Modelling the Effects of Green Infrastructures on Water Quantity Under Different Rainfall Characteristics

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Abstract: Under the dual impacts of climate change and rapid urbanization, urban pluvial flooding disasters in China are increasingly serious, which cause huge economic losses and even serious casualties. Green infrastructure (GI), a kind of resilient measure, can control rainfall runoffs and improve water quality. Modelling the effects of GIs on controlling stormwater runoff under different rainfall characteristics plays an important role in planning and designing GIs that are adapted to both local conditions and future climate change. In this paper, we set nine rainfall scenarios with varying rainfall characteristics (intensity-duration-frequency, IDF) and then study the effects of the combined GIs on water quantity in the Jinan pilot area. The results show that GIs have good control effects on the inundation areas and runoff coefficients under rainfalls with small return periods. With the increases in return periods and rainfall intensities, the control effects of GIs on inundation areas decrease significantly. However, with the increases in rainfall intensities, the control effects on runoff coefficients are not that obvious. In addition, rainfall duration variations have little impact on reducing rates of controlling inundation areas and runoff coefficients.

1 INTRODUCTION

In the past few decades, China's urbanization construction has developed rapidly. By the end of 2020, the urbanization rate in China has increased from 17.9% in 1978 in the early stage of reform and opening up to more than 60% (NBS, 2021), followed by the increases in urban densities, changes in land use and increases of the rate of surface impermeability. However, the development of urban flood control and drainage systems lags behind the rate of urbanization, and rivers and lakes lose their ability to regulate and store water. In addition, short-term heavy rainfall events occur more frequently with climate change (Min et al., 2011). Therefore, under the dual pressures of urbanization developments and climate change, the urban flooding problems in China are increasingly severe. According to the *China Flood and Drought Disaster Bulletin*, since 2008, an average of 158 cities in China have experienced fluvial or pluvial flooding, most of which is caused by heavy rainfalls.

To simultaneously alleviate the urban flooding problems and solve water environmental and ecological problems, Sponge City Construction (SCC) has been put forward in China since 2013 (Li et al., 2017). A total of 30 national pilot cities have been chosen to construct sponge cities. The core concept of a sponge city is low impact development (LID) or in other words green infrastructure (GI). LID/GI is a kind of resilient practice, including grass swales, bioretentions, green roofs, vegetated filter strips, etc., to reduce negative impacts caused by urbanization (Ghodsi et al., 2016). GIs are designed to capture, hold, and permeate urban runoff (Elliott et al., 2007), and improve water quality. Previous studies have revealed that the GIs are effective in controlling water quantity under small to medium rainfalls (ATKINS, 2015; Yu et al., 2021). However, research on effects of GIs on water quantity under different rainfall characteristics, e.g., rainfall intensities and durations, are rarely studied. According to the latest report published by IPCC (IPCC, 2021), the frequency and intensity of heavy precipitation events have increased over the most land area since the 1950s. In recent years, several heavy rainfall events have caused serious economic loss and casualties, such as the "7.21" storm in Beijing, in 2012, and the "7.20" storm

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in Zhengzhou, in 2021. Hence, it is necessary to study the effects of GI on water quantity under different rainfall characteristics (intensity-duration-frequency, IDF), which will provide more practical experiences and technical support for the SCC under future climate changes.

Given the above considerations, the present study employed the Flood Risk Analysis Software (FRAS), independently developed by the China Institute of Water Resources and Hydropower Research, to model and analyse the effects of GIs on water quantity under different rainfall characteristics.

2 STUDY AREA

Jinan, one of the first batch of pilot SCC cities, is located in the east of China with an average annual rainfall of 672.8mm. Our study area is located in the main urban areas of Jinan with a total area of about 39km^2. The overall terrain of the study area is higher in the south, lower in the north, higher in the east, and lower in the west (see Figure 1 left). Rainstorms in the summer result in serious flood disasters. The eastern and southern regions are mountainous areas, and the central area is the piedmont slope. There are four small watersheds within the study area, including Guangchangxigou, Guangchangdonggou, Xingji River, and Shiliuli River (see Figure 1 right).

According to the *Implementation Plan of Sponge City Construction Pilot Project in Jinan, Shandong Province (2015-2017)* (hereinafter referred to as the implementation plan). Five kinds of GIs are designed within the study area: green roofs (0.26km^2), sunken greenbelt (0.31km^2), retained greenbelt (1.32km^2), intensified infiltration greenbelt (0.46km^2), and permeable pavement (0.18km^2) (see Figure 1 right).

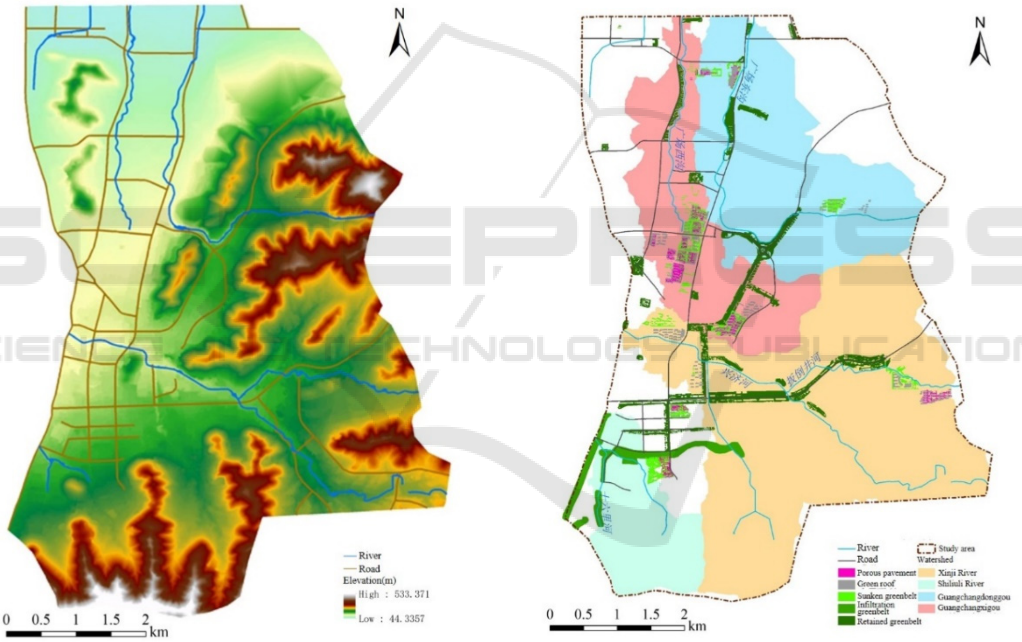

Figure 1: Topography (left) and distributions of GIs (right).

3 DATA AND METHODS

3.1 Data

The following basic geographic data is used for scenario modelling: 1:2000 DLG data and 1:1000000 soil data (1995). DLG data includes roads, residential areas, and land use data. The aforementioned data are adopting CGCS2000 coordinate system, Gauss Kruger projection, and the coordinate unit is a meter. The 1985 national elevation datum is adopted.

In addition, the following hydrological and meteorological data are also collected: the river systems and the main cross-section data, the monitoring precipitation data at Guishan, Xinglong, and other precipitation stations and hydrological stations, and the design storm data as well, including 5-year return period, 10-year return period and 20-year return period. Furthermore, data on drainage systems are also collected. At present, the drainage pipe network within the study area is designed according to the standard of 2-year or 3-year return period.

3.2 Rainfall Scenarios

3.2.1 Rainfall Frequency

In this study, the return period is used to represent the frequency. Three rainfall frequency scenarios (see Figure 2) based on typical rainfall processes are set for modelling: 5-year return period, 10-year return period and 20-year return period.

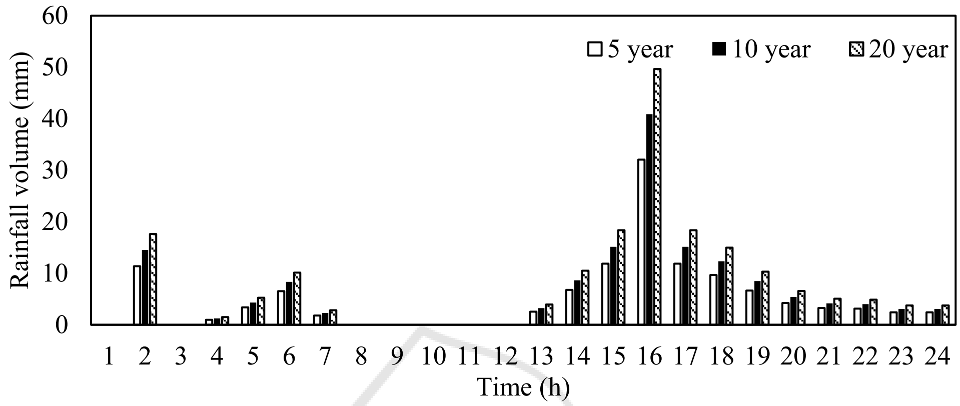

Figure 2: The 24h design rainfall process under three different rainfall frequency scenarios.

3.2.2 Rainfall Duration

According to the actual conditions of Jinan city, the inundation within the study area after rainfall events is usually drained within 3~6h. Based on the usual 5-year, 24-hour rainfall process in Jinan, we design three possible scenarios for rainfall duration. As the rainfall-runoff at the early stage (2~7h) is usually drained within the first 12h (see Figure 2). Therefore, we selected the last 12h continuous rainfall process with a rainfall volume of 96.84 mm (see Figure 2). The three rainfall duration scenarios are shown in Figure 3.

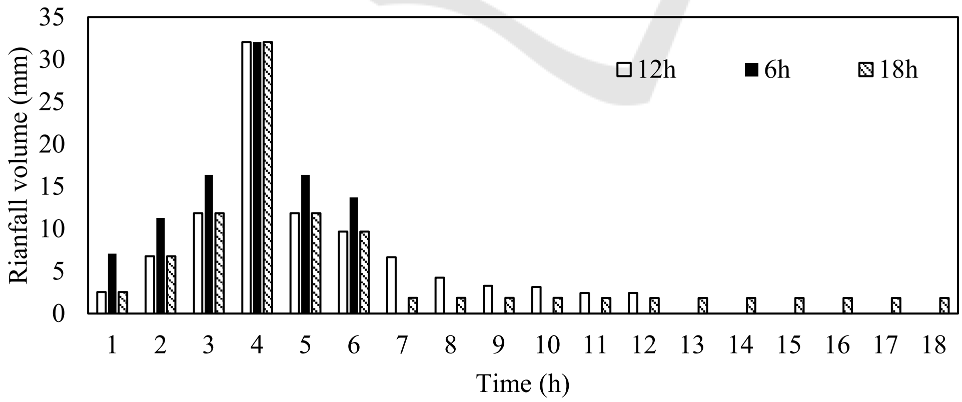

Figure 3: 24h design rainfall process under 3 different rainfall duration scenarios.

3.2.3 Rainfall Intensity

Based on the short-duration rainstorm intensity formula in Jinan (see equation 1), the design rainstorm intensity with different return periods is calculated.

$$i = \frac{35.0185(1+1.6868\lg T)}{(t+27.7543)^{0.9973}} \qquad (1)$$

Where i is rainfall intensity, mm/min, T is the return period, a, t is rainfall duration, min. The design rainfall intensity under different return periods is shown in Table 1.

Table 1: Design rainfall intensity.

Return period (a)	Duration (180min)	i (mm/min)
1	180	0.171
2	180	0.258
5	180	0.373
10	180	0.459
20	180	0.546
50	180	0.661
100	180	0.748
200	180	0.835

On "7.18", 2007 in Jinan, an extreme rainfall event caused huge economic loss and serious casualties. Hence, we select the heaviest 3h process (16:00-18:00) of the natural rainstorm at the rainfall station of the flood control office of Shizhong District on “7.18” as the typical rainfall process. The rainfall volume of 3h was 142.3mm. We set three different rainfall intensity scenarios (see Figure 4).

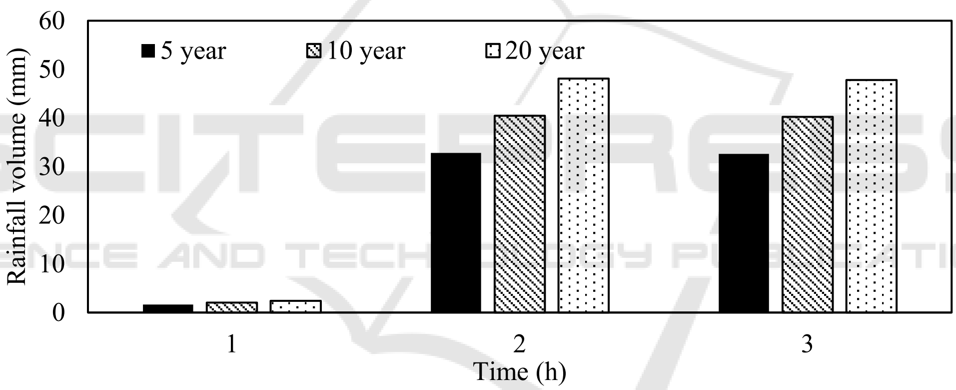

Figure 4: The 24h design rainfall process under three different rainfall intensity scenarios.

3.3 Hydro-Hydraulic Model

FRAS is used to simulate the inundation areas under different rainfall characteristics. FRAS is an integrated software that can simulate the whole flood process, mainly including 1D-2D coupling hydraulic model, hydrological model, and drainage model (Li et al., 2018). The hydraulic model can simulate the surface flow well, including flow simulations in wide or narrow rivers and the flow spreading along streets. In this software, the 1D hydraulic model is coupled with the 2D hydraulic model by calculating the flow exchanges between the passage and grids on both sides. The SCS-CN model is selected in this research to simulate the runoff production. In addition, the equivalent pipe network model is used to simulate underground drainage.

A total of 26659 irregular grids are divided with an average grid area of 1500m^2 (38m×38m). The rivers and roads are set as special passages. The roughness coefficients are set according to the soil types. Four kinds of GIs are modified by changing parameters, i.e., elevations, roughness, and values of CN (see table 2). Retained greenbelt is also considered an intensified infiltration greenbelt.

The calibration and validation details of the model can be found in our previous paper (Li et al., 2018), which is then not elaborated in this paper.

Table 2: Parameters used for GIs in the FRAS model.

Measures	Elevation	Roughness	Value of CN
Sunken greenbelt	Lower 20cm	0.06	61
Increased infiltration greenbelt	Unchanged	0.06	39
Porous pavement	Unchanged	0.035	66
Green roof	Unchanged	0.07	61

4 RESULTS AND DISCUSSION

4.1 Effects of GIs on Inundation Areas under Different Rainfall Characteristics

Table 3 and Figure 5 show the effects of the implementation of GIs on inundation areas under different rainfall characteristics. The results show that the inundation areas are reduced after the implementation of GIs under different rainfall frequency-duration-intensity, which suggests that GIs have control effects on reducing the inundation areas to some extent. In addition, GIs have the most obvious control effect under 5-year events. With the increases of rainfall volumes varying with the return periods, the control effects of inundation areas decrease. Moreover, with the increases of rainfall intensities, the reduction rate of controlling inundation areas decreases as well. Compared to the obvious impacts of rainfall return periods and intensity on the control effects, rainfall duration variations have little effect on the reduction rates of controlling inundation areas. The simulation results are consistent with the field observations conducted by Carpenter and Kaluvakolanu (2010) and Lewellyn et al. (2015). In fact, grey infrastructures play a more important role in controlling urban pluvial flooding. GIs can help grey infrastructures control rainfall runoff at the sources. Although the relatively weak control effects compared to grey infrastructures, GIs have more comprehensive benefits, such as improving surface water quality and enhancing public awareness on water security, which is very important in view of many water problems facing to urban areas (Yu et al., 2020).

Table 3: Effects on inundation areas under different rainfall characteristics.

No.	Rainfall characteristics	Scenarios	Inundation area (km^2)		Reduction (km^2)	Reduction ratio (%)
			Before	After		
1	Frequency	5 year	2.003	1.782	0.221	11.02
2		10 year	3.000	2.720	0.279	9.32
3		20 year	3.927	3.613	0.315	8.02
4	Duration	6h	1.823	1.588	0.235	12.89
5		12h	1.241	1.104	0.137	11.08
6		18h	1.303	1.114	0.189	14.47
7	Intensity	5 year	1.176	0.939	0.237	20.14
8		10 year	1.919	1.643	0.276	14.37
9		20 year	2.797	2.501	0.296	10.58

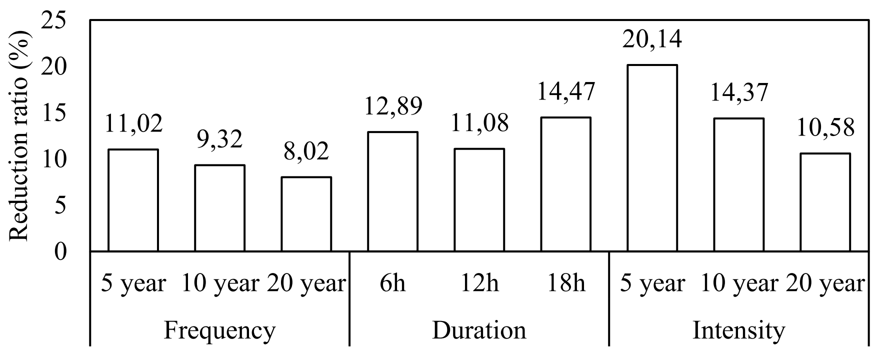

Figure 5: Reduction ratios of inundation areas under different rainfall characteristics.

4.2 Effects of GIs on Comprehensive Runoff Coefficients under Different Rainfall Characteristics

Table 4 and Figure 6 show the effects of GIs on runoff coefficient control under different rainfall characteristics. The results show that the runoff coefficients after the implementation of GIs are smaller than those before the implementation under different rainfall characteristic scenarios, which means that GI can control rainfall runoffs. In addition, with the increases of rainfall return periods, rainfall intensities and durations, the corresponding runoff control coefficients of GIs decrease. The simulation results are consistent with the field investigations conducted by Carpenter and Kaluvakolanu (2010). They found that the average runoff coefficient on green roofs is 0.044 under small rainfalls (<12.7 mm), 0.131 under middle rainfalls (12.7~25.4mm), and 0.591 under heavy rainfalls (>25.4mm), based on 21 rainfall events. According to the study of US EPA (2015), the LID and related measures can only reduce rainfall runoffs with 12.7~50.8 mm. With regard to rainfall intensity, the heavier the rainfall is, the more prone to generate runoffs. Lewellyn et al. (2015) found that the study area generated runoffs even though the total rainfall volume did not reach the design storage volume.

With the increases of rainfall return periods, the reduction ratios of control effects decrease obviously. The reduction ratios of control effects under 5-year and 20-year events are 10.148% and 6.611%, respectively. The simulation results are consistent with Yin et al. (2021), which found that the runoff control rate is 98.1% under a small rainfall (<10 mm), 73.8% under a middle rainfall (10~15 mm) and 52.9% under a heavy rainfall (>25 mm), respectively. However, compared to the obvious control effects on runoff coefficients with the increases of return periods, the reduction ratios of control effects are not that obvious with the increases of rainfall intensities and durations. Yin et al. (2021) also observed that the control effects of rainfall durations on control effects are not obvious.

Table 4: Effects on runoff coefficient under different rainfall characteristics.

No.	Rainfall characteristics	Scenarios	Runoff coefficient		Reduction ratio (%)
			Before	After	
1	Frequency	5 years	0.517	0.465	10.148
2		10 years	0.559	0.512	8.406
3		20 years	0.578	0.540	6.611
4	Duration	6h	0.372	0.323	13.364
5		12h	0.453	0.403	10.977
6		18h	0.460	0.409	11.135
7	Intensity	5 years	0.281	0.236	16.053
8		10 years	0.319	0.258	19.082
9		20 years	0.350	0.291	17.066

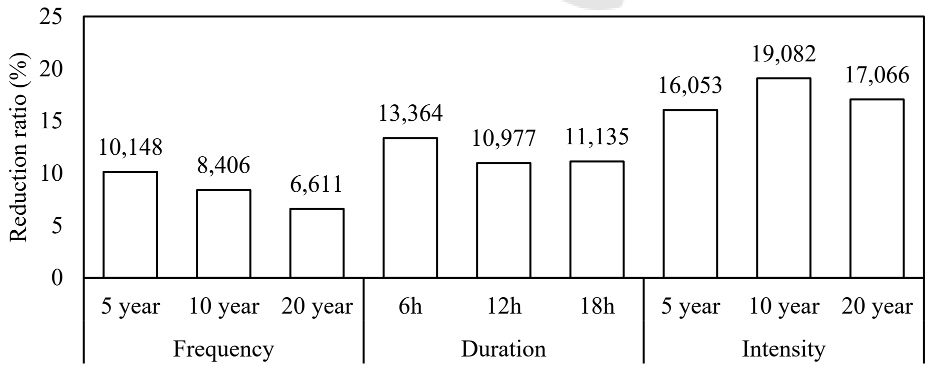

Figure 6: Reduction ratio of runoff coefficient under different rainfall characteristics.

5 CONCLUSIONS

Hydrological performances of combined GIs under nine rainfall scenarios are modeled using FRAS. The results showed that GIs have good control effects on water quantity in the study area under rainfalls with small return periods. As the rainfall volumes grow with the return periods, the control effects of GIs on inundation areas and runoff coefficients decrease significantly. In addition, with the increases in rainfall intensities, the control effects on inundation areas decrease obviously. However, the reduction ratios of GIs on controlling runoff coefficients are not that obvious with the increases in rainfall intensity. The rainfall duration variations have little impact on the reduction ratios of controlling rainfall runoffs.

GIs can design and accompany grey infrastructures, such as deep tunnels and drainage pipe networks, together to control rainfall runoffs effectively. In order to provide technical assistance for GIs to better adapt to climate change and improve urban resilience, more studies should be conducted to examine the control impacts of combined green and gray infrastructures on rainwater runoff under future climate change scenarios.

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