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Application of the TONIC model to assess the effectiveness of green roofs for a combined sewer network in Thu Duc City

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ABSTRACT

Urban flooding in cities in Vietnam presents a complex challenge from natural occurrences and human activities. This research investigates the effectiveness of nature-based solutions (NbS) in fostering sustainable urban water management. The study utilized the TONIC model (Tools fOr greeN resilient Cities) to evaluate spill events within the combined sewer system of a drainage catchment in Thu Duc City, Ho Chi Minh City, Vietnam. The occurrence and magnitude of spills will likely escalate with the expansion of non-absorbent surfaces, indicating a pattern of unsustainable urban growth. The implementation of Green Roofs (GR) as an NbS measure was examined. In 2020, there were 16 days with stormwater spills totaling 3,035 m³. However, introducing GRs significantly decreased total discharge, from 2.78 million m³ to 2.17 million m³, and eliminated spill days in the study area. GRs effectively reduced impermeable areas and runoff coefficients (RC), achieving a 22% reduction in discharge volume and preventing spills during heavy rainfall. Although the real-world accuracy of these findings may vary, the study underscores the potential of NbS to improve urban water management practices. Thus, the TONIC simulation highlighted the benefits of GRs in lessening the hydraulic pressure on the sewer system and reducing pollution in urban canals due to overflow.

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1. INTRODUCTION

Urban flooding in cities in Vietnam is a complex problem caused by a mix of natural and human-made factors, including rapid urban growth, urban heat islands, climate change, low-lying coastal and delta regions, deforestation, land degradation, domestic migration, and insufficient sewerage systems (Tyler et al. 2016; Thiep and Truong 2020; Jack 2020). Rapid urban growth often results in more surfaces that do not absorb water, reducing the land's natural ability to soak up rainwater. This, in turn, increases runoff and the risk of flooding. The drainage systems in many cities in Vietnam are not adequately designed to handle large volumes of water during heavy rains, leading to overflows and flooding (Tyler et al. 2016). These challenges necessitate comprehensive urban planning and management strategies to mitigate flood risks and adapt to evolving environmental conditions.

Various studies and projects have focused on integrated measures to mitigate urban flooding in Vietnam. These measures include constructing dikes, dams, and sluice gates to control water flow and protect against high tides and heavy rainfalls, enhancing and expanding drainage systems to improve capacity and efficiency, developing early warning systems for timely evacuation, and incorporating flood risk management into urban planning, including zoning regulations to prevent construction in flood-prone areas (C40 Cities 2018; Georges et al. 2021; Quang and Tallam 2022). Le et al. (2023) have underscored the role of reservoirs and green infrastructure in reducing urban flooding by using lakes, ponds, and simulation technology to forecast rain-induced flooding in Hue City.

A traditional urban water management system is used in major cities like Ho Chi Minh City, Hanoi, and Da Nang. This centralized approach combines wastewater and rainwater collection, directing it to wastewater treatment plants (WWTPs) or discharging it directly into urban canals. This system has led to storm overflows and water pollution (Oral et al. 2020; Nguyen et al. 2020). Ho Chi Minh City faces exacerbated flood risks due to heavy rains and high tide levels, threatening water safety because of insufficient Urban Water Management (UWM) infrastructure (Kumar 2019). These challenges could be addressed by adopting nature-based solutions for sustainable urban water management (UNEP-DHI 2018). Thien-An and Thu-Huong (2023) highlighted that green infrastructure (GI), a form of NbS, which integrates vegetation, natural processes, and land use into the built environment through elements like urban tree canopies, bioswales, rain gardens, green roofs, and permeable pavements, can yield numerous benefits. These include reducing stormwater runoff, enhancing water quality, mitigating climate change impacts, and fostering healthy, sustainable communities. However, GI in urban flood management is still overshadowed by conventional gray infrastructure, such as roads, drainage networks, and sewage or water treatment systems, which tend to be less sustainable.

A green roof (GR) comprises multiple components, including vegetation, substrate, filter layer, drainage material, insulation, root barrier, and waterproofing membranes, each playing a vital role in the system's performance. GRs offer multiple benefits, including stormwater retention, water quality enhancement, reduced energy costs, air purification, noise reduction, and more (Zhang et al. 2015; US EPA 2018). Among these, stormwater retention is particularly notable, with plants and substrate layers capable of storing significant amounts of water. Zhang et al. (2015) observed 19 rainfall events and found that GRs retained runoff at an average rate of 77.2%. Similarly, a Manchester (UK) study reported that GRs retained 65.7% of runoff across 69 rainfall events (Speak et al. 2013).

Studies on the efficacy of GRs for urban flood mitigation in Vietnam are limited. This research quantitatively evaluates spill events in Ho Chi Minh City, advocating GRs as an effective measure to alleviate the load on drainage systems and WWTPs. Utilizing the TONIC hydraulic model, the study assesses drainage scenarios during dry and wet seasons, gauging the impact of NbS, such as green roofs, on urban spill reduction.

Recently, GIZ and IKI (2024) have highlighted several applications of NbSs in Ho Chi Minh City. The Rex Hotel features 600 m² of vertical green walls, while the City Oasis Apartment boasts naturally curved balconies with a green layer of various tropical trees and climbing plants. These implementations help reduce stormwater runoff from buildings and increase green space. Ngo et al. (2023) utilized two local plants, Vernonia elliptica and Trumpet vine, in a lab-scale wetland GR with rock, oyster shells, and charcoal as the plant support media. Their experimental results showed significant reductions in domestic wastewater concentrations: Chemical Oxygen Demand (COD) reduced from 335–35 mg/L to 30–13 mg/L, NH_4^+-N reduced from 21–12 mg/L to 3–0.8 mg/L, and PO_4^{3-} reduced from 2.0 ± 0.8 mg/L to 1.0 ± 0.4 mg/L (Ngo et al. 2023).

The TONIC model (Tools fOr greeN resilient Cities) is a streamlined hydrological and hydraulic model crafted at the DEEP laboratory (INSA Lyon, France). It serves as a decision-support tool for municipalities, guiding the selection of urban water management strategies incorporating NbS for stormwater control (Néméry et al. 2022; Michel 2021). The model's objectives include addressing climate change repercussions, mitigating flood risks, and endorsing NbSs. Implementing TONIC necessitates detailing the watershed characteristics (impervious surface percentage), the sewer system's geometry (diameter, length, slope, Combined Sewer Overflow (CSO) structure dimensions, or operational guidelines), and input data (population, per capita water usage, rainfall, infiltration rate). TONIC evaluates various factors, including hydrological and hydraulic elements, to assist cities in making decisions that foster resilient and eco-friendly urban growth. Moreover, TONIC champions cutting-edge methods like NbS and adaptive systems, enabling comparative analyses among different cities to unearth successful resilience-building practices.

The TONIC model provides a holistic representation of the urban drainage system by incorporating detailed sewer system characteristics, combined wastewater, and I&I dynamics (Néméry et al. 2022). Moreover, the model can explicitly simulate both wastewater and rainfall inputs, and the impact of green roofs on reducing runoff and spill volumes and frequency. Thus, the TONIC model can assess the effects of GRs and how they would change water flow through a drainage network. Besides, the TONIC model allows for a more detailed representation of the sewer network than many traditional hydrological models. It also uses more complete information, such as the pipes' slope, diameter, and roughness (Michel 2021).

The limitations of the TONIC simulation include the need for coordination among various stakeholders, extensive data collection, and specialized expertise. The model's effectiveness is also contingent upon the local context, governance frameworks, and resource availability. Despite these challenges in data gathering, the TONIC model, as applied in this study, emerges as a novel and effective tool for determining discharge volumes, the number of spill days, and spill volumes within the combined sewerage system of Thu Duc City's drainage catchment in Ho Chi Minh City.

2. STUDY AREA AND METHODOLOGY

2.1 Study area

The study area in Thu Duc City (Figure 1) encompasses 1,469 hectares and is home to 74,137 inhabitants. It features a combined sewer system consisting of five outfall pipes that channel effluent into local rivers and canals. The sewerage infrastructure is designed with a circular cross-section, maintaining an average diameter of 0.8 meters and extending over 2,103 meters. The system's slope is engineered to satisfy minimum regulatory standards, ensuring that spill events comply with the national technical regulations on domestic wastewater. About 69% of the terrain is impermeable, a condition that has remained relatively unchanged due to the ongoing preparatory phase of construction projects in the vicinity (Figure 2).

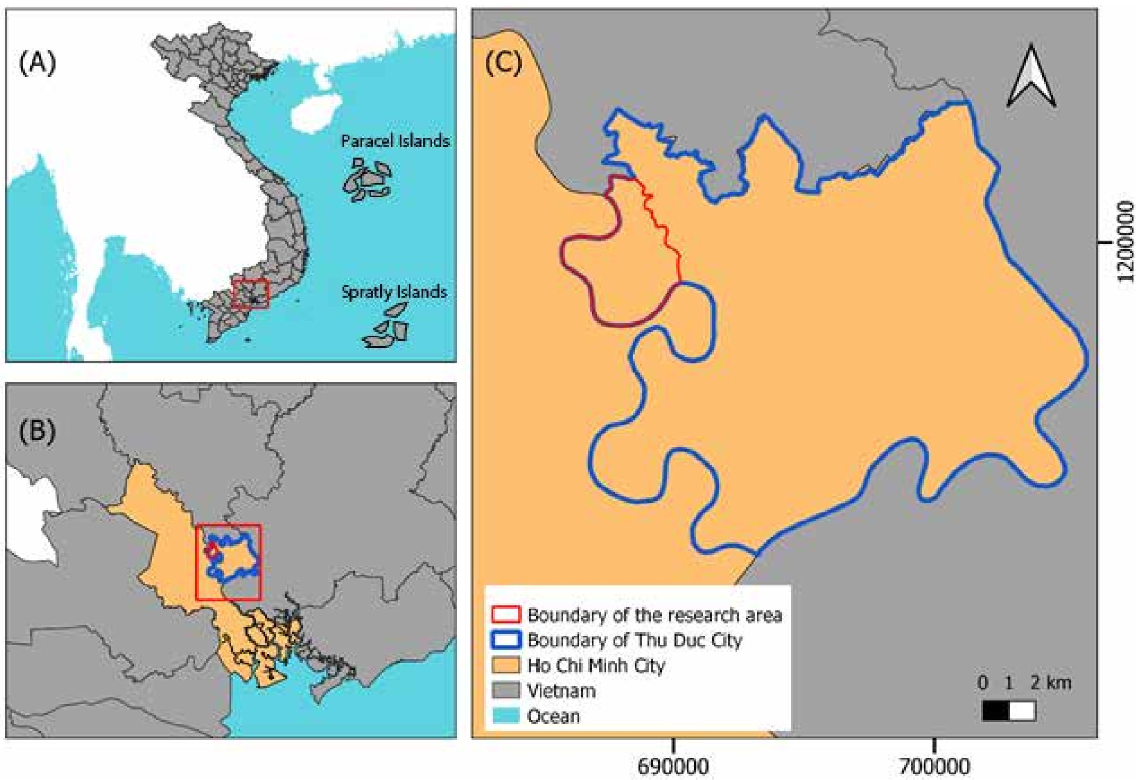


Figure 1 Map of Thu Duc area in Vietnam (A), Thu Duc sub-basin in Ho Chi Minh City (B), and the research area in Thu Duc City (C).

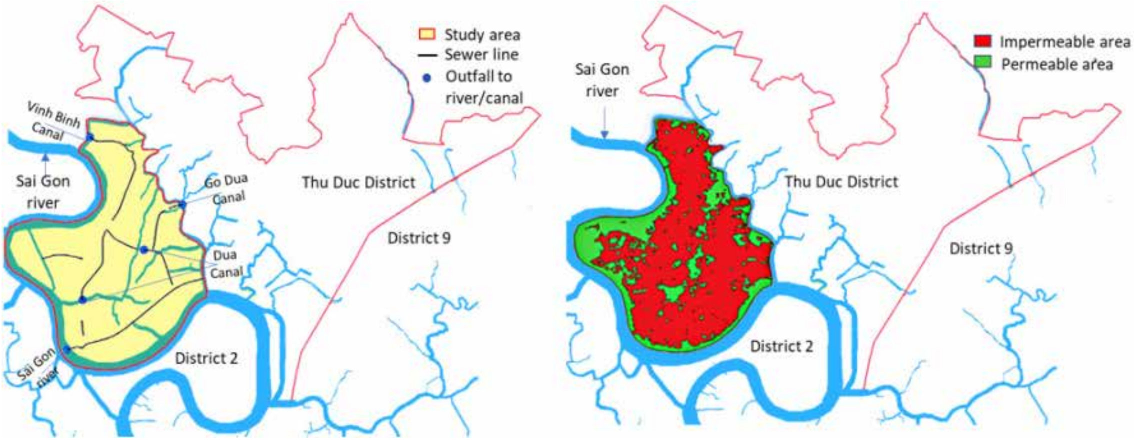


Figure 2 Research area with outfall points and the fraction of impermeable-permeable area.

2.2 Methodology

This study focused on a combined sewer system that collects wastewater and stormwater. During rain events, hydraulic structures called CSOs prevent flooding by discharging excess untreated water into the river. The TONIC model used for the simulation of the outflow rate from CSOs requires two crucial datasets: rainfall data and daily wastewater flow, which show hourly variations in domestic wastewater flow. Rainfall intensity was gathered from a weather station at the CARE Center on HCMUT's campus in District 10, approximately 13 km from the study area in Thu Duc City. Rainfall data is available as open source at http://carerescif.hcmut.edu.vn/

The flow chart below outlines the steps and input parameters for running the TONIC model. Initially set up for the Ecully urban watershed case study in Lyon (France), some parameters and coefficients were measured and explicitly calibrated for Ecully (Néméry et al. 2022). Therefore, to apply the TONIC model to the present study area, specific parameters and coefficients, such as initial loss, run-off coefficient, and some transfer phase calculation coefficients, were used with the same values as those from Lyon.

To achieve the objectives, the following phases were implemented:

1. Production phase,
2. Transfer phase, and
3. Determining the number of spill days and the total spilled volume (Figure 3).

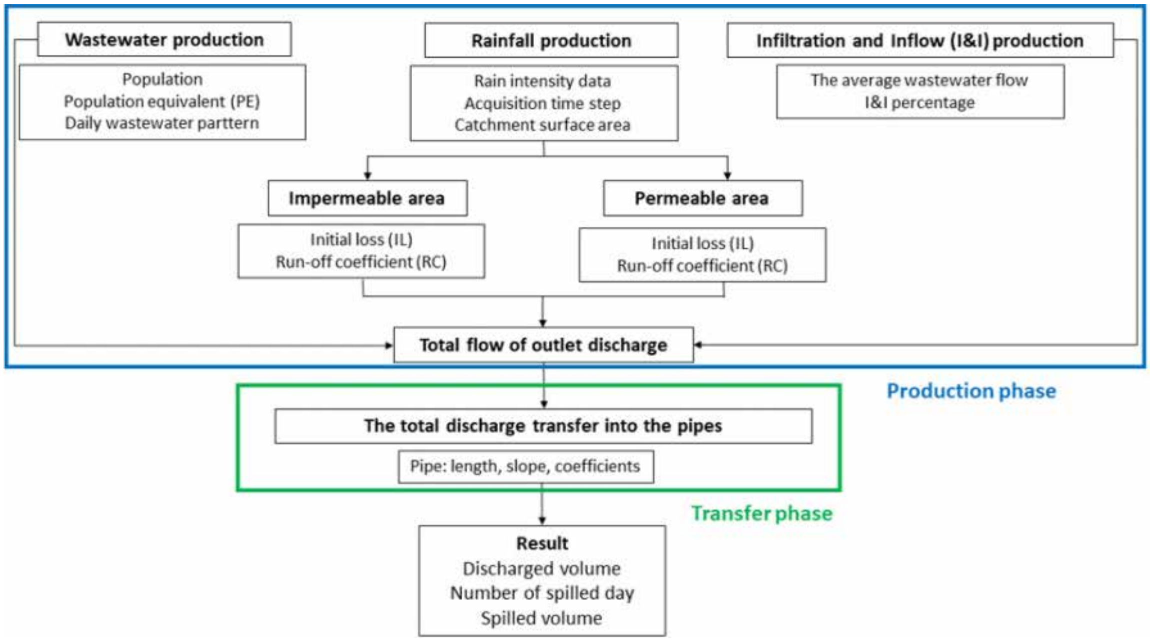


Figure 3 Flowchart of TONIC model (Néméry et al. 2022).

Calculation steps in the TONIC model

This phase focuses on determining the outlet discharge flow, including contributions from rainfall, wastewater, and infiltration and inflow. Since the rain data is presented as rain intensity every 10 minutes, the time step is set to 10 minutes, and the total discharge at the outlet ($Q_{total\ discharge\ outlet}$) is calculated for each 10-minute interval, denoted as (t) in the formula.

$$Q_{total\ discharge\ outlet}(t) = Q_{rain\ outlet}(t) + Q_{ww\ outlet}(t) + Q_{I\&I\ outlet}(t) \quad (1)$$

Where:

$Q_{rain\ outlet}$ = discharge of rainfall (m^3/s),

$Q_{ww\ outlet}$ = wastewater flow rate at the outlet (m^3/s), and

$Q_{I\&I\ outlet}$ = discharge of infiltration and inflow (m^3/s).

Rainfall production

Rain data was collected from the Centre of Asian Research on Water-Ho Chi Minh City University (CARE-HCMUT) gauge station to run the model. There are assumptions for calculating the flow of rainwater, including:

1. Rainfall is distributed in all the catchments with the same intensity,
2. No lag time in the rainfall transfer function,
3. Only considering initial losses, and
4. The maximum number of hours of rain is 4 hours.

The flow of rain is divided into two areas, including permeable and impermeable, with different initial losses and run-off coefficients. For each rain, the adequate rain is determined by cutting initial losses (*IL*), then calculated by Equation 2:

$$Q_{rain\ outlet}(t) = \frac{EI(t)}{\Delta t} \cdot S \cdot R_c \cdot u \tag{2}$$

Where:

$Q_{rain\ outlet}$ = discharge at the outlet is caused by rainfall events over time (m^3/s), and

EI = effective intensity over specific duration (mm).

EI is determined by Equation 3:

$$EI = GI - IL \tag{3}$$

Where:

GI = gross intensity of the total rainfall over a specific period (mm),

IL = initial loss (mm),

Δt = rain gauge acquisition time step (minutes),

S = catchment surface area (ha),

R_c = run-off coefficient associated with rainfall, and

u = 0.16666667: unit conversion factor to cubic meters per second (m^3/s).

Wastewater flow rate

The total wastewater flow rate is determined by using the wastewater generation per capita and the population of the research area (Equation 4):

$$Q_{ww\ total}(t) = Q_{ww\ per\ capita}(t) \cdot P \tag{4}$$

Where:

$Q_{ww\ per\ capita}$ = wastewater generation per capita (m^3/day/capita), and

P = population of research area (inhabitants).

Infiltration and inflow discharge (I&I)

The I&I discharge at the outlet is estimated by using a percentage of the average daily wastewater flow rate (Equation 5):

$$Q_{I\&I\ outlet}(t) = Q_{ww\ average}(t) \cdot 10\% \tag{5}$$

Where:

$Q_{I\&I\ outlet}$ = I & I discharge (m^3/s), and

$Q_{ww\ average}$ = daily average flow of wastewater (m^3/s).

Transfer phase

The reservoir discharge ($Q_{reservoir}$) within the network is calculated using the linear reservoir model formula at each time step (t). This formula is widely utilized in hydrology to simulate the flow and storage of water in a reservoir (Oosterbaan 2019).

$$\begin{cases} Q_{reservoir}(t=0) = Q_{total\ outlet}(t=0) \\ Q_{reservoir}(t+1) = C_1 \cdot Q_{reservoir} + C_2 \cdot Q_{total\ discharge\ outlet}(t+1) \end{cases} \quad (6)$$

Where:

C_1 = $e^{-dt/K_{reservoir}}$,

C_2 = $1 - C_1$, and

dt = 1.

$K_{reservoir}$ (min) is the empirical value from Desbordes (1974), derived using sewer length, slope, and practical considerations. This value corresponds to the lag time between the effective rain peak and the produced discharge peak. These coefficients were taken from Ecully and applied to the research area (Montoya Coronado et al. 2024; Néméry et al. 2022).

$$K_{reservoir} = 0.494 \cdot S^{-0.0076} \cdot 0.55^{-0.512} \cdot i^{-0.401} \cdot L^{0.608} \quad (7)$$

Where:

C_1 = reservoir coefficient,

C_2 = total discharge outlet coefficient,

i = sewer pipe slope (%), and

L = sewer pipe length (m).

Determine the number of spill days and the total volume of spilled discharge

The following formulas (Harlan 2011; Ismail 1993) are used to determine the spilled volume for the circular sewer:

$$R_h = \frac{D}{4}\left(1 - \frac{\sin(\theta)}{\theta}\right)\ and\ \theta = 2 \cdot \arccos(1 - 2 \cdot h/D) \quad (8)$$

Where:

R_h = hydraulic radius (m),

D = inner sewer pipe diameter (m),

θ = wet angle (radian), and

h = water level in the sewer pipe (m).

Based on the Manning equation, the reservoir discharge of the combined sewer system is computed as follows (Harlan 2011):

$$Q_{reservoir} = K_s \cdot I^{0.5} \cdot \frac{\left(\frac{1}{8}\cdot(\theta-\sin(\theta))\cdot D^2\right)^{\frac{5}{3}}}{(0.5\cdot\theta\cdot D)^{\frac{2}{3}}} \quad (9)$$

Where:

$Q_{reservoir}$	=	reservoir discharge of the sewer network (m^3/s),
K_s	=	Strickler coefficient ($m^{1/3}/s$), and
I	=	hydraulic sewer slope (dimensionless).

Spills occur when the water level in the sewer exceeds the threshold height of the CSO. Q_{lim}, the critical discharge for spill events, is defined as the minimum rainfall required to dilute wastewater and meet the QCVN 14:2008/BTNMT standards. Q_{lim} corresponds to the $Q_{reservoir}$ value at the threshold angle $\theta_{threshold}$:

$$Q_{lim} = K_s \cdot I^{0.5} \cdot \frac{\left(\frac{1}{8}\cdot(\theta_{threshold}-\sin(\theta_{threshold}))\cdot D^2\right)^{\frac{5}{3}}}{(0.5\cdot\theta_{threshold}\cdot D)^{\frac{2}{3}}} \quad (10)$$

Where:

Q_{lim}	=	critical discharge for spill events (m^3/s), and
$\theta_{threshold}$	=	threshold angle at the critical discharge (radian).

When there is any timestep in a day having the $Q_{reservoir}$ higher than Q_{lim}, that day is recorded as the spill day, and the total spill volume is determined by Equation 11:

$$Spill\ volume = \int_0^t (Q_{reservoir} - Q_{lim})\, dt \quad (11)$$

Where:

Spill volume	=	total volume spilled (m^3), and
dt	=	simulation time step (s).

2.3 Model set-up

The TONIC model simulates the discharge of wastewater and rainwater into combined sewer pipes, which eventually direct the flow to an outfall that transports water to the river during spill events. In the research area, five outflows are discharging into rivers and canals. To run the TONIC model, the area was redefined to have a single outfall. Consequently, the area and population values were adjusted to be one-fifth of the initial research area's values.

Additionally, the research area was divided into impermeable and permeable zones, each with different initial loss (IL) and run-off coefficient (RC) values, which will be detailed in the next section. The TONIC model used the same values as those from the Ecully study for any unavailable data (Montoya Coronado et al. 2024; Néméry et al. 2022).

The TONIC model simulations rely on specific boundary conditions. The model accounts for three main inputs at the upstream boundary: rainfall, wastewater, and Inflow and Infiltration (I&I). Rainfall is assumed to be uniformly distributed across the catchment area, with data collected from the CARE weather station in District 10, Ho Chi Minh City. Wastewater flow is based on daily water consumption patterns in the study area, while I&I is estimated to be 10% of the wastewater flow and rainfall.

The downstream boundary is characterized by a single outflow discharging into rivers and canals. The system assumes a continuous flow without backflow, meaning all water will move downstream. This is determined by the flow calculations defined in Equations 8, 9, and 10 and the threshold flow. All water is assumed to be discharged into the canals or rivers.

2.4 Scenarios

The TONIC model was run under three scenarios to assess the spill situation in the research area for 2020 and explore improvements through green roofs (Table 1).

Scenario 1: The model was run for 24 hours on a dry weather day, specifically on January 1, 2020.

Scenario 2: The model was run for the entire year of 2020, from January 1 to December 31, to account for dry and rainy weather conditions.

Scenario 3: The model was run for the entire year of 2020 with the application of green roofs. In this scenario, the runoff coefficient (RC) was adjusted due to the implementation of green roofs.

According to Kolasa-Więcek and Suszanowicz (2021), the RC can decrease by 20–30% with green roofs. This study assumed that green roofs would be constructed over one-third of the impermeable area, decreasing the impermeable area to 46%, and reducing the RC to 0.23.

Table 1 Value of parameters used in three scenarios.

Scenario	1	2	3
	24h on a dry weather day	One-year period (2020)	One-year period (2020) with the application of green roofs
Population[a] (inhabitant)	14,828	14,828	14,828
Total area (ha)[b]	293.8	293.8	293.8
Impermeable area (%)	0.69	0.69	0.46
PE[c] (*L/d* · capita)	200	200	200
I&I (%)	10	10	10
IL[d]	1	1	1
RC[d]	0.25	0.25	0.23
Strickler coefficient	75	75	75
Pipe diameter (m)	0.8	0.8	0.8
Pipe length (m)[e]	2,103	2,103	2,103
Pipe slope[f]	1/800	1/800	1/800
Threshold height (m)[g]	0.4	0.4	0.4

NOTE:

a. *The population is calculated based on the ratio of the area between the research area and Thu Duc City. The population in the Thu Duc area is from Resolution 1111/NQ-UBTVQH14 on arranging administrative units at district and commune levels and establishing Thu Duc City under Ho Chi Minh City (National Assembly of Vietnam 2020).*

b. *The total area is determined by using QGIS software. The proportion of impermeable area is determined by processing the Land Cover Map of the Southern Region of Vietnam 2017 in QGIS (ALOS 2019).*

c. PE is taken from the general master plan for Ho Chi Minh City until 2025 (Prime Minister 2014).

d. These values are unavailable for Vietnam, so the Ecully (France) catchment values were used. As mentioned above, the research area is divided into impermeable and permeable areas (Montoya Coronado et al. 2024). The values of IL and RC in the above table are applied in the impermeable area. In the permeable area, IL and RC are equal to 0.

e. The sewer's length and diameter are based on the Second Ho Chi Minh City Environmental Sanitation Project (World Bank Group 2024).

f. The minimum slope = 1 / Pipe diameter determines the pipe slope.

g. The threshold height is determined that on the spill day, the wastewater will be diluted with stormwater, and the outlet will meet the QCVN14:2025/BTNMT, column A (Ministry of Natural Resources and Environment 2025)

The modeling scenarios assumed that all wastewater from this area is directed to the central WWTP. However, the operation of the central WWTP designated for the Nhieu Loc–Thi Nghe watershed has been postponed to 2026.

3. RESULTS AND DISCUSSION

This dataset captures the rain intensity for each 10-minute interval throughout 2020, as depicted in Figure 4. The figure indicates that the rainy season commenced in May and concluded in December, with several intense rainfall events exceeding 20 mm per 10 minutes from June to November. Most rainfall events in 2020 had an average intensity ranging between 5 mm and 8 mm per minute. Figure 5 illustrates the daily wastewater generation per capita, which is estimated to be 80–90% of the daily water consumption per capita or 200 litres per capita per day (Ministry of Construction 2023). The hourly variation in municipal wastewater flow in cities in Vietnam is subject to factors such as population density, industrial activities, and daily human routines (World Bank Group 2018). Notably, wastewater flow surges during peak activity times in the morning and evening. Large cities like Hanoi, Ho Chi Minh City, and Da Nang have wastewater systems engineered to accommodate these variations, with lower flows typically recorded during the late-night and early-morning hours when human-related activity levels decrease (World Bank Group 2018), as depicted in Figure 5.

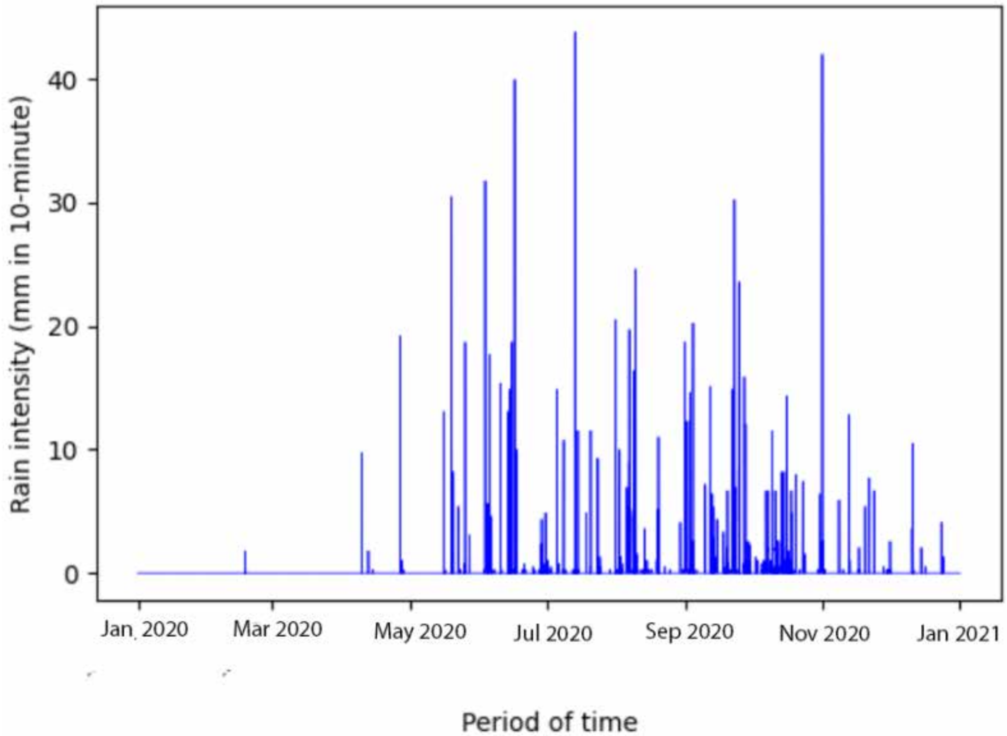


Figure 4 Rain intensity in 2020 in District 10, Ho Chi Minh City.

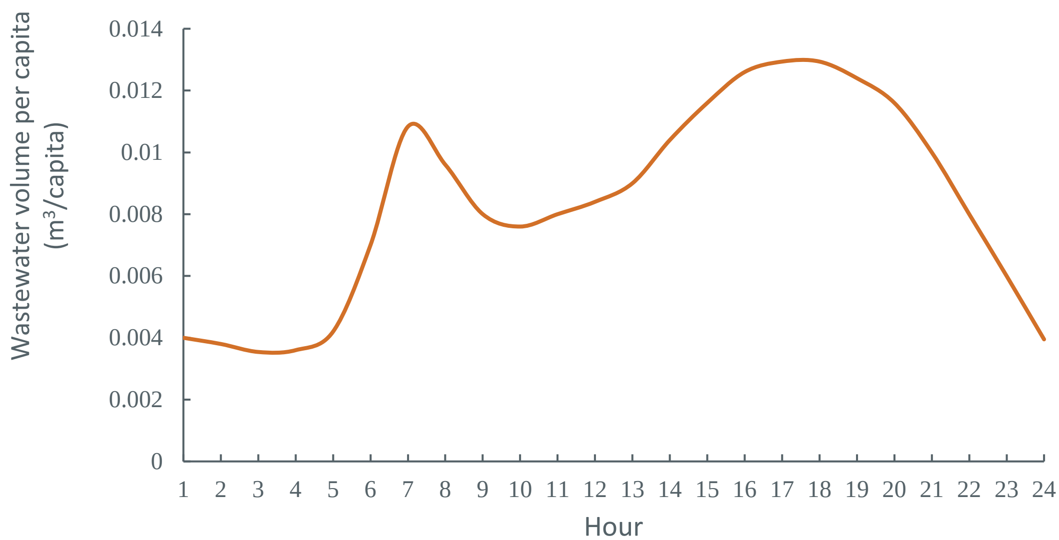


Figure 5 Variation of domestic wastewater generation per capita in HCMC.

Moreover, it is crucial to consider the infiltration and inflow of excess water into the sewer system. Infiltration refers to groundwater and canal water that seep into the combined sewer system used in Thu Duc City when the water level exceeds the height of the sewer pipes. In contrast, inflow describes surface water entering the wastewater system from sources such as yards, roofs, and footing drains, as well as from connections with storm drains, downspouts, and openings in manhole covers. Inflow is primarily driven by storm events that increase sewer flow. The Construction Master Plan of Ho Chi Minh City states that infiltration and inflow contribute ten percent to the daily wastewater flow (Prime Minister 2020).

Given that the runoff coefficient (RC) for permeable areas is set to 0, these areas have no runoff flow. As a result, runoff from permeable areas was excluded from consideration in the three scenarios. In the first scenario, the TONIC model simulated a typical dry weather day, specifically on January 1st, 2020, when no rainfall occurred. Figure 6B depicts the daily wastewater flow pattern within the study area. There were two peak flows, approximately 0.045 m^3/s at 7 am and 0.055 m^3/s between 5 and 6 pm. The total discharge volume mirrored the wastewater flow since there was no rainfall, and the inflow and infiltration (I&I) discharge was negligible. The overall discharge volume for the study area was 3,273 m^3, with no spills recorded on this dry weather day.

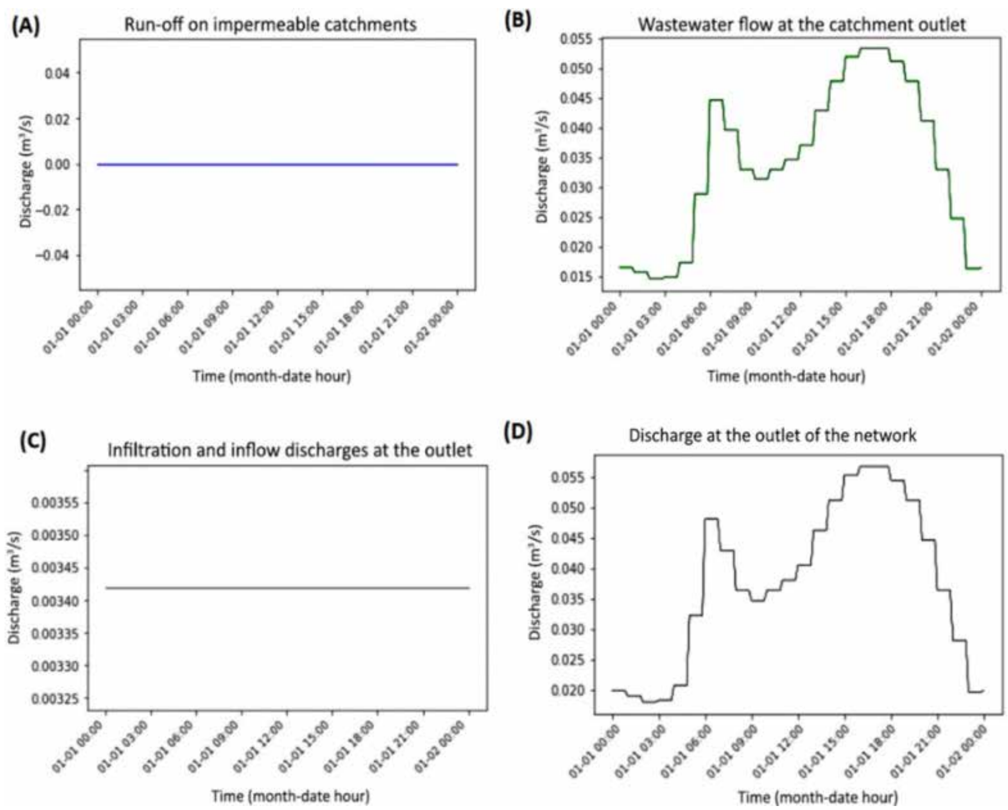


Figure 6 Results of Scenario 1 (24 h without rain).

In the second scenario, the TONIC model was run throughout 2020, showing that the rainy season influenced the results. Figure 7A illustrates the rainwater flow over the impermeable catchment area. Throughout the year, the wastewater and infiltration and inflow (I&I) remained constant and were relatively insignificant compared to the runoff flow. Consequently, the discharge at the outlet closely mirrored the runoff flow. In 2020, the total discharge amounted to 2,780,063 m³. Regarding stormwater spills, there were 16 days with spills totaling 3,035 m³. The frequency and volume of spills tend to increase with the rise of impermeable surfaces, highlighting the concerning trend of unsustainable urban development (Bates et al. 2008).

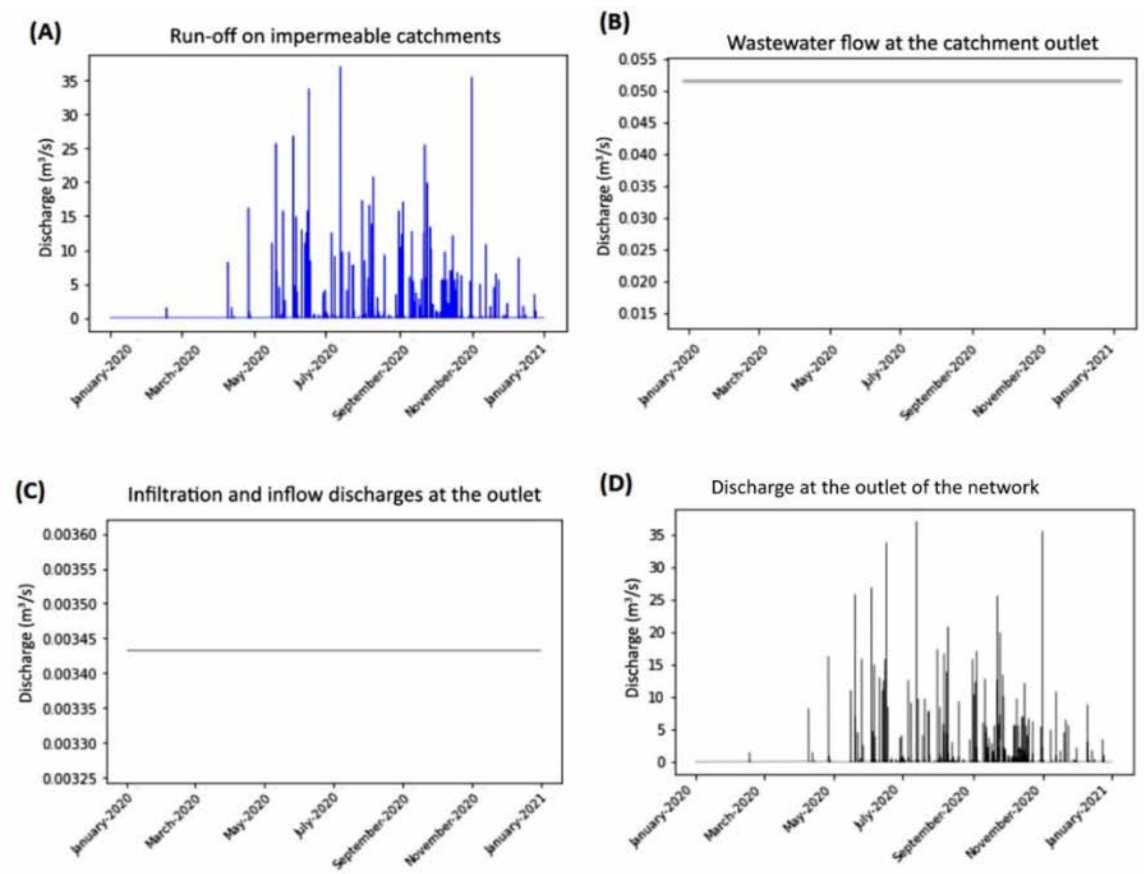
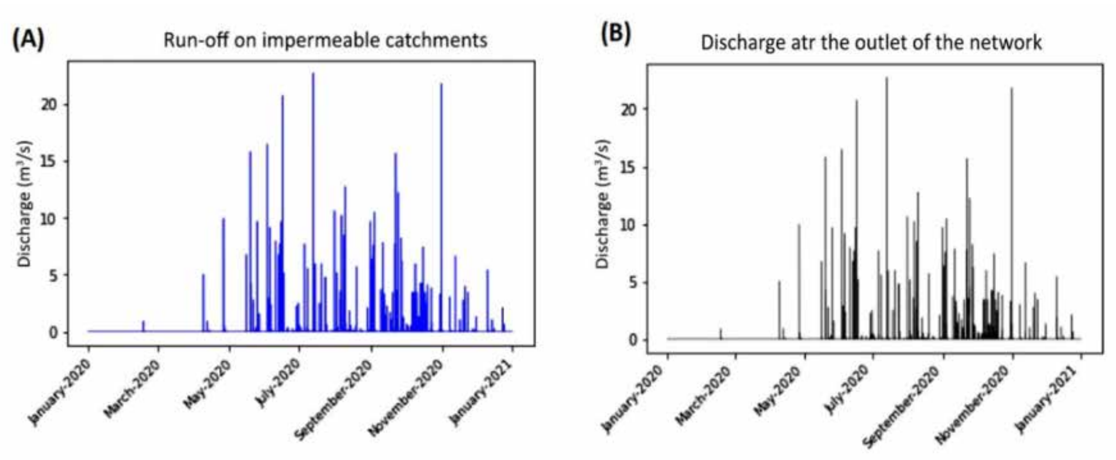


Figure 7 Results of Scenario 2 (one-year period (2020) *without* GR application).

In the final scenario, the TONIC model was utilized throughout 2020 with the implementation of GRs. The reduction of impermeable surfaces resulted in a significant decrease in runoff flow, as illustrated in Figure 8A. Some previous studies indicated that disconnecting 20% of impervious surfaces may lead to a reduction of 30% to 75% in CSO volume (D'Ambrosio et al. 2022; Joshi et al. 2021). This confirms the effectiveness of GRs in mitigating rainwater runoff by absorbing water, delaying runoff, and gradually releasing stored water from the substrate layer (Mentens et al. 2006). The wastewater and I&I flows remained consistent, as shown in Figures 7B and 7C, as they were unaffected by changes in impermeable areas and RC. These flows were minimal compared to the runoff flow, making the sewer outlet discharge nearly equivalent. With GRs in place, the total discharge volume was reduced from 2,780,063 m³ to 2,166,752 m³, and no spill days were recorded in the study area. Previous studies have shown that GRs could significantly reduce and retain runoff by delaying peak flows (Amaram and Ahmad 2023; Raimondi and Becciu 2021). Figures 7D and 8B demonstrate that the peak discharge differences at the outlet with and without GRs ranged from 1 to 14 m³/s, depending on the flow, resulting in an average reduction of 35% in runoff from impermeable catchments. This reduction is due to the retention of stormwater runoff and the subsequent delay in peak flow. Amaram and Ahmad (2023) also noted that GRs can retain up to 54% of water runoff, reducing the average volume and delaying its release by up to 15 minutes.

Figure 8 Results of Scenario 3 (one-year period (2020) *with* GR application).



4. CONCLUSIONS

The results from the TONIC simulation have highlighted the effectiveness of implementing GRs in reducing the hydraulic load on the combined sewer system and the pollution levels in urban canals receiving overflow. No spills were recorded during dry weather, though spills occurred during intense rainfall. Applying NbS, specifically GRs, reduced the impermeable surface area and the runoff coefficient (RC). Consequently, the discharge volume decreased by nearly 22%, with no spills observed even during heavy rain events. These findings suggest that city planners should prioritize the strategic adoption of green roofs, including creating policies that mandate the incorporation of green infrastructure into new development projects and creating incentive programs to encourage the retrofitting of existing buildings with GRs.

The results show that the calibrated TONIC model can be used in other areas to evaluate how different strategic implementations of green roofs could affect urban flooding and, therefore, should be used as a data-driven planning tool in future urban development. While the TONIC model simulation is promising, our findings underscore the need for real-world data and empirical studies to validate the simulated impact of green roofs on urban flooding. Future research should focus on field studies that allow for better calibration and validation of the model, as well as the study of other green infrastructure solutions and their integration into an extensive system to address urban flood management

These findings offer preliminary insights, suggesting the need for empirical surveys on spill volumes and hydraulic flows to achieve more consistent outcomes. These surveys provided data for the subsequent calibration and validation of the TONIC model. Tidal influences are significant factors that can impact practical outcomes. However, with the major anti-flooding project reaching 95% completion as of April 2024, future applications of the TONIC model can disregard tidal effects. Future studies will focus on evaluating the efficacy of GRs in mitigating pollution in urban canals, considering variations in evapotranspiration rates and the pollutant removal capabilities of GRs, as well as implementing the calibration of the TONIC model, which is based on practical surveys.

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