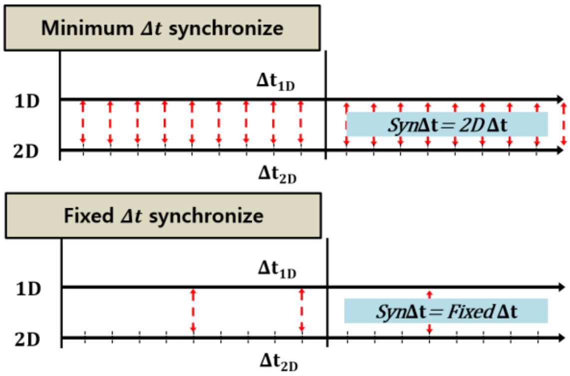

Figure 2. Time Synchronization Types

Laboratory Experiment and Study area

To validate the HC-SURF model, it was applied to a hydraulic experiment case that replicated a small-scale urban area. The experimental facility reproduces a T-shaped intersection spanning an area of 100 m², connected to a sewer system, and is equipped with a rainfall simulator that can uniformly produce rainfall intensities of 30, 50, and 80 mm/h.

For real-world urban watershed application, the Sillim drainage area in the Dorim-river basin watershed was selected. This area experienced flood damage during the concentrated heavy rain that hit southern Seoul in 2022. Located in the midstream region of Dorim-river, the Sillim drainage area covers approximately 5.14 km². The low-lying areas adjacent to the river are prone to flooding, as stormwater tends to remain on the road surfaces during rainfall events. A schematic of the experimental watershed and the status of the Sillim drainage area are shown in Fig. 3 below.

In the laboratory catchment, the HC-SURF model was validated with the surface-distributed runoff option and a fixed synchronization interval of 1s. The skill metrics from this baseline run will serve as the reference when we later quantify, over the real Sillim watershed, how model accuracy varies with longer synchronization times and with the alternative runoff treatment. All results for Δt_{fixed} > 1 s in the field study will therefore be expressed relative to this 1-s benchmark.

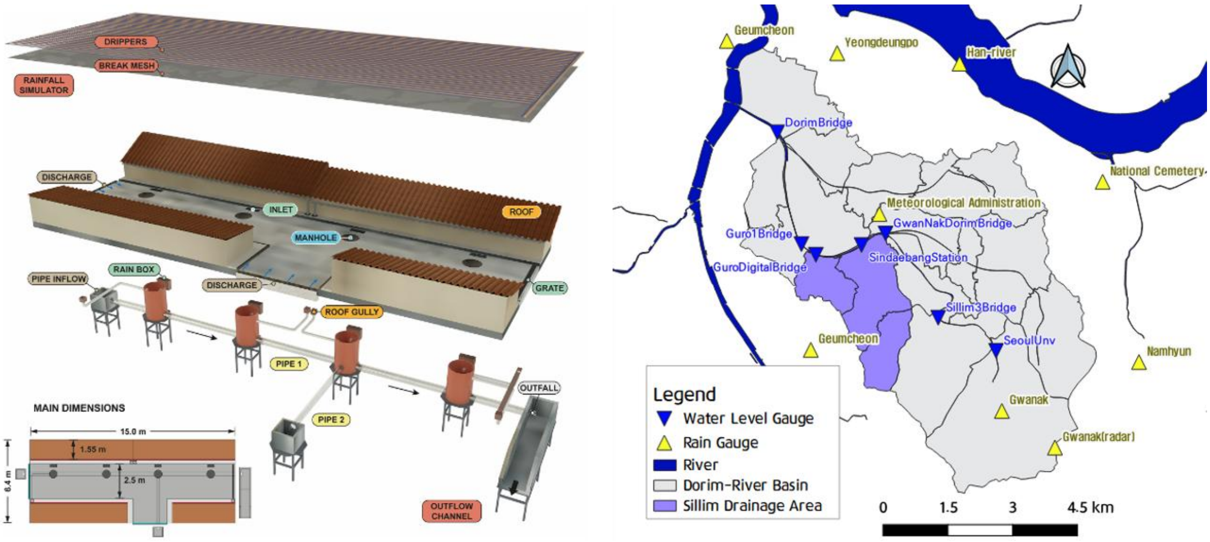

Figure 3. Study Area(Left : Laboratory experiment, Right : Sillim drainage area)

Results

Laboratory-scale Validation Results

The HC-SURF model was first benchmarked in a 100 m^2 T-intersection laboratory basin configured with the surface-distributed rainfall-runoff option and a fixed synchronization interval of Δt = 1s. A programmable rainfall simulator delivered three events—30, 50, and 80 mm/h—while flow rates were monitored at roofs, street inlets, manholes, and the outfall. Across all intensities, the discrepancy between the simulated and observed cumulative discharge was limited to 0.3–1.2 L/sec, i.e. < 1 % of the total volume, demonstrating tight mass balance. Individual hydrographs were reproduced with MAE = 0.004–0.127 L/sec and RMSE = 0.005–0.177 L/sec, values that meet the “very good” threshold for urban drainage applications. The model also captured the observed hierarchy of inflow contribution—roofs ≫ street inlets > manholes > outfall—and correctly predicted that no surcharging occurred at any inlet or manhole under the tested storms. These findings confirm that a 1-second fixed-time synchronization step can maintain both mass conservation and hydraulic fidelity at small scale, and they establish a rigorous baseline against which the forthcoming full-scale sensitivity tests (longer Δt and alternate runoff treatment) will be gauged(fig. 4).

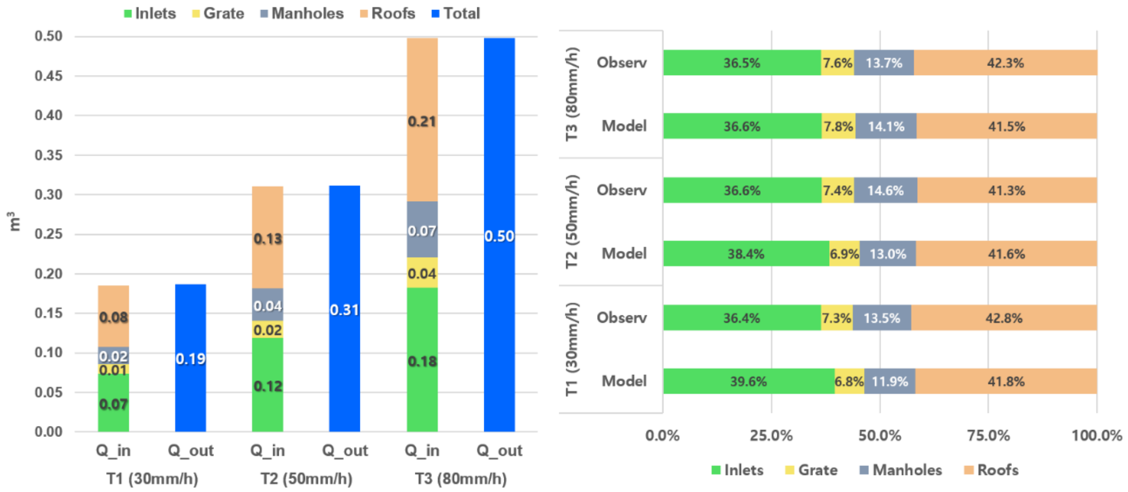

Figure 4. Laboratory-scale validation results: (a) mass-balance error under each rainfall intensity; (b) inflow contribution by hydraulic element (roofs, inlets, manholes, outfall).

Sillim Drainage Area Analysis Results

Starting from the 1s laboratory benchmark, we progressively lengthened the synchronization interval to 10, 30, 60, 120, 180 and 300 s and applied both rainfall–runoff treatments.

When the node-lumped runoff method—which injects effective rainfall directly at sewer nodes—was used, model skill stayed essentially unchanged up to 60s and remained acceptable at 120s: surcharge RMSE hovered around $2m^3$/sec and the maximum inundation area differed from observations by less than 10.5%, all while total CPU time fell by about 18 % (1,388s → 1,112s). Once Δt_{fixed} exceeded 180 s, however, linear interpolation no longer captured rapid stage changes; at 300 s discharge RMSE doubled, and at 600 s it reached 3.7 $m^3\ s^{-1}$ with the flooded area over-predicted by 4.7 %, even though the run sped up by roughly 20 %.

Applying the surface-distributed runoff method, in which rainfall is applied to every 2-D cell and travels overland before entering surcharged manholes, yielded a similar escalation of error with increasing Δt_{fixed}, yet two urban-specific effects became evident. In Seoul’s narrow streets and courtyards rainfall landing on densely packed roofs can be hydraulically “trapped,” so coarse surface meshes (> 5 m) damp lateral runoff and under-predict peak depths; the distributed scheme therefore reproduced more than 85 % of the observed flood footprint but kept maximum water depth below 1.2 m, whereas the node-lumped approach captured the observed ~1.5 m. Because the distributed treatment is also about 40 % more computationally demanding, its advantage is limited to plan-view accuracy gains that are modest unless a fine grid is used.

Taken together, the experiments indicate that $\Delta t_{fixed} \approx 60$ s offers the best compromise between accuracy and efficiency. For rapid operational forecasts a node-lumped runoff treatment combined with this interval identifies critical inundation sooner and is less sensitive to mesh resolution, whereas the surface-distributed approach remains valuable for detailed hydraulic studies performed on high-resolution grids.

Results and Discussion

This study focused on presenting an efficient and accurate analytical technique for urban flood prediction using the HC-SURF model. Through both experimental tests and analyses of a real urban watershed, it was confirmed that the HC-SURF model, even when applying a fixed time-step synchronization technique, maintains high accuracy while significantly improving computational efficiency.

The HC-SURF model and fixed time-step flow synchronization method proposed in this study have proven to be effective tools for addressing complex flood issues caused by urbanization and climate change. By intricately combining surface flow and sewer flows, the model achieves both high accuracy and computational efficiency. However, to broaden its practical applications, more precise sensitivity analyses for various watershed scales and geographic characteristics are needed, along with additional research to enhance real-time forecasting capabilities. These efforts are expected to play a pivotal role in minimizing urban flood damage and establishing rapid disaster response systems.

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