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The Impact of Storm Sewer Network Simplification and Rainfall Runoff Methods on Urban Flood Analysis

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Abstract: Due to the impact of climate change, the importance of urban flood analysis is increasing. One of the biggest challenges in urban flood simulations is the complexity of storm sewer networks, which significantly affects both computational time and accuracy. This study aimed to analyze and evaluate the impact of sewer network simplification on the accuracy and computational performance of urban flood prediction by comparing different rainfall runoff methods. Using the hyper-connected solution for urban flood (HC-SURF) model, two rainfall runoff methods, the SWMM Runoff method and the Surface Runoff method, were compared. The sewer network simplification was applied based on manhole catchment areas ranging from 10 m^2 to 10,000 m^2. The analysis showed that the computation time could be reduced by up to 54.5% through simplification, though some accuracy loss may occur depending on the chosen runoff method. Overall, both methods produced excellent results in terms of mass balance, but the SWMM Runoff method minimized the reduction in analytical performance due to simplification. This study provides important insights into balancing computational efficiency and model accuracy in urban flood analysis.

Keywords: urban flood model; sewer simplification; rainfall runoff method

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1. Introduction

With global warming caused by climate change and the resulting changes in rainfall amounts and durations [1–3], urbanization has rapidly increased the area of impervious surfaces, exacerbating urban flood damage [4,5]. In response to such damage, the active development of flood analysis models and the use of these models in analyses have increased.

As a case study on urban flood analysis models, research has been conducted on methods to handle the physical complexity of urban environments in dual drainage models, allowing physical elements to be incorporated into the modeling process [6]. In addition, a new approach using remote sensing has been developed to calibrate the performance of dual drainage systems and improve the accuracy of flood prediction [7,8]. Research combining storm sewer models, two-dimensional (2D) surface flow models, and pumping station operations has also been carried out to develop an urban flood model that is calibrated and validated for individual storm events [9]. Furthermore, an integrated model has been developed to simulate the complex flows in urban drainage basins. This model used 1D/2D models to calibrate 1D/1D urban flood models, but it encountered issues with a lack of field data [10,11].

New models integrate 2D surface flow models to simulate urban flooding in situations where the hydraulic capacity of the sewer system is exceeded, achieving consistency with observed channels and maximum surface flood levels [12]. There are also studies that have tested dynamic, bidirectional interactions between sewer networks and surface flows based on water level differences between 1D and 2D flood models in both virtual and real case studies [13]. A 1D-2D dual drainage model has been proposed to calculate changes in rainfall runoff in urban environments, and this model is widely used in urban flood simulations [14]. Recently, the dual drainage model using the U.S. Environmental Protection Agency (EPA)'s open-source Storm Water Management Model (SWMM) has been widely adopted globally [15].

Urban flood analysis is challenging due to the complex storm sewer networks and densely packed buildings, which require extensive computation time. For this reason, research has been conducted to simplify sewer networks to improve computational efficiency and optimize the speed of urban flood simulations. Excessive simplification of sewer models has been identified as a potential risk [16], and analyses of the impact of sewer network complexity on flood simulation results have shown that greater network complexity leads to decreased computational performance [17]. Research on the impact of network simplification on flood prediction under various rainfall conditions has concluded that while simplification reduces computation time, maintaining accuracy is crucial [18]. Additionally, recent studies have proposed a catchment area-based simplification method that reduces unnecessary complexity while preserving the main flow paths of sewer networks, demonstrating the potential to improve both the efficiency and accuracy of urban flood prediction [19], and studies comparing the computational efficiency and accuracy of simplified networks in real-time flood prediction models have been conducted [20].

Complex storm sewer networks are key factors influencing the simulations, and research on simplifying these networks to reduce simulation time is ongoing. However, it has been warned that even in simplified sewer networks, the accuracy of flow exchanges may decrease, highlighting the need for more precise simplification techniques [21]. Research on the impact of sewer network overload on flood occurrence has also confirmed that excessive simplification can negatively affect network performance [22].

Although many studies have analyzed numerical simulations using dual drainage models, sewer network simplification techniques, and the impact of network simplification on urban flood analysis, few have analyzed the effects of simplification on urban flood analysis based on differences in rainfall analysis modules. In this study, we aim to simulate and compare the performance of two rainfall runoff methods—using the SWMM Runoff block and Surface Runoff—within the HC-SURF model for urban flood prediction.

2. Literature Review

2.1. Hydraulic Modeling

This study uses the HC-SURF model to compare the performance of the two runoff methods (SWMM Runoff and Surface Runoff) under simplified sewer network conditions. The HC-SURF model is a dual drainage model that simulates both surface water and sewer system flows during urban flooding. It combines a 2D surface flow model with the SWMM 5.2 version [23] for sewer flow to perform dual drainage simulations. This model was validated for high accuracy in urban flood prediction by Sim et al. (2024) [24].

2.1.1. Two-Dimensional Surface Flow

The two-dimensional model for surface flow is based on the shallow water equations and uses the finite volume method to calculate water depth and velocity. The conservative form of the shallow water equations can be expressed as Equation (1). The conservative variable vector U, flux rate vectors in the x direction F and y direction G, and the source term SSS are as follows:

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

In Equation (2), h represents the water depth, and u and v are the depth-averaged velocities in the x and y directions, respectively. The source terms S_o and S_f represent the bed slope and friction slope, which can be applied using Manning's equation or Chezy's formula. Rainfall on urban basins is reflected in the source term e of the continuity equation, and the infiltration on permeable surfaces is incorporated in the governing equation through the source term d. The variables in Equation (2) are defined at the center of the triangular computational grid. Flow rates are calculated at the cell interfaces of the grid, and the physical changes in the grid caused by flow rates are analyzed to interpret stormwater flows.

$$\mathrm{U} = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, \mathrm{F} = \begin{pmatrix} hu \\ hu^2 + gh^2/2 \\ huv \end{pmatrix}, \mathrm{G} = \begin{pmatrix} hu \\ huv \\ hv^2 + gh^2/2 \end{pmatrix}, \mathrm{S} = \begin{pmatrix} R - f \\ gh\left(S_{ox} - S_{fx}\right) \\ gh\left(S_{oy} - S_{fy}\right) \end{pmatrix} \quad (2)$$

2.1.2. One-Dimensional Drainage Network

The HC-SURF model incorporates parts of the SWMM 5.2 EXTRAN block for sewer flow analysis. The basic equations for flow in the EXTRAN block are the continuity equation and the one-dimensional Saint-Venant equation for unsteady gradually varied flow in open channels, as shown in Equations (3) and (4) [23,24]. SWMM was chosen because it is a reliable tool developed by the U.S. Environmental Protection Agency (EPA) for accurately simulating dynamic flows in sewer networks, making it highly suitable for urban flood analysis [25,26].

$$\frac{\partial \mathrm{A}}{\partial t} + \frac{\partial \mathrm{Q}}{\partial x} = 0 \quad (3)$$

$$\frac{\partial \mathrm{Q}}{\partial t} + \frac{\partial\left(Q^2/A\right)}{\partial x} + \mathrm{gA}\frac{\partial \mathrm{H}}{\partial x} + \mathrm{gA}S_f = 0 \quad (4)$$

2.2. Rainfall Runoff Methods

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).

The Surface Runoff method calculates effective rainfall using the SCS Curve Number method [27] and directly discharges rainfall onto the surface. By assigning a Curve Number (CN) based on the SCS Curve Number characteristics of the basin's soil and land cover, direct runoff can be calculated. The CN varies depending on the soil moisture conditions before the rainfall, and the antecedent soil moisture condition is set based on the size of the antecedent precipitation. The total rainfall–effective rainfall relationship, which is the basis of the SCS effective rainfall calculation, is expressed as follows.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (5)$$

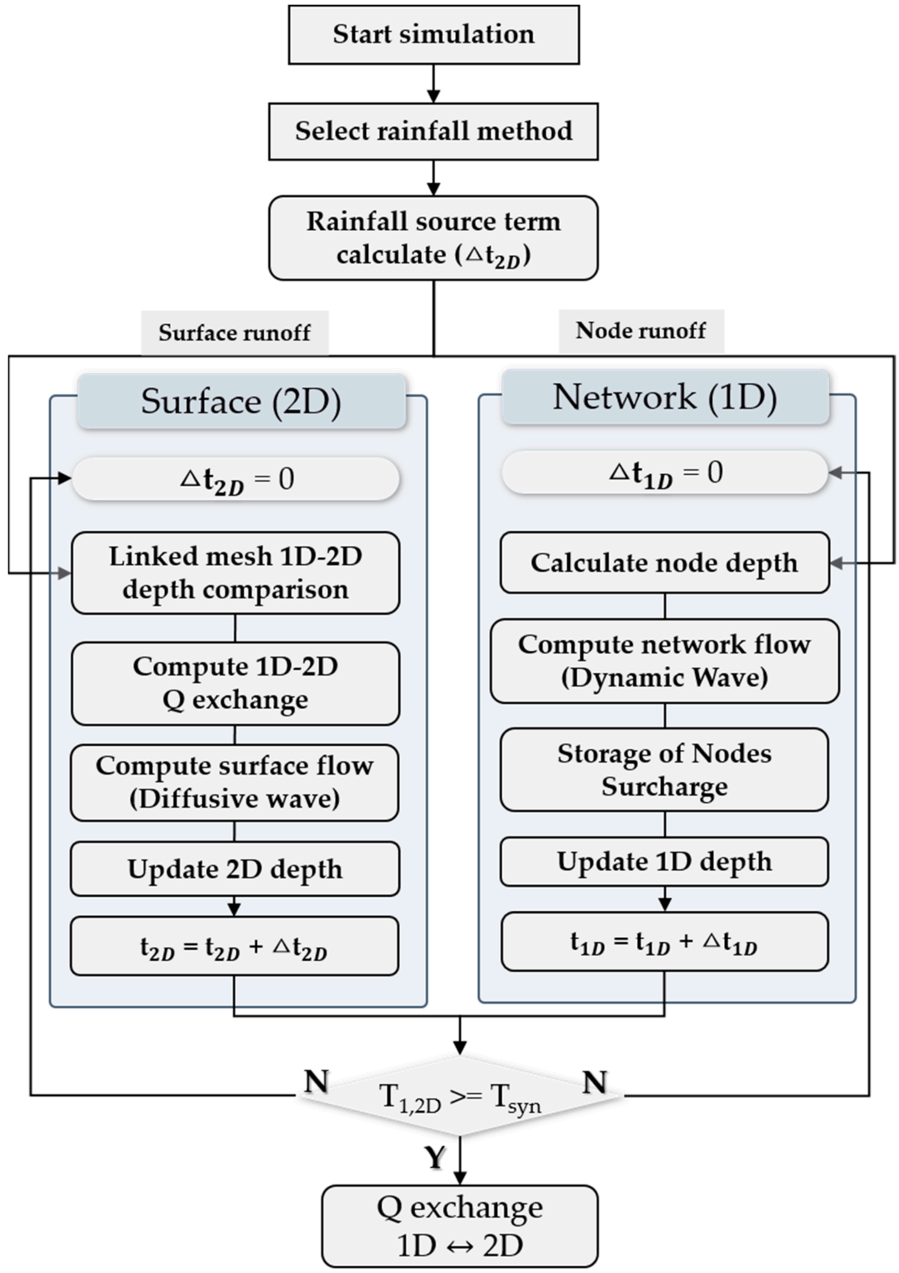

Figure 1. HC-SURF model flow chart by rainfall method.

On the other hand, the SWMM Runoff method assumes the catchment area of the node as a nonlinear reservoir, and the RUNOFF block uses the continuity equation and Manning's equation for calculations, as shown in Figure 2. The initial surface storage of the catchment generating surface runoff is zero, and there is no external inflow. The outlet cross-section is assumed to be the point where the basin meets the main drainage channel, and the total runoff is calculated considering the discharge speed. Equation (6) is the continuity equation, and Equation (7) is the formula for surface runoff using Manning's equation.

$$\frac{dV}{dt} = A_s \frac{dd}{dt} = A_s \times i_e - Q \tag{6}$$

$$\begin{gathered} Q = AV = W\left(d - d_p\right)\left\{\frac{1}{n}\left(d - d_p\right)^{\frac{2}{3}} S^{\frac{1}{2}}\right\} \\ Q = W\frac{1}{n}\left(d - d_p\right)^{\frac{5}{3}} S^{\frac{1}{2}} \end{gathered} \tag{7}$$

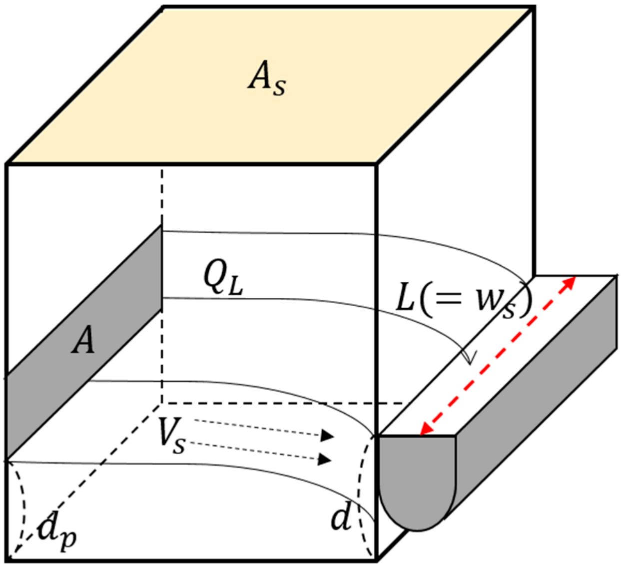

Figure 2. SWMM Runoff method.

In Equation (6), V is the water volume, d is the depth, t is time, A_s is the surface area, i_e is the effective rainfall, and Q is the runoff. In Manning's Equation (7), W is the width of the basin, n is Manning's roughness coefficient, d is the depth, d_p is loss depth, and S is the surface slope.

2.3. Simplification Method for Sewer Networks

There are various techniques for simplifying sewer networks in urban areas, each designed to balance accuracy and computational efficiency. However, in this study, the focus was on analyzing the impact of different rainfall runoff methods. Thus, the simplification approach was chosen based on the catchment area of each manhole, as it directly influences runoff collection and flow distribution within the network [28,29].

Nodes with small catchment areas were assumed to have minimal influence on the overall flow and flood extents, making them primary candidates for removal to reduce network complexity. The catchment area of the manholes corresponds to the watershed area, denoted as A_s in Equation (6). Simplification based on the catchment area allows the model to approximate flow behavior by reducing the complexity of the network while retaining key hydraulic characteristics. The simplification process follows a systematic set of steps, outlined as follows:

1. Identify Target Nodes for Deletion:

Nodes (or manholes) where the catchment area does not meet the predefined simplification criteria are identified as target nodes for deletion. These criteria are established to maintain a balance between reducing network size and retaining important hydraulic details. Nodes with very small catchment areas contribute minimally to the overall flow, and are therefore prime candidates for removal to streamline the network.

2. Upper and Lower Node Processing:

For each target node, the uppermost node in its branch is identified. This upper node serves as a reference point for redistributing flows and catchment areas of the deleted nodes. A summation process is performed, aggregating the catchment areas from the upper node to all connected lower nodes within the branch. This step ensures that any flow contributions from the deleted node are preserved within the simplified network. If there are multiple upper nodes (two or more nodes connected upstream of the target node), the links connecting these upper nodes are classified and stored based on their catchment areas. This classification allows for an organized flow redistribution when multiple inflows converge.

The lower nodes connected to the target node are then identified. The approach taken here depends on the structure and pipe dimensions of these lower nodes. If there are two or more lower nodes, they are connected to the link with the largest pipe diameter. This prioritization maintains the capacity of the network to handle larger flows, as the largest pipe typically has the greatest flow capacity. The watershed area from the deleted node is then added to the connected nodes, and the area-weighted watershed factor is adjusted accordingly. This factor helps preserve the flow distribution characteristics in the simplified network. If the pipe diameters of the lower nodes are the same, both nodes are connected, and the watershed area is equally divided and summed across these nodes. The area-weighted watershed factor is adjusted to reflect this distribution, maintaining hydraulic consistency within the network.

3. Special Case—No Upper Nodes:

In cases where no upper nodes are connected to the target node, the upper link processing is skipped, and only the lower node processing steps are performed. The target node is deleted, and its catchment area is summed with the lower nodes. The area-weighted watershed factor is also adjusted accordingly to account for the redistributed watershed area. If the lower nodes have equal pipe diameters, the watershed area is divided equally between them, and the area-weighted watershed factor is modified to reflect this balanced distribution. This structured approach allows for a simplified representation of the sewer network while maintaining critical flow paths and hydraulic behavior. Figure 3 visually demonstrates each step of this process.

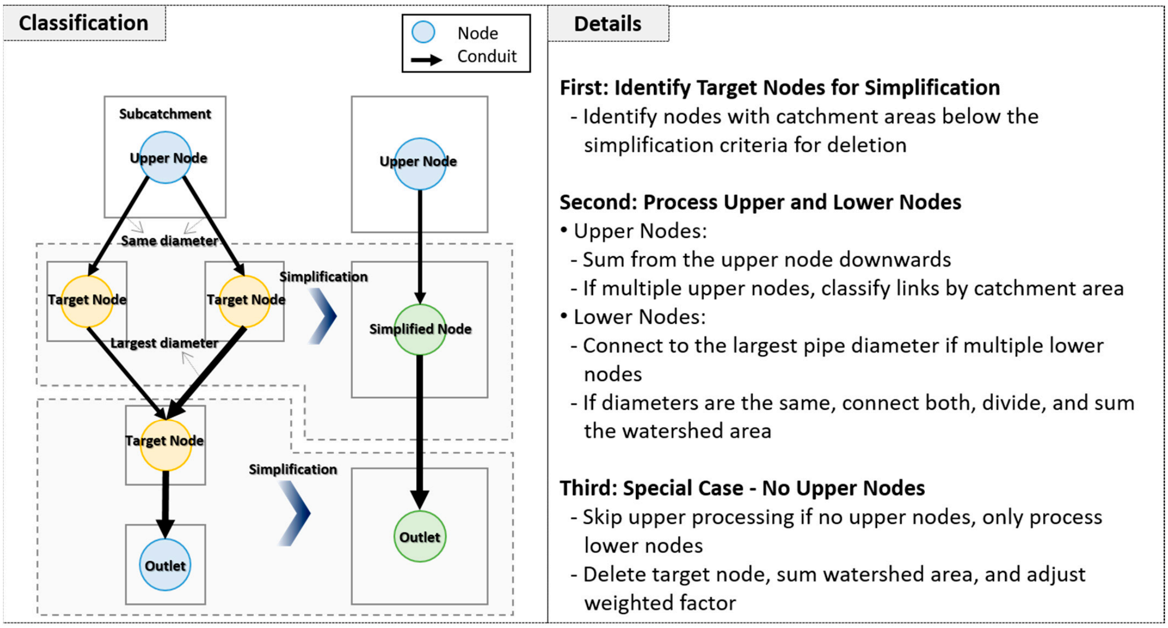

Figure 3. Process of sewer networks simplification method.

3. Materials and Method

3.1. Target Area Selection

The study area for this research is the Sinlim drainage basin within the Dorimcheon watershed, which experienced severe flooding due to rainfall exceeding disaster prevention performance targets in August 2022. The Sinlim drainage basin is located in the middle of the Dorimcheon's main stream and has a catchment area of 5.12 km^2. Since the surface elevation is relatively lower than that of adjacent watersheds, surface water is expected to concentrate in this area during rainfall events.

Hydraulic and hydrological data were collected to construct the model. The hydraulic data were based on the "Flood Control Plan Summary Report for Specific River Basins [Dorimcheon, Siheungcheon] (2022.05)" [30], which provided initial data for the stormwater and sewer networks. GIS data, including digital terrain models, detailed soil maps, and land-use information, were used to analyze hydrological factors such as the impervious surface ratio, watershed slope, land cover, and infiltration capacity. The antecedent soil moisture condition was set as AMC II (normal runoff rate). Figure 4 shows the status of the Sinlim drainage basin, its land use, and the results of digital elevation model (DEM) analysis.

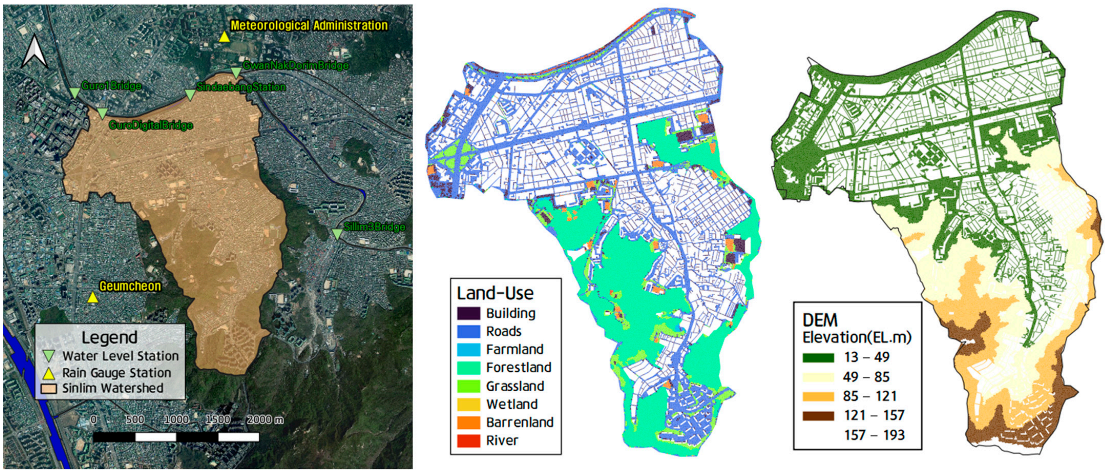

Figure 4. Status of the study area and initial model setup.

The sewer network simplification technique described in Section 2.3 was applied to the actual basin, and simplification was performed based on the catchment areas of manholes. The distribution of manhole catchment areas in the study area is shown in Figure 5. The largest number of manholes in the area had a catchment area of less than 100 m^2 (686 manholes), while the fewest number of manholes had a catchment area of more than 2000 m^2 (483 manholes).

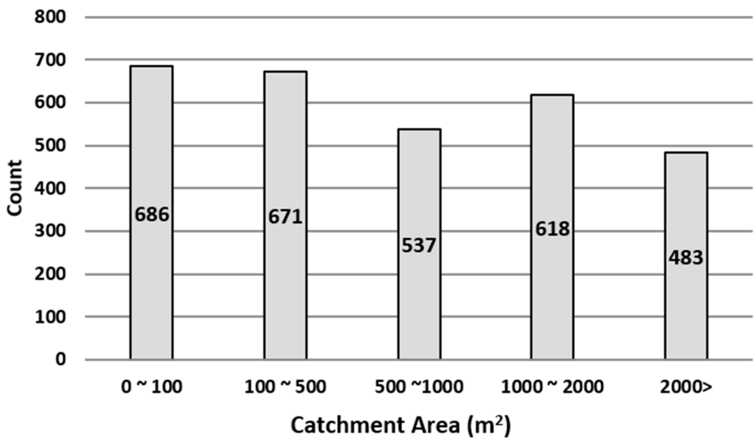

Figure 5. Number of manholes per catchment area.

The Sinlim drainage area suffered significant human and property damage due to the overflow of Dorimcheon caused by heavy rainfall on 8–9 August 2022. In this study, initial simulations were performed using the rainfall event, and two-dimensional flood analysis results were compared between the SWMM Runoff method and the Surface Runoff method. To accurately reflect rainfall characteristics, minute-by-minute rainfall data were obtained from the Korea Meteorological Administration (KMA)'s Automatic Weather System. The Thiessen weighting method was applied, and rainfall data from nearby observation stations (KMA, Geumcheon, Gwanak, etc.) were used to calculate the rainfall amount for the Sinlim drainage area. The rainfall events are listed in Table 1.

Table 1. Rainfall scenarios.

Station	Rainfall Amount (mm)	Rainfall Intensity (mm/h)	Thiessen Coefficient
Meterological Administration	515	141.5	0.64
Geumcheon	445	94.0	0.36

3.2. Simplification of Sewer Network

To evaluate the simulation performance according to the simplification of the sewer network, simplification was performed by classifying the manhole catchment areas into five categories (10 m^2, 100 m^2, 500 m^2, 1000 m^2, and 10,000 m^2). Simplifications ranging from 10 m^2 to 1000 m^2 were performed to confirm relatively uniform results, while the 10,000 m^2 simplification was set to examine the impact of extreme simplification on the model. Compared to the initial network, a maximum of 93% and a minimum of 39% simplification was achieved. When the 10,000 m^2 simplification was applied, it was confirmed that only a very simplified sewer network remained, as shown in Table 2 and Figure 6.

Table 2. Results of sewer network simplification by catchment area.

Case	Catchment Area (m^2) Count	Nodes	Links	Simplified Ratio
base	4394	3855	4107	0
10 m^2	2431	2466	2584	39%
100 m^2	2038	2073	2173	49%
500 m^2	1623	1658	1737	59%
1000 m^2	1305	1341	1404	67%
10,000 m^2	272	308	325	93%

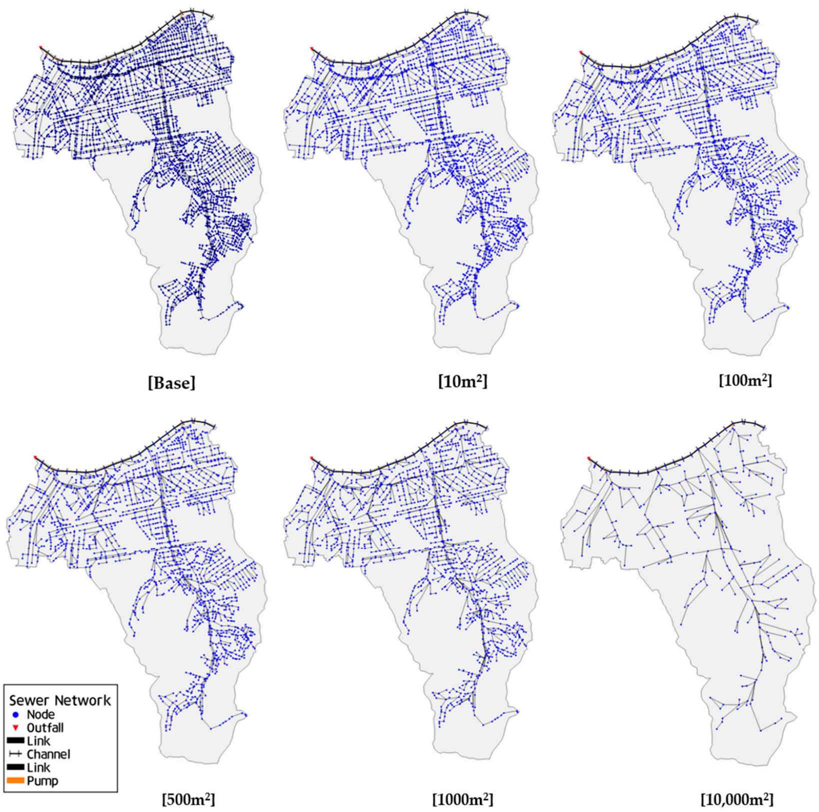

Figure 6. Visualization of sewer network simplification by catchment area.

4. Analysis Results

4.1. Model Validation

Simulations were performed and analyzed using the SWMM Runoff method and the Surface Runoff method for the initial network without simplification. In the SWMM Runoff method, all rainfall is discharged into the manholes, and surface flow is simulated based on the overflow from the manholes. As a result, the amount of rainfall that entered the nodes was 1,052,340 m^3, and the amount of overflow re-entered by surface flow was 170,630 m^3. Since all rainfall is directed into the manholes, the surface water retention was 72,880 m^3 less than that in the Surface Runoff method, while the manhole overflow was 239,262 m^3 greater. In contrast, the Surface Runoff method involves rainfall being discharged to the surface, so the re-entered volume included both the rainfall inflow and the re-entered overflow, showing only about a 1% difference from the SWMM Runoff method.

Although there were differences in the captured volumes between the two rainfall simulation methods, when the errors in total rainfall and runoff were analyzed, the SWMM Runoff method showed an error of −0.93%, and the Surface Runoff method showed an error of 0.19%. Considering the catchment area of the study area, the error levels were judged to be negligible, confirming that both methods performed well in terms of mass balance analysis (Figure 7).

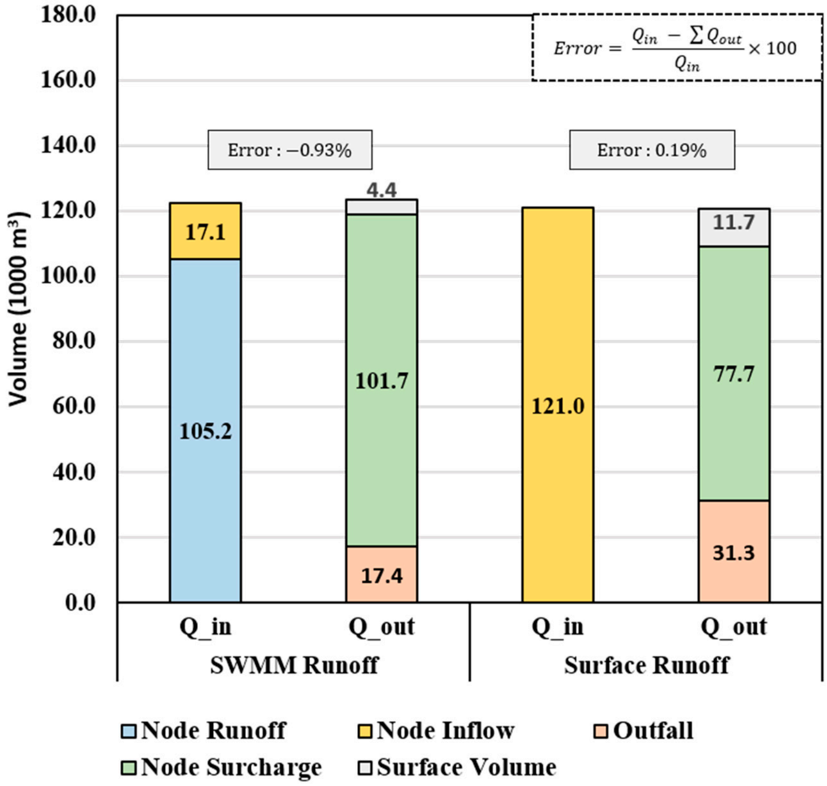

Figure 7. Comparison of mass balance between SWMM runoff and surface runoff.

In the Surface Runoff method, the flow path is determined by various factors such as the shape of the computational grid, the digital elevation model (DEM), and building density. Accordingly, the flow exchanges with manholes located along the surface flow path, and when the capacity of the manholes is exceeded, the excess water is discharged to the surface, where the flow is recalculated. As a result, it was confirmed that flooding occurred in the upper part of the watershed where no manhole overflow occurred. In contrast, the SWMM Runoff method directs all rainfall to the manholes and only simulates surface flow based on manhole overflow. Therefore, flooding was concentrated at the points where manhole overflow occurred.

This difference between the simulations led to variations in the flooded area. Figure 8 shows the comparison of maximum flooded areas for the two simulation methods, with areas exceeding 0.1 m of flood depth highlighted. The areas shown in purple are the results from the Surface Runoff method, while the areas shown in green are the results from the SWMM Runoff method. The analysis showed that the maximum flooded area was 0.45 km^2 for the Surface Runoff method and 0.42 km^2 for the SWMM Runoff method, resulting in a difference of about 0.03 km^2. This difference in flooded areas occurred mainly in the upper part of the watershed and in some densely built-up areas.

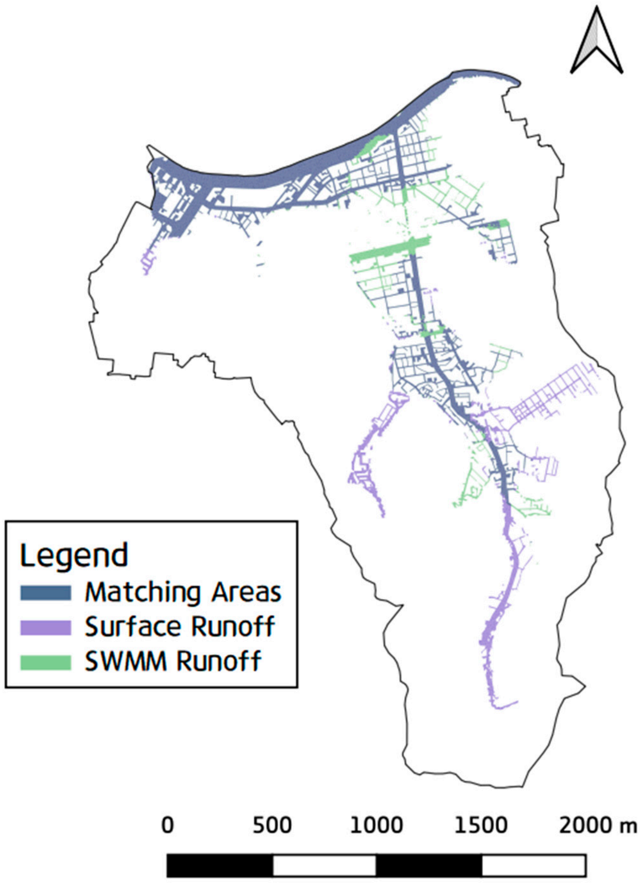

Figure 8. Comparison of initial simulation results by rainfall runoff method.

4.2. Analysis Results of Flow Exchange by SWMM Runoff and Surface Runoff Methods

The simulation performance of the model was evaluated based on the amount of inflow and outflow at the manholes, depending on the level of sewer network simplification for each rainfall runoff method. Figure 9 compares the surcharge and discharge for the simplified sewer network, with simplifications performed based on the catchment areas of manholes using the SWMM Runoff method. Depending on the level of simplification, the surcharge amount ranged from a maximum of 173.6 m^3/sec to a minimum of 135.2 m^3/sec. For simplifications below 500 m^2 of manhole catchment area, the results were similar, but when simplification was performed for 1000 m^2, the surcharge decreased by about 20% compared to the initial network, the onset of initial outflow was delayed, and the peak surcharge time was advanced. Additionally, when simplification was performed based on a 10,000 m^2 catchment area, the onset of initial outflow was delayed by approximately 40 min. Analysis of this result revealed that it was mainly due to the reduction in the volume of water re-entering the manholes from the surface flow, and the reductions in the surcharge amount, time of occurrence, and peak surcharge were attributed to the omission of flooded branches due to simplification. For discharge, it was confirmed that the re-entry volume into the manholes was smaller than the surcharge amount. The peak discharge ranged from a maximum of 44.4 m^3/sec to a minimum of 8.5 m^3/sec, with a decreasing trend according to the level of simplification. This trend of decreasing discharge was considered to be due to the reduction in the number of manholes exchanging flow with surface water. Additionally, manholes located in narrow roads or between buildings, where surface flow accumulates, were often parts of branches, and these branch conduits were omitted during simplification, which affected the total discharge. These results suggest that when performing rainfall runoff simulations using the SWMM Runoff method, performing a simplification beyond 1000 m^2 of manhole catchment area can significantly affect the model's performance and should be conducted with caution.

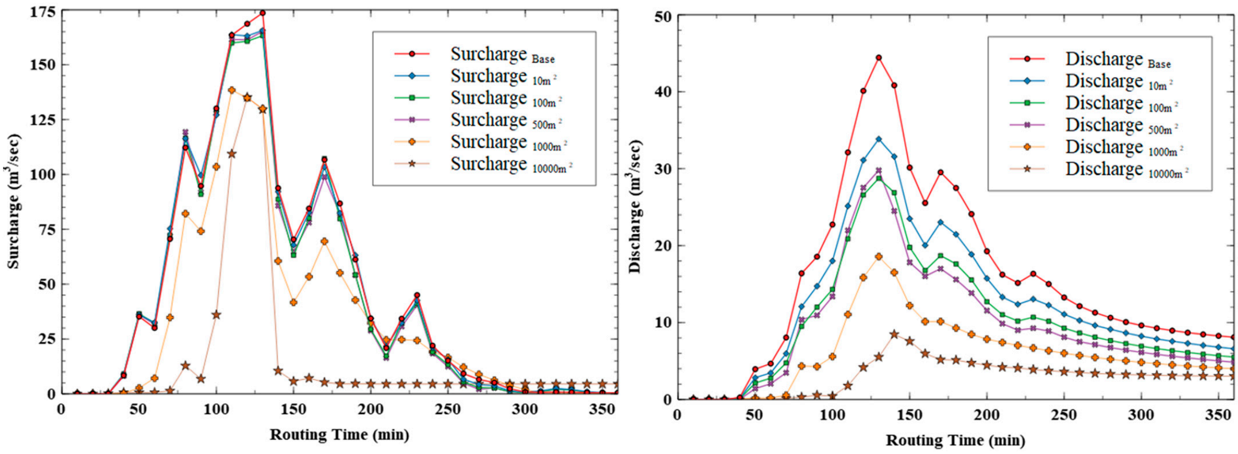

Figure 9. Comparison of surcharge and discharge based on sewer network simplification—SWMM Runoff method.

Figure 10 shows the simulation results for surface runoff discharge. It was observed that the amount of surcharge and discharge to manholes changed significantly depending on the level of sewer network simplification, more so than with the SWMM Runoff method. The surcharge amount ranged from a maximum of 133 m^3/sec to 35.4 m^3/sec, and the discharge ranged from a maximum of 122.7 m^3/sec to 18.5 m^3/sec. It was also observed that significant changes occurred when the simplification criterion exceeded 1000 m^2. The peak surcharge decreased by up to 73% compared to the initial network simulation, and the discharge decreased by 85%. These results were attributed to the reduction in water entering the manholes due to the simplification of the sewer network, resulting in a decrease in surcharge volume. This analysis suggests that excessive simplification can significantly affect the accuracy of simulation results in urban flood analyses, and caution should be exercised, especially when performing dual drainage simulations using the Surface Runoff method, as it can lower the reliability of the simulation results.

Table 3 summarizes the analysis results, with R^2 and RMSE (Root Mean Squared Error) calculated for each rainfall runoff method based on the initial simulation results. The results showed that for the SWMM Runoff method, the R^2 for surcharge decreased from 99.8% to 57.1%, and for discharge, it decreased from 99.8% to 47.94%. For the Surface Runoff method, the R^2 for surcharge decreased from 97.6% to 1.3%, and for discharge, it decreased from 97.6% to 78.6%. Since the surcharge and discharge were analyzed using the initial sewer network for each rainfall treatment method, the R^2 values for simplifications below 1000 m^2 of manhole catchment area were relatively good. This is because nodes with small catchment areas, which have minimal impacts on the overall flow and flood extents, were removed. Consequently, key flow paths and flow exchanges within the network were largely unaffected by this level of simplification, allowing the model to retain accurate flow and flood predictions even with reduced network complexity.

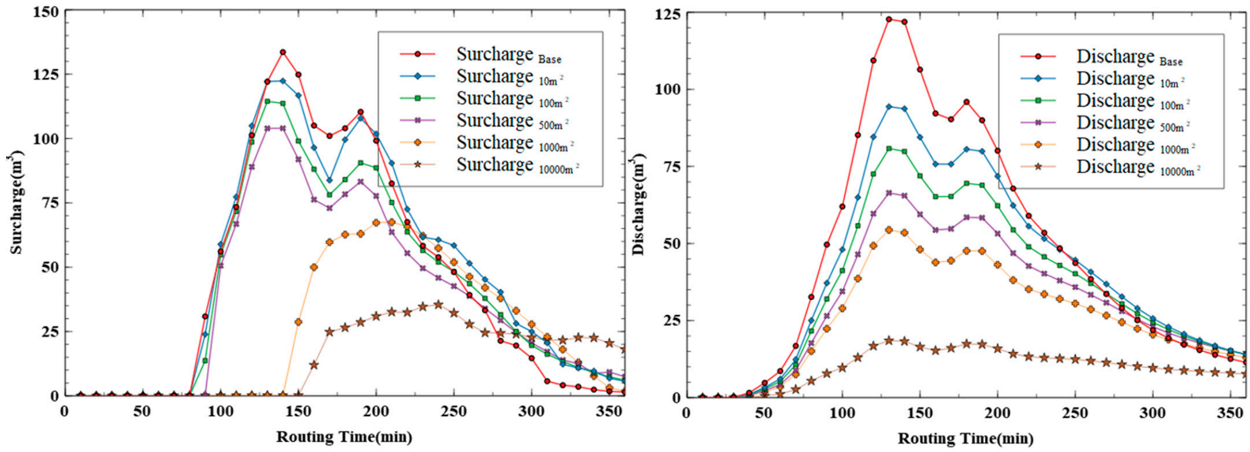

Figure 10. Comparison of surcharge and discharge based on sewer network simplification—Surface Runoff method.

Table 3. Analysis of inflow and outflow based on sewer network simplification results.

Simplification Condition	SWMM Runoff				Surface Runoff			
	Surcharge		Discharge		Surcharge		Discharge	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
10 m^2	99.8%	6.98	99.8%	17.97	97.6%	61.08	97.6%	127.50
100 m^2	99.7%	14.69	99.6%	45.94	97.5%	104.57	96.4%	308.56
500 m^2	99.6%	17.20	98.7%	55.59	96.1%	227.09	93.9%	585.14
1000 m^2	96.2%	411.90	92.3%	147.15	21.5%	2028.74	92.4%	922.46
10,000 m^2	57.1%	2248.57	47.9%	267.78	1.3%	2967.39	78.6%	2418.55

However, the RMSE for surcharge ranged from a minimum of 6.98 m^3/sec to a maximum of 2967.39 m^3/sec. The highest RMSE was observed in the surcharge for the Surface Runoff method.

4.3. Comparison of Maximum Inundation Area

A comparison of the maximum inundation area was performed based on sewer network simplification levels for each rainfall runoff method. The comparison was made by displaying computational grid cells that showed a flood depth of more than 0.1 m in the simulation results. Figure 11 shows the comparison of the maximum inundation areas for the two rainfall runoff methods based on sewer network simplification levels. As analyzed in Section 4.2, it was expected that the maximum inundation area would decrease due to the reduction in the surcharge and discharge amounts as the sewer network was simplified. However, the maximum inundation area showed a tendency to increase as the sewer network was simplified, as the reduction in discharge was greater than the reduction in surcharge.

In the SWMM Runoff method, the increase in the inundation area due to simplification was concentrated mainly in the downstream part of the watershed, while in the Surface Runoff method, the increase in the inundation area was observed in the upper part of the watershed. It was judged that the concentration of the increase in inundation area in the downstream part of the SWMM Runoff method was due to the concentration of surcharge at manholes as simplification progressed. On the other hand, in the Surface Runoff method, the increase in inundation area was caused by water being retained in the upper part of the watershed due to reduced re-entry into manholes as the sewer network simplification increased. Additionally, in this study, the computational grids that were generated excluded building areas, and it was observed that surface flow was retained between buildings due to the composition of the DEM and building density.

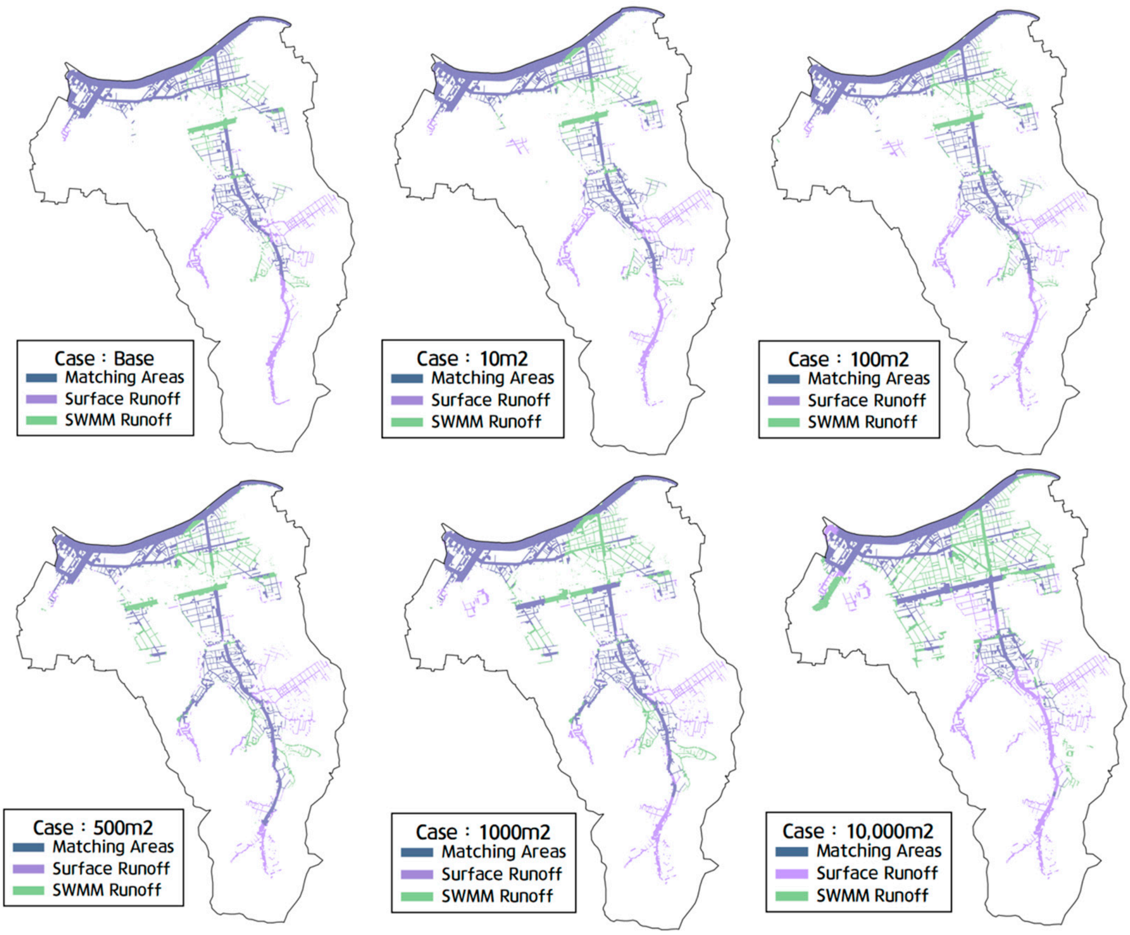

Figure 11. Comparison of inundation areas based on simplification and rainfall runoff method.

Table 4 shows the changes in the maximum inundation area and the matching area of the maximum inundation areas for each rainfall runoff method according to simplification levels. As explained earlier, the maximum inundation area gradually increased with the level of simplification, and this trend was observed for both rainfall runoff methods. On the other hand, the matching area between the two methods increased as the simplification criterion approached a manhole catchment area of 1000 m^2 but then showed a decreasing trend.

Table 4. Analysis of inundation area based on simplification by rainfall runoff method.

Simplification Condition	SWMM Runoff (km^2)	Surface Runoff (km^2)	Matching Area (km^2)
base	0.455	0.425	0.350
10 m^2	0.462	0.427	0.346
100 m^2	0.474	0.439	0.352
500 m^2	0.489	0.525	0.399
1000 m^2	0.492	0.520	0.383
10,000 m^2	0.540	0.558	0.349

The reason for the increase in matching area with simplification is believed to be due to the increase in surface water retention as the amount of water re-entering the manholes decreased. However, when the simplification criterion exceeded 1000 m^2, the matching area decreased as the surcharge in the SWMM Runoff method became concentrated in the downstream part of the watershed, leading to a reduction in the inundation area in the upstream part of the watershed.

4.4. Simulation Time

The simulation time was analyzed for each rainfall runoff method and sewer network simplification level, and the reduction in simulation time was calculated based on the initial simulation time for the Surface Runoff method. The simulation time reduction reached a maximum of 54.5%, with the SWMM Runoff method showing a more effective reduction in simulation time.

In the Surface Runoff method, all rainfall is discharged onto the surface, and since the flow in every grid cell must be calculated, the two-dimensional analysis took a significant amount of time, leading to longer simulation times. In contrast, in the SWMM Runoff method, only the surface flow at manholes with surcharge is analyzed, resulting in shorter simulation times (Table 5).

Table 5. Comparison of simulation time based on simplification and rainfall runoff method.

Simplification Condition	Simulation Time (s)		Speed Increase (%)	
	SWMM Runoff	Surface Runoff	SWMM Runoff	Surface Runoff
Base	267.6	528.6	49.4	0
10 m^2	267	526.2	49.5	0.5
100 m^2	256.3	510.6	51.5	3.4
500 m^2	253.7	487.4	52	7.8
1000 m^2	250.5	472.5	52.6	10.6
10,000 m^2	240.4	462.5	54.5	12.5

5. Discussion

This study evaluated the impact of sewer network simplification on computational performance and model accuracy in urban flood prediction, focusing on different rainfall runoff methods. The simplification of sewer networks contributed to a significant reduction in computation time while maintaining relatively high accuracy. However, several factors require further discussion and research.

First, there is a lack of diversity in rainfall events. The rainfall scenarios used in this study are based on a single rainfall case, which does not sufficiently validate the model's performance under various climate conditions. The selected rainfall event was chosen based on a high-intensity storm that occurred in the study area and is considered representative of the region's typical flood-prone conditions. This approach allowed the study to focus specifically on assessing the impact of sewer network simplification on simulation performance in response to a significant storm event. Future studies should incorporate a variety of rainfall patterns and intensities to assess the model's performance across multiple weather scenarios. Such additional simulations would help evaluate whether the model maintains reliability under diverse climatic conditions, ultimately enhancing its applicability to broader urban flood prediction contexts.

Second, further in-depth review is needed on the reduction in flow exchange in simplified networks. Although this study aimed to maintain mass balance while minimizing performance degradation in simplified networks, excessive simplification may result in insufficient flow exchange between surface water and sewer systems, leading to reduced accuracy. This issue was particularly noticeable in simplifications exceeding 1000 m^2, and the development of more detailed simplification criteria and algorithms is necessary to address this problem.

Third, validation with real flow data is essential for assessing the model's reliability in practical applications. In this study, the analysis was limited to comparing simplified network performances against the original network structure through simulations. However, real flow data from the sewer storm network would provide valuable insights into the model's accuracy and robustness. Future research should incorporate validation with empirical data to evaluate how well the simplified model approximates actual flow conditions in sewer networks. This additional validation would strengthen the model's credibility and ensure its applicability to real-world flood prediction.

Lastly, the exclusion of building areas within the computational grid presents a limitation in accurately modeling flood flow paths in urban environments. Buildings can significantly impact flood dynamics, and their absence in the grid may reduce accuracy, especially in densely built areas. Future studies should incorporate more refined grid data, including building structures, to improve flood prediction accuracy in complex urban settings and to better account for the effects of building density on flow distribution and inundation patterns. This would contribute to improving flood prediction accuracy, particularly in densely built areas.

6. Conclusions

This study evaluated the impact of sewer network simplification on urban flood prediction using the HC-SURF model. A comparison between the SWMM Runoff method and the Surface Runoff method showed that while network simplification significantly improved computational performance, in some runoff methods, flood prediction accuracy was compromised.

By performing sewer network simplifications of up to 93% compared to the initial network, computation time was reduced by up to 54.5%. In particular, the SWMM Runoff method showed significant reductions in computation time due to the reduced number of computational grid cells. The SWMM Runoff method maintained relatively high accuracy even in simplified networks. The analysis of surcharge, discharge, and flood area predictions using the SWMM Runoff method provided stable results, suggesting that this method is a useful approach for efficiently simplifying complex sewer networks. However, in the Surface Runoff method, the accuracy of flood area prediction decreased in simplified networks, and performance degradation was particularly noticeable when the simplification exceeded 1000 m^2. Based on these findings, simplification up to 1000 m^2 was analyzed as an appropriate level to balance computational efficiency and accuracy, offering an optimal simplification limit that reduces computation time while maintaining reliable prediction accuracy.

The reduction in surcharge volume due to storm sewer network simplification reflects the limitations in accurately representing complex urban hydrodynamics. As the storm sewer network is simplified, it becomes challenging to adequately consider flow dynamics involving reverse slopes, main and branch lines, and combined sewers, resulting in an artificial decrease in surcharge. In particular, the reduction in surcharge volume is mainly attributed to fewer inflow points caused by a decrease in the number of manholes, where surface flow enters the sewer system.

Future research should apply more diverse rainfall scenarios to expand the model's application range and evaluate analysis performance in densely populated urban areas through grid analysis that includes the impact of buildings. Additionally, the possibility of applying the model in a wider variety of urban environments should be explored, and methods for maximizing prediction performance in simplified networks should be sought.

In conclusion, this study proposes a practical analysis method by demonstrating that network simplification significantly improves computational performance in urban flood prediction while offering optimization strategies for maintaining accuracy. Future research should focus on analyzing changes in flow exchange under various rainfall conditions with simplified networks, which will further enhance the reliability of urban flood analysis.

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