



Stormwater runoff reduction simulation model for urban flood restoration in coastal area

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Received: 17 August 2021 / Accepted: 29 June 2022 / Published online: 27 July 2022
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Abstract

Urban floods caused by expanding impervious areas due to urban development and short-term heavy precipitation adversely affect many coastal cities. Notably, Seoul, one of the coastal cities that experiences acute urban floods, suffers annually from urban floods during the rainfall season. Consequently, to mitigate the impacts of urban floods in Seoul, we established flood-vulnerable areas as target areas where green infrastructure planning was applied using the Stormwater Runoff Reduction Module (SRRM). We selected the Gangdong, Gangbuk, and Dobong districts in Seoul, Korea, all of which demonstrate high flood vulnerability. Analyses in reducing the runoff amount and peak time delay effect were estimated by model simulation using the SRRM. The reduction in peak discharge for the whole area occurred in the following order: Gangdong district, then Gangbuk district, and lastly Dobong district. In contrast, the reduction in peak discharge per unit area was most prominent in Gangbuk district, followed by Dobong and Gangdong districts. However, the delay effect was almost identical in all target areas. Based on the simulation results in this study, we planned green infrastructure, including green roofs, infiltration storage facilities, and porous pavement. We believe that the results of this study can significantly enhance the efficiency of urban flood restoration and green infrastructure planning in coastal cities.

Keywords Green infrastructure · System dynamics · Urban flood restoration · Flood vulnerability · Peak discharge

1 Introduction

The expansion of urban areas due to development and urbanization has intensified rainfall runoff and has drastically increased the probability of urban flooding (Eliasson 2000; Chen et al. 2009; OECD 2009). Urban floods are caused by rainfall concentrated in cities in a short time period. The resultant damage in the city tends to vary depending on the design of the impacted areas, which include residential areas, commercial areas, industrial areas, and transportation areas (IPCC 2007; Ha and Jung 2017). The frequency and

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scale of heavy rainfall have greatly increased worldwide, causing damage to urban floods (World Bank 2008; IPCC 2011). In East Asia, including South Korea, the impacts of heavy rains resulting from climate change continue to increase. The damage from urban floods intensifies as surface runoff increases, which is the direct result of the expansion of the impermeable area due to urbanization (Satterthwaite 2011). Recently, this surface runoff has not only created the problem of flooding itself, but has also been strongly implicated in the increased spread of infectious diseases such as COVID-19, mostly because of sewage overflow and contamination through sewer pipes (Han and He 2020). Therefore, surface runoff in areas with rapid urbanization aggravates the damage caused by urban flooding (Randolph 2004). The occurrence of urban floods in cities is not only determined simply by rainfall intensity but also by rainfall duration. Heavy rainfall over a short period of time is the main cause of urban flooding, which is called peak discharge (Randolph 2004; Ha and Jung 2017). In conclusion, flood damage caused by urban floods is a major problem with respect to increasing amounts of peak discharge, as well as the persistence of runoff (Bronstert et al. 2002).

Cities located in coastal areas have geographical characteristics determined by their proximity to the ocean, and these characteristics permit the runoff caused by urban floods to reach the coast via river discharge (Li et al. 2014). In coastal cities, urban flooding occurs due to heavy rainfall combined with climate factors, urban infrastructure drainage systems, and tidal effects resulting from rising sea levels (Shahapure et al. 2010). In addition, the urbanization of coastal cities expands the impermeable area, and the runoff of low-lying areas causes frequent urban flood damage (Shahapure et al. 2011). The problems resulting from urban flooding in coastal areas are also a major cause of sea water pollution because of the characteristics of land–ocean coupling (Novotny 1995). The coastal area, as the boundary of land and ocean, is an important transition zone (Levin et al. 2001), and yet, at the same time, it is an ocean hot spot affected by river discharge, as it processes materials moving from the land to the ocean (Schlacher and Connolly 2009). Therefore, the runoff generated from residential areas, industrial facilities, commercial facilities, and transportation areas from urban flooding causes severe water pollution in all forms, including organic and inorganic matter, for marine ecosystems (Schiff et al. 2003; Walsh 2004; Lee et al. 2019). The problem of runoff due to urban floods in coastal areas is serious in that it extends from the city scale to the coastal scale and the coastal scale to the ocean.

In South Korea, the plan adopted to address urban floods that was proposed at the city level focuses mostly on the built environment or gray infrastructure (Koh and Lee 2012). In the basic plan for sewage maintenance proposed in 2009, the government tried to minimize flooding damage by reinforcing the capacity of the facility with sewage pipes and rainwater pumping stations. However, approximately 34.9 million dollars of property damage occurred during the heavy rains in 2010, and flood damage occurred in 2011 from heavy rains of up to 113 mm per hour (Ministry of the Interior and Safety 2015). Following these incidents, there has been a continuous implementation of sewer pipe expansion plans, rainwater pumping stations, and rainwater reservoir installations. However, recent damage has limited the reinforcement and expansion of existing drainage facilities called gray infrastructure (Koh and Lee 2012). This means that existing gray infrastructure will contain rainwater during urban floods caused by heavy rains, even though this infrastructure is relatively limited in its ability to reduce peak discharge and runoff delay.

Green infrastructure that can manage urban floods is defined as a system, technology, or facility that causes the water circulation process of a city to mimic that in nature by focusing on rainwater management (EPA 2007). Green infrastructure integrates the concept of low-impact development (LID) through nature-friendly rainwater management techniques

such as green roofs, rainwater gardens, vegetation waterways, permeability pavement, and rainwater storage facilities in its approach toward rainwater management for urban floods (Lee et al. 2014). The green infrastructure approach reduces peak discharge by introducing greening elements to existing impermeable areas and delays the runoff effect, thereby increasing the restoration effect by incorporating gray infrastructure such as existing sewer pipes (Fletcher et al. 2013; Schubert et al. 2017). For coastal cities, the ecosystem services provided by green infrastructure can strengthen resilience to urban floods and adapt to the problems that cause urban floods (Jeong et al. 2020). In the existing green infrastructure studies on urban flood management, the impact of green infrastructure on runoff reduction ability was analyzed (Bin et al. 2008; Kim et al. 2011). Most studies have focused on the effect of green infrastructure (Davis 2008; Emerson and Traver 2008; Li et al. 2009; Driscoll et al. 2015) or the reduction in runoff (Shuster and Rhea 2013; Loperfido et al. 2014; Bhaskar et al. 2016; Lim and Welty 2017). Therefore, in terms of rainfall intensity and duration, the peak discharge reduction and the runoff delay effect due to green infrastructure should be analyzed for the restoration effect of urban flood damage.

This study aims to improve flood resilience through green infrastructure application planning by applying a stormwater runoff reduction module (SRRM) to flood-vulnerable areas in Seoul. The specific aims of this study are (1) to select the target area by analyzing the flood-vulnerable area to be restored after the urban flood, (2) to analyze the effect of the Stormwater Runoff Reduction Module (SRRM) that can restore the damage from the urban flood, and (3) to apply the SRRM as green infrastructure; the effect of and plan for urban flood restoration in the target area are suggested. The green infrastructure plan proposed in this study shows the delayed effect of runoff speed from the artificial ground due to gray infrastructure and focuses on reducing peak discharge as a solution to address urban flooding more flexibly than the existing plan.

2 Materials and methods

2.1 Study site

South Korea suffers damage from floods caused by typhoons and heavy rains every summer. Seoul is the capital and largest coastal city in Korea and is geographically adjacent to the Yellow Sea; since the 1960s, it has undergone rapid industrialization and urbanization (Fig. 1). As a result of the increasing population concentration, approximately 10 million people (20 percent of the Korean population) live in Seoul (The Seoul Research Service 2013). Seoul city is located at 37° 34' 00" N, 126° 58' 41" E and has an area of approximately 605.25 km². Since the 1970s, lowland areas have been established as urbanized areas. Exposure to disasters has increased due to the concentration of the population and economic assets in disaster-prone areas. The vulnerability to urban floods has increased following the increase in impermeable surfaces, the expansion of sewer pipes, and the conservation of natural water (Yoon and Moon 2009). In Seoul, heavy rainfall occurred in the Gangseo district in September 2010, with the equivalent of up to 500 years of heavy rainfall. In July 2011, rainfall, which corresponded to approximately 40% of the average annual precipitation, was concentrated over three days (Koh and Lee 2012; Lee and Kang 2018). Following these incidences, large and small flood damage has increased steadily, and in August 2020, flood damage occurred following heavy rain that exceeded 50 mm per hour (Ministry of the Interior and Safety 2020).

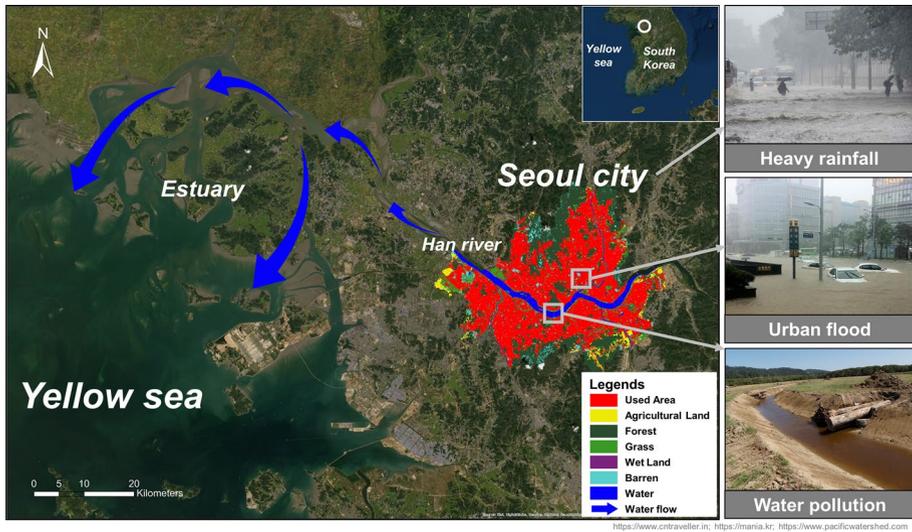


Fig. 1 Causes (heavy rainfall) and impact (water pollution) of urban flood in the study site, Seoul city

As a response measure to this damage, the city of Seoul has focused its resources on dredging sewage pipes in 34 vulnerable lowlands, and the area is expanding infrastructure and water circulation improvement systems throughout the city (Choi 2019). Additionally, Seoul has designated disaster risk zones to respond to flood damage. In 2017, nine flood-prone zones were designated as disaster risk zones in Seoul (Water Resources Management Information System 2013). However, despite the strengthening of the flood response, the damage caused by floods centered on impermeable areas persists, as evidenced by the recent heavy rain damage. From 2010 to 2018, the average annual rainfall in Seoul was 1360.32 mm/year, with most of the rainfall concentrated in the summer months of July and August (Seoul Metropolitan Government 2019). Seoul records flooding every year due to the heavy rainfall in the summer season and the topographical characteristics of the lowlands. The runoff from floods in Seoul flows along the Han River to the Yellow Sea region, which affects the ecological system of the Yellow Sea. Consequently, Seoul was selected as the study site to analyze the areas vulnerable to flooding and to identify the effects of stormwater runoff reduction (Fig. 1).

2.2 Flood vulnerability analysis

To quantitatively measure flood vulnerability, we adopted a flood vulnerability index (Sakieh 2017). Originally, in the referenced paper, the author suggested six indices, i.e., topographic wetness index, distance to river networks, elevation, ordered river networks, stream density, and maximum 24-h rainfall, for evaluating flood vulnerability. However, in this study, we excluded river networks and ordered river networks because these variables have similar meanings to stream density. Therefore, the flood vulnerability index in this study consisted of elevation, a topographic wetness index (TWI), stream density, and maximum 24-h rainfall. First, an elevation map was derived from the digital topographic map provided by the National Geographic Information Institute in South Korea. Second, TWI, a steady-state wetness index, was mainly used to quantify topographic control on

hydrological processes (Sørensen et al. 2006); to calculate TWI spatially, we extracted a digital elevation map (DEM) using a digital topographic map, and then we conducted cell calculation analysis based on Eq. (1) as follows (Beven and Kirkby, 1979):

$$TWI = \ln \frac{a}{\tan b} \quad (1)$$

where a is the local upslope area draining through a certain point per unit contour length and $\tan b$ is the local slope in radians. Third, stream density refers to the length of all channels within the basin divided by the basin area. Areas with a high stream density accelerate the flow of surface runoff. Therefore, stream density is considered one of the most significant characteristics for evaluating potential runoff and flooding. To measure the stream density of the study site, the order of the stream in the study site was determined by applying the derived DEM. Fourth, maximum 24-h rainfall is one of the most influential factors of flooding. In this context, we measured the maximum 24-h rainfall by using rainfall data from the automatic weather station monitoring system managed by the Korea Meteorological Administration. It is imperative to select target areas and test the effect of SRRM on a trial basis, rather than introduce SRRM throughout the study site, to adapt SRRM to the study area effectively within limited social resources and budgets. In this context, we applied SRRM to a target area with high flood vulnerability.

2.3 Flood restoration simulation

In this study, the SRRM was applied for the restoration process after stormwater runoff caused by urban floods. This module accounts for the fact that most of the runoff comes from artificial ground areas. The SRRM aims to reduce the runoff caused by floods and delay the runoff speed, thereby maintaining a constant outflow. The SRRM increases the runoff reduction effect by applying low-impact development (LID) soil, and it provides ecological effects by increasing the green space. The module structure is 50 cm*50 cm*20 cm, LID soil is applied to the upper 10 cm for planting, and the lower 10 cm is configured to store the rainwater by forming a reservoir (Fig. 2a). Next, this study developed a simulation model that can analyze the effects of stormwater runoff reduction based on the analysis of flood vulnerability areas using GIS and the developed SRRM using STELLA professional (Fig. 2b). This model consisted of three sectors. First, a basic sector was constructed by applying precipitation, site area, and the runoff coefficient. Second, a module sector was constructed to analyze the effect of stormwater runoff reduction by applying the SRRM and biotope area ratio. Data were collected to structure the model for each sector (Table S1). The data related to precipitation lasted for 2 h, which were set to a total precipitation amount of 85 mm and were calculated as a 20-year frequency of the Huff quartile distribution. To calculate runoff, rainfall intensity, area, and runoff coefficient variables are needed; thus, runoff coefficient data were collected in this study. The range of runoff coefficients was calculated by land use (Ponce 1989). However, since runoff coefficients reflecting the specificity of each region should be used, this study adopted the standard value and range of the runoff coefficients calculated for Seoul (Seoul city 2002).

The target area was constructed through land-cover maps of flood-vulnerable areas as established in the previous step. The land-cover map used was provided in 2017 by the Ministry of Environment; it was generated using ArcGIS 10.2.2. In this study, the areas of the artificial ground area applicable to the SRRM used for the model are included with the land-cover classifications. The types of artificial ground areas classified in

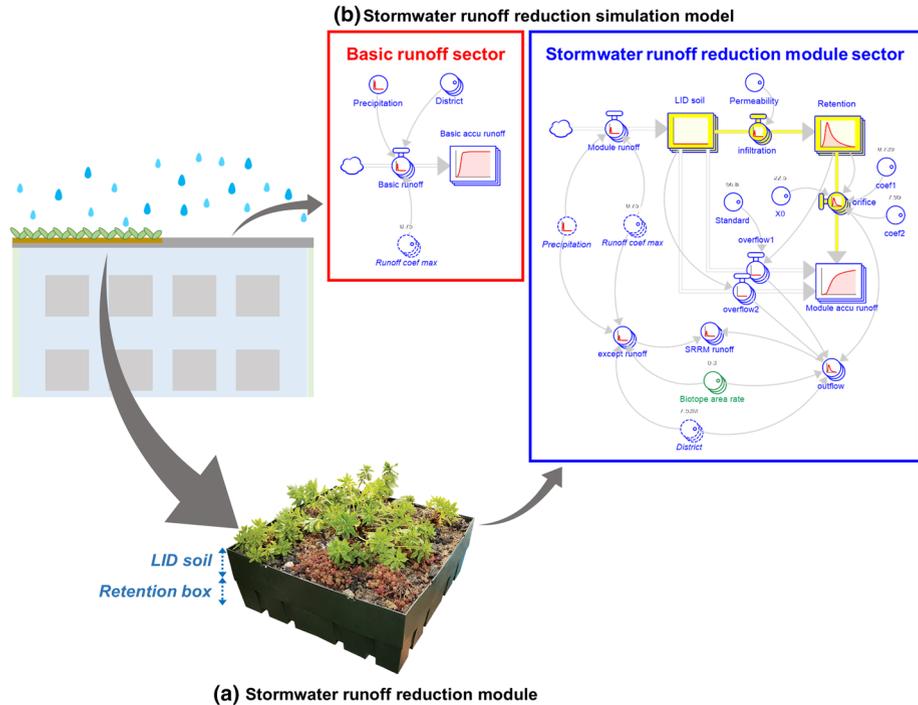


Fig. 2 Simulation model structure

this study are residential areas, industrial areas, commercial areas, entertainment areas, transportation areas, and public facilities areas. For a residential area, single-family house, row-house, and apartment buildings are included as spaces where people live. The industrial area is a large industrial facility, which includes land and attached facilities used for manufacturing. The commercial area includes areas where business buildings, large discount stores, and malls are located. The entertainment area includes cultural areas, sports areas, and recreation areas, such as amusement parks, resorts, stadiums, and accommodations. The transportation area includes airport and port facilities, railroad facilities, roads, and parking lots. The public facilities area includes schools, hospitals, libraries, environmental infrastructure, military facilities, and administrative agencies (Ministry of Environment 2020). Other arable lands, forests, grasslands, wetlands, and bare lands were excluded from this study because they cannot be categorized as artificial ground areas. The area was calculated by the classification of each land cover and used for the simulation model.

SRRM-related data correlate with the specification of SRRM, such as the standard module, the permeability of low-impact development (LID) soil, and the amount of runoff per hour through an orifice. This is based on the results of SRRM development and experimentation. In this study, SRRM was applied to the area of artificial ground based on the biotope area ratio provided by Seoul city (Ministry of Environment 2016; Choi 2019). The biotope area ratio is equivalent to the ratio of green areas with ecological function among artificial ground or development areas. The biotope area ratio is applied differently according to land-cover or land-use (Table S1).

3 Results

3.1 Flood-vulnerable area in Seoul

The results of analyzing the flood vulnerability of Seoul city and extracting the target areas are as follows (Fig. 3). In the case of the stream density map (Fig. 3c), we made basic maps, such as fill, flow direction, and flow accumulation, using the hydrological toolbox in ArcGIS 10.2.2. We then extracted cells with values greater than 8000 from the basic flow accumulation map; these cells were considered streamlines. Based on the streamlines, we conducted a D8 stream density analysis to determine the stream density. For the maximum 24-h rainfall map, we extracted 67 branches located in and around the study site based on the rainfall data (Fig. 3d). Subsequently, inverse distance weighting interpolation analysis was conducted in ArcGIS 10.2.2 (Ouma and Tateishi 2014). Finally, we normalized the four derived maps and conducted overlay analysis to derive flood vulnerability maps (Fig. 3e). All of the maps in this study were created as a continuous raster map at a 10 × 10 m resolution.

We standardized the cell values composed of derived flood vulnerability maps to determine target areas, and we divided the standardized map into 25 administrative districts. We counted the number of cells with the top 5% value in each administrative district through spatial descriptive statistics, indicating an extremely vulnerable region to flooding. We selected Gangbuk district, Dobong district, and Gangdong district as target areas since only these three districts had cells with the top 5% value. For the selected target areas, we checked the effect of SRRM and suggested a green infrastructure plan specifically considering the land-cover status.

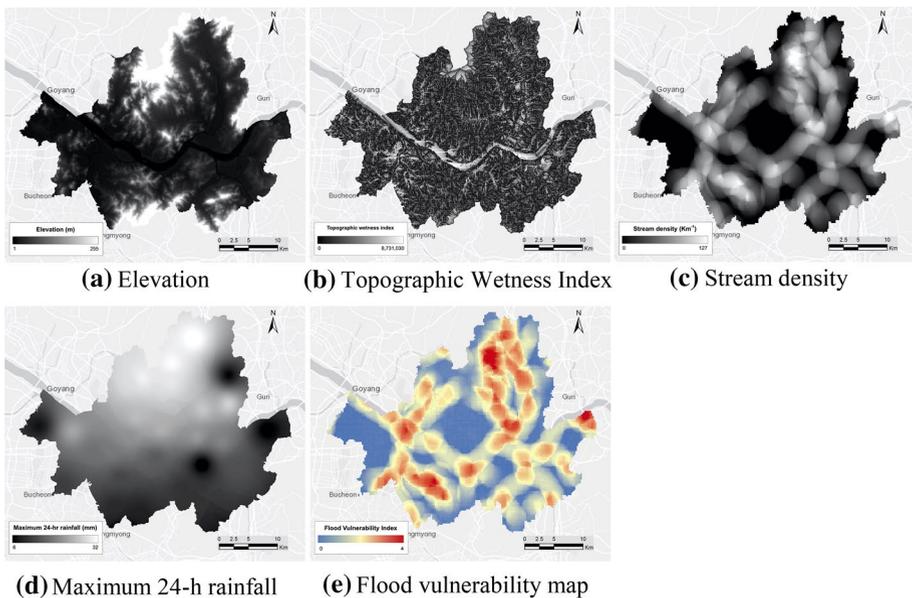


Fig. 3 Flood vulnerability index map

3.2 Stormwater runoff reduction module (SRRM) simulation

To analyze the effects of the SRRM, we compared the basic runoff without the module and the runoff with the SRRM (Fig. 4). To analyze the effects of stormwater runoff reduction, it is necessary to identify (1) the peak discharge reduction amount and (2) the delay of stormwater runoff (Table 1). First, we compared the reduction in peak discharge: the basic runoff was 2.71 mm/min in 40 min, but the SRRM runoff was 0.74 mm/min in 60 min. Therefore, the peak discharge was reduced by 1.97 mm/min when the module was applied.

The delay of stormwater runoff is based on a comparison of the time from the start of the runoff to the end of the runoff. Basic runoff occurred for approximately 2 h, whereas SRRM runoff occurred continuously from the beginning of the rainfall and lasted approximately 4 h, resulting in a delay of stormwater runoff of approximately 2 h. Based on this, SRRM was applied to Gangdong district, Gangbuk district, and Dobong district, the flood-vulnerable areas derived from the previous stage, to analyze the effect of stormwater runoff reduction.

3.3 Urban flood restoration by green infrastructure application

The results were analyzed by applying SRRM as the GI scenario for the Gangdong district area (Fig. 5). The peak discharge from the artificial ground in Gangdong district was 28,699.05 m³ in 40 min under the basic scenario, with a corresponding peak discharge of 22,597.79 m³ under the GI scenario (Table S2). This result indicates that the GI scenario reduced the amount of runoff by 6,101.26 m³ when compared to the basic scenario. This is the amount of runoff reduced across the total artificial ground area

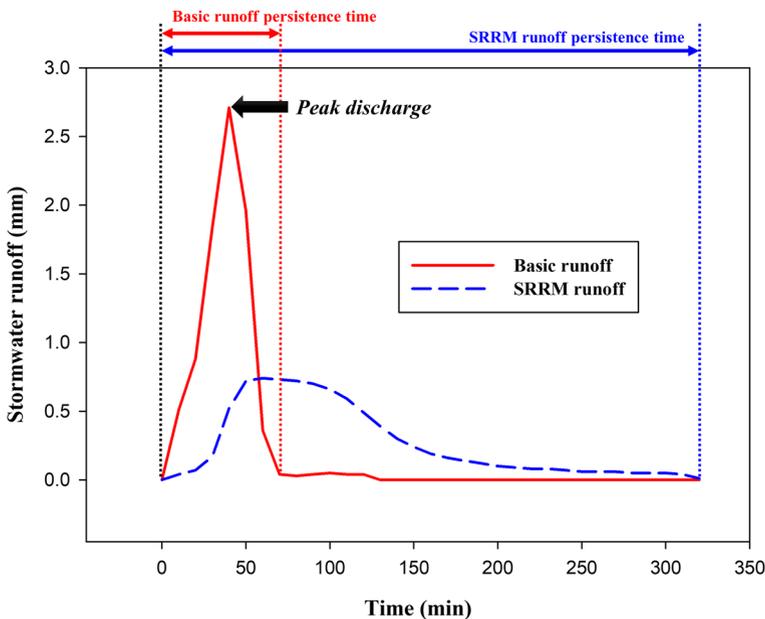


Fig. 4 Basic and SRRM stormwater runoff

Table 1 Differences in basic and SRRM stormwater runoff

Time (min)	Basic runoff	SRRM runoff	Time (min)	Basic runoff	SRRM runoff	Time (min)	Basic runoff	SRRM runoff
10	0.51	0.04	60	0.36	0.74	110	0.04	0.59
20	0.88	0.07	70	0.04	0.73	120	0.04	0.49
30	1.84	0.17	80	0.03	0.72	:	:	:
40	2.71	0.52	90	0.04	0.70	310	0	0.04
50	1.96	0.72	100	0.05	0.66	320	0	0.01

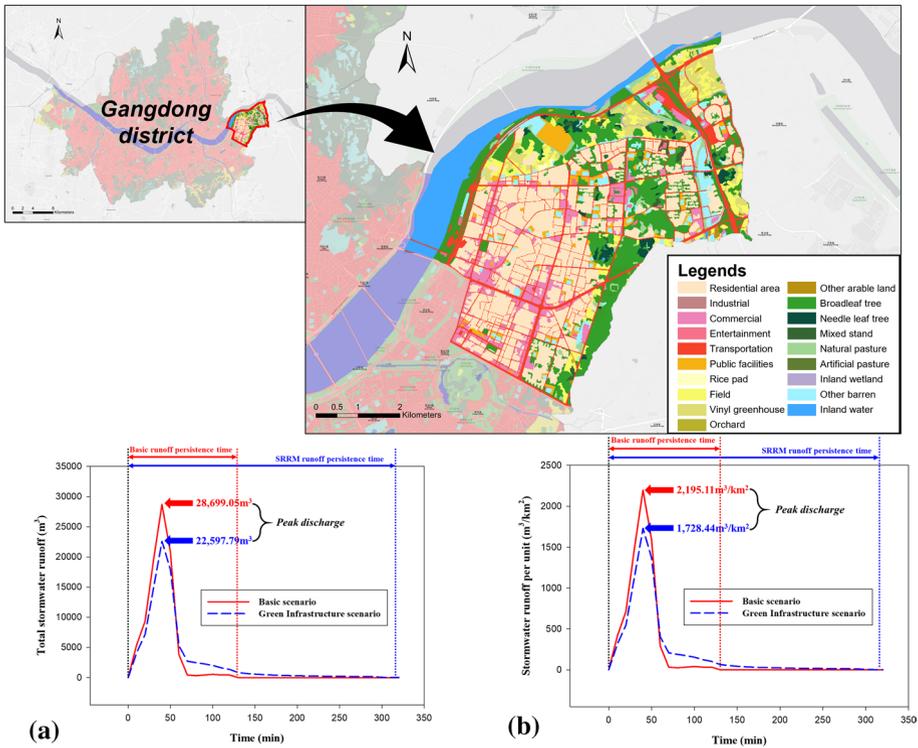


Fig. 5 **a** Total amount of stormwater runoff (m^3) in Gangdong district and **b** amount of stormwater runoff per unit area (m^3/km^2) in Gangdong district

(13.07 km^2) of Gangdong district. In the Gangdong district area, the peak discharge under the basic scenario was $2,195.11\text{ m}^3/km^2$, and the peak discharge under the GI scenario was $1,728.44\text{ m}^3/km^2$. Accordingly, the amount of stormwater runoff reduction per unit area in Gangdong district was $466.67\text{ m}^3/km^2$.

The comparison results for the effects of the stormwater runoff reduction in the Gangbuk district area are as follows (Fig. 6). The peak discharge under the basic scenario for the artificial ground area in Gangbuk district (9.23 km^2) was $19,723.21\text{ m}^3$ over a period of 40 min, and the peak discharge under the GI scenario was $15,290.11\text{ m}^3$, resulting in a reduction of 4433.1 m^3 . In terms of the amount of stormwater runoff per unit area, the peak discharge under the basic scenario was $2,136.03\text{ m}^3/km^2$, and the peak discharge under the GI scenario was $1,655.92\text{ m}^3/km^2$. The amount of stormwater runoff reduction per unit area was $480.11\text{ m}^3/km^2$ in Gangbuk district (Table S3).

The basic scenario and GI scenario results in the Dobong district area are as follows (Fig. 7). The peak discharge reduction was compared across 9.28 km^2 of the total area of Dobong district, and the reduction in the peak discharge per unit area was also compared. For the basic scenario, a peak discharge of $20,175.68\text{ m}^3$ occurred over a period of 40 min, and for the GI scenario, the peak discharge was $15,800.66\text{ m}^3$ for the same time period. This resulted in a reduction in the stormwater runoff amount of $4,375.02\text{ m}^3$. According to the basic scenario per unit area, the peak discharge was $2,173.47\text{ m}^3/$

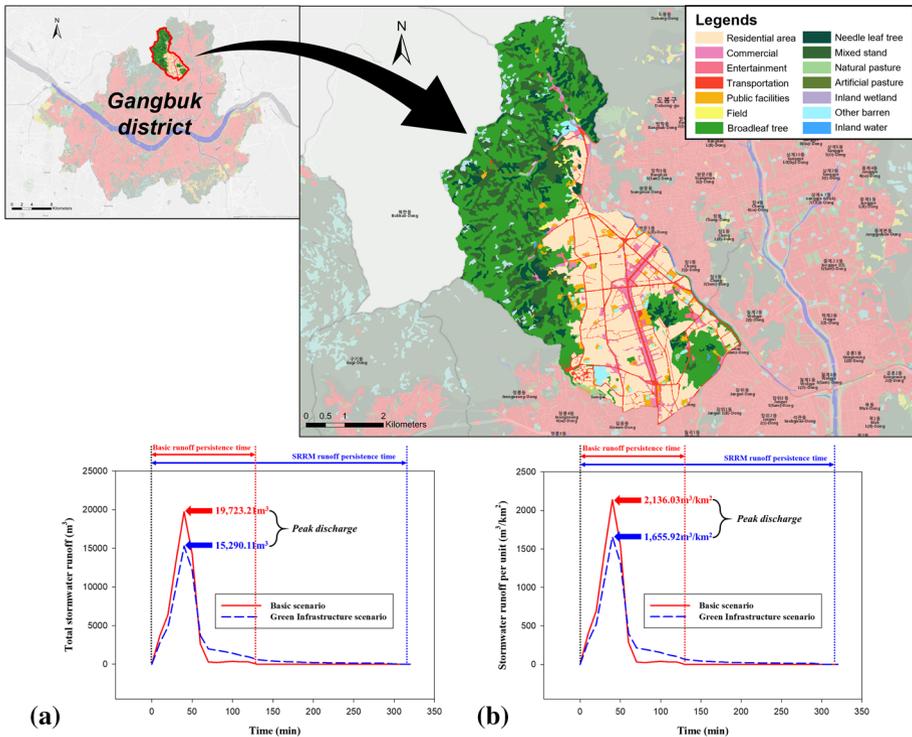


Fig. 6 **a** Total amount of stormwater runoff (m³) in Gangbuk district and **b** amount of stormwater runoff per unit area (m³/km²) in Gangbuk district

km², and that of the GI scenario was 1,702.16 m³/km², resulting in a total stormwater runoff reduction amount of 471.31 m³/km² (Table S4).

The peak discharge reduction in Gangdong district was 6,101.26 m³, whereas that in Gangbuk district was 4,433.1 m³ and that in Dobong district was 4,375.02 m³ (Fig. 8b). The Gangdong district area had the highest peak discharge reduction, and that of Dobong district had the lowest. In the case of the peak discharge reduction per unit area, the Gangdong district value was 466.67 m³/km², that of Gangbuk district was 480.11 m³/km², and that of Dobong district was 471.31 m³/km² (Fig. 8c). Since the total Gangdong district area is larger than that of the other two regions, the amount of stormwater runoff reduction was the highest. Dobong district has a larger area than Gangbuk district, but its commercial area and transportation area are wider than those of Gangbuk district, although the residential area is smaller; hence, the stormwater runoff reduction amount was lower. For the peak discharge reduction per unit area, Gangbuk district presented the highest value, and Gangdong district had the lowest value. This is because Gangbuk district has a smaller industrial area, commercial area, and transportation area than the other two regions. In contrast, Gangdong district has a relatively large area where runoff occurs compared with the other two areas; hence, the total peak discharge reduction was the highest, but the peak discharge reduction per unit area was the lowest.

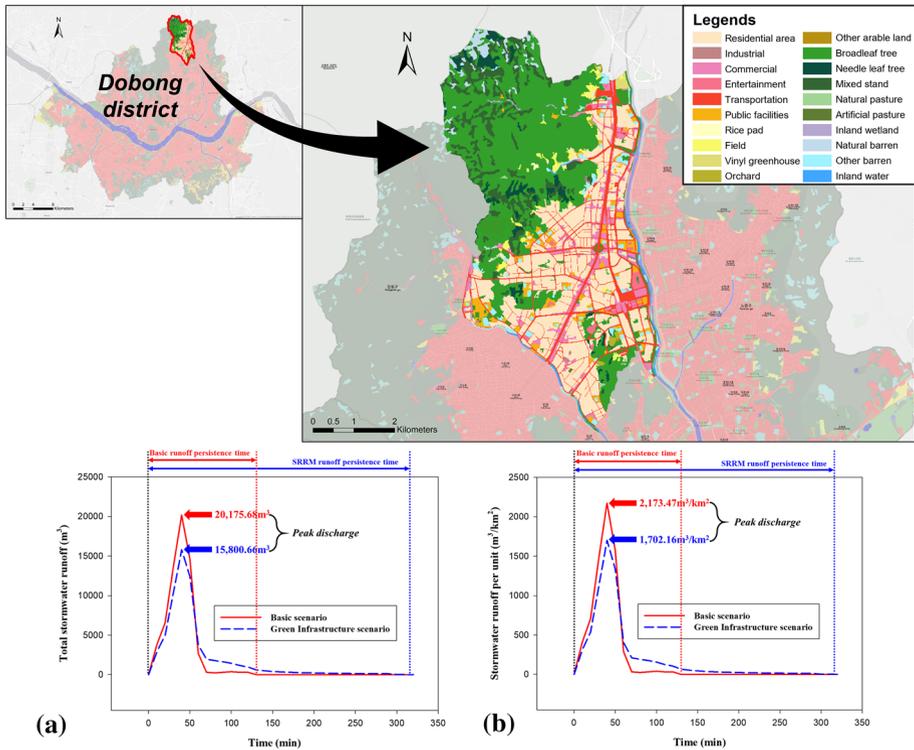


Fig. 7 **a** Total amount of stormwater runoff (m^3) in Dobong district and **b** amount of stormwater runoff per unit area (m^3/km^2) in Dobong district

4 Discussion

Based on the results analyzed in the previous section, this study aimed to suggest a plan to link green infrastructure through SRRM to the urban flood restoration policy currently planned in Seoul. Seoul city, including Gangdong district, Gangbuk district, and Dobong district, plans to construct disaster prevention infrastructure for flood-prone areas to enhance climate change adaptability (Kim et al. 2015). The present design aims to reduce peak floods through rainwater pumping stations and rainwater leakage reduction facilities, called gray infrastructure, to achieve this objective. This plan intends to install 45 rainwater reservoirs in Seoul and expand the storage capacity to 502,805 m^3 in 2021. However, there are no rainwater reservoirs in Gangbuk district and Dobong district. Therefore, it is necessary to expand green infrastructure in areas where gray infrastructure development may be reduced or delayed at a regional scale. Additionally, according to the comprehensive plan for creating a healthy water circulation city planned by the Seoul Metropolitan Government, we are trying to manage urban floods by introducing measures such as expanding water-penetrating road pavement, improving rainwater-invasive sewerage, and introducing green rainwater infrastructure. However, the plan to introduce green rainwater infrastructure in Seoul is not defined; it is gradually expanding to public buildings after verifying the effect through monitoring. Since there are many gradual trends and introductions in public buildings following such

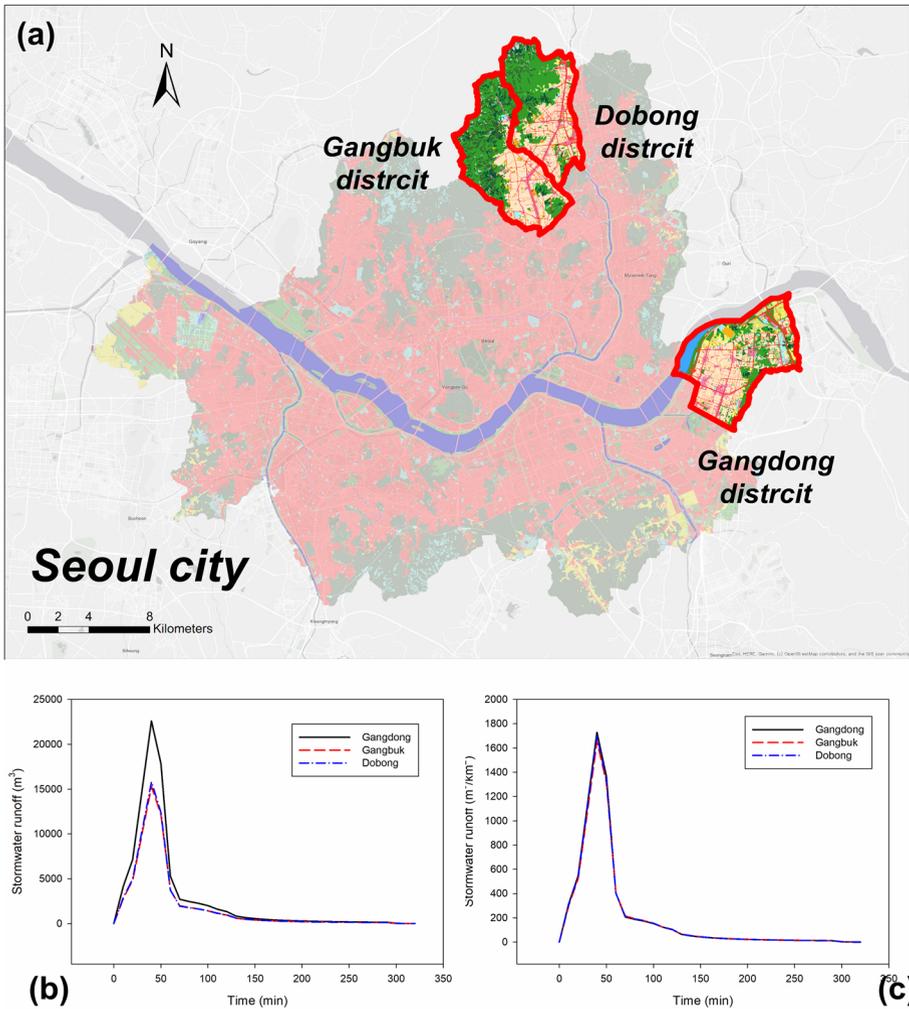


Fig. 8 a Comparison the target area in Seoul city about b the total amount of stormwater runoff (m^3) and (c) the amount of stormwater runoff per unit area (m^3/km^2)

plans, as presented in this study, concrete plans for each land-use should be established and presented for the district unit, as suggested in this study.

Seoul city aims to introduce green infrastructure by 2030 in the urbanized area where green areas are designated for expansion through the urban greening plan (Kim et al. 2015). Notably, the expansion of green spaces is urgently needed, and the central greening district that designates areas has recorded the plan. However, the areas of Gangdong district, Gangbuk district, and Dobong district are excluded. The design of a green roof project allows the expansion of the green area, aesthetic effect, and stormwater runoff. As of 2014, the green roof project for the entire city of Seoul had 661 locations, covering approximately $280,320 m^2$ (Kim et al. 2015). Gangdong district had a green roof area of $9,676 m^2$ in 25 locations as of July 2020. This is only 0.25% of the total artificial ground area of Gangdong district, as established in this study, compared to the biotope application

area (3.92 km²). As of September 2020, Gangbuk district constructed a green roof area of 5,742 m² in 17 locations. This corresponds to approximately 0.2% of the area applied with the biotope area ratio within the total artificial ground area of Gangbuk district. In the case of Dobong district, green roofs were built over an area of 5,075 m² in 16 locations as of September 2020. This is only approximately 0.18% of the total artificial ground area of Dobong district, as derived from this study, compared to the biotope application area (2.77 km²). Considering this, even if other green infrastructures that have been created but not disclosed are considered, the figure remains very low. Accordingly, green infrastructure expansion plans, including green roofs, are necessary.

The stormwater runoff reduction amounts in Gangdong district, Gangbuk district, and Dobong district, derived from the previous results, indicate the need for green infrastructure plans suitable for the region. The size of the area is ranked as Gangdong district (24.6 km²), Gangbuk district (23.6 km²), and Dobong district (20.7 km²). In the case of the artificial ground area, Gangdong district has 13.1 km², Gangbuk district has 9.2 km², and Dobong district has 9.3 km²; consequently, the area of artificial ground compared to the total area is 53% in Gangdong district, 39% in Gangbuk district, and 45% in Dobong district. Accordingly, the results of this study indicate that the peak discharge reduction was the greatest in Gangdong district. However, the peak discharge reduction per unit area was the highest in the Gangbuk district area because the areas with a high biotope area ratio (residential area, public facilities area) are larger than other areas (industrial area, commercial area, transportation area, etc.). In contrast, Gangdong district exhibited the highest total peak discharge reduction, but the peak discharge reduction per unit area was the lowest compared to other regions. This can be interpreted as the lowest peak discharge reduction per unit area because the areas with a low biotope area ratio (commercial area, transportation area) were extensive in the whole Gangdong district area. In Gangdong district, the ratio of areas is ranked as the residential area, transportation area, commercial area, and public facilities area; therefore, green roof construction for residential areas should be considered in addition to the construction of additional green infrastructure such as infiltration storage facilities and porous pavement in the transportation area and commercial area. In Gangbuk district, most of the residential areas are occupied, followed by transportation areas and commercial areas, so the construction of green roofs focused in residential areas needs to be considered first. The rankings of Dobong district are similar to those of Gangdong district; they are the transportation area, commercial area, and public facilities area next to residential areas. Therefore, green infrastructure plans such as infiltration storage facilities and porous pavement that can be constructed in transportation areas and commercial areas should be considered along with green roof construction in residential areas. In terms of runoff delay, as presented by the basic module results, delay effects of approximately 3 h and 10 min were common in the region. This means that the runoff delay did not differ based on region (Gangdong district, Gangbuk district, Dobong district), in contrast to the peak discharge amount. However, since the runoff reduction applied through the module to the artificial ground area in each region eventually appeared as delayed runoff in the basin unit, it can be concluded that the effect of the delayed runoff was shown at the city scale.

In this study, flood restoration was approached by engineering resilience. There are four characteristics of engineering resilience: robustness, redundancy, rapidity, and resourcefulness (Bruneau et al. 2003). The reduction in the peak discharge amount and delay effect in this study can be discussed as robustness and rapidity in the engineering resilience concept. Robustness is a level of system performance (Simonovic and Arunkumar 2016), a quantitative aspect that can be reduced against the disturbance of urban floods (Song et al. 2018).

Rapidity is a time difference in system performance (Simonovic and Arunkumar 2016), focusing on the temporal aspect of slowing the delay rate of runoff (Song et al. 2018). Therefore, the green infrastructure application plan using SRRM in this study can improve the restoration effect aspects of robustness (reduction in peak discharge) and rapidity (delayed effect of runoff) in response to urban floods.

5 Conclusions

In this study, we established flood vulnerability areas in Seoul city, a coastal city where damage is caused annually by heavy rains and typhoons. We also analyzed the effect of reducing stormwater runoff reduction using SRRM in the area. Based on these findings, we proposed green infrastructure plans in the discussion section for urban flood restoration. The results of this study are significant considering their application to the target area (district unit), which was obtained based on the results of flood vulnerability in Seoul by expanding spatially through SRRM based on the module developed at a small scale. However, this aspect necessitates further research considering that the result of the module was expanded to the urban unit, and the number of modules applicable to land use, the biotope area ratio, and the area were then determined. When the module is expanded to the city level, additional factors, such as weather factors affecting rainfall, vegetation in the module and evaporation from soil, should be accounted for in future research. It is also necessary to analyze the impact of runoff from cities adjacent to coastal areas on coastal ecosystems (ecological systems such as water quality and biodiversity). This module can be used for coastal urban policy based on expansion to the urban unit and the experimental results and predicted peak discharge amount as well as runoff delay for urban floods. By using SRRM to predict urban flood restoration, this module can assist with suggesting policy directions for establishing a green infrastructure plan in other coastal regions.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11069-022-05477-7>.

Acknowledgements This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2021R1A6A3A01087973). This work was also supported by the project entitled “Development of Advanced Science and Technology for Marine Environmental Impact Assessment” [grant number 20210427], funded by the Ministry of Oceans and Fisheries of Korea (MOF).

Authors’ contribution KS involved in conceptualization, model simulation, and writing—original draft. MK involved in investigation and writing—original draft. H-MK involved in stormwater runoff reduction module development and simulation model construction. E-KH involved in stormwater runoff reduction module development and visualization. JN involved in network analysis and writing—review and editing. JSK involved in validation and writing—review and editing. JC involved in supervision, writing—review and editing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2021R1A6A3A01087973). This research was also supported by OJEong Resilience Institute (OJERI).

Availability of data and material If it is needed, the data can be available.

Code availability If it is needed, the data can be available.

Declarations

Conflicts of interest There is no conflicts of interest or competing interests.

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