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Adapting green roofs to climate change: Insights from case studies across four typical climates in China

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ABSTRACT

As an effective measure for urban stormwater management, green roofs contribute to alleviating urban flood events and improving urban sustainability. To analyze the stormwater retention performance of green roofs and determine optimal designs under climate change conditions, this study used a hydrological model to evaluate their stormwater retention performance during 1970–2018 (49 years) and 2052–2100 (49 years) across four typical climates in China, including arid (Urumqi), semi-arid (Lanzhou), semi-humid (Beijing) and humid (Guangzhou) climates. Rainfall events in four cities were classified into non-extreme and extreme rainfall events using a percentile threshold method. The stormwater retention performance of green roofs was analyzed for long-term periods, non-extreme and extreme rainfall events. Results indicate that compared to 1970–2018, all four cities are projected to experience shortened antecedent dry periods, along with increased rainfall depth and frequency in 2052–2100. Under climate change conditions, the long-term stormwater retention rates (SRRs) of green roofs in the four cities are as follows: Urumqi (70.9–85.8 %) > Lanzhou (66.2–83.3 %) > Beijing (41.4–55.0 %) > Guangzhou (24.7–33.5 %). These findings demonstrate that green roofs can effectively retain rainfall under changing climate scenarios and perform better in arid and semi-arid climates than in semi-humid and humid climates. In future climate change projections, green roofs are effective at retaining non-extreme rainfall in all four climates, with SRRs exceeding 60 %. For extreme rainfall events, green roofs exhibit moderate SRRs (15.2–42.6 %) in arid and semi-arid climates but are less effective in semi-humid and humid climates (SRRs: 1.8–13.3 %). To achieve greater SRRs in the future, substrates with higher stormwater retention capacity are recommended for green roofs in arid, semi-arid and semi-humid climates, while high water-using plants and substrates with lower stormwater retention capacity are more suitable for humid climates. This study provides a comprehensive assessment of stormwater retention performance and offers a scientific basis for optimizing green roofs configurations across diverse climates under climate change conditions.

1. Introduction

Over recent decades, rapid urbanization has significantly expanded impermeable surfaces such as roads, parking lots and plazas [1]. This change disrupts rainwater infiltration and soil moisture evaporation, disturbs the urban hydrological cycle, and increases surface runoff [2–4]. Consequently, urban areas become more prone to pluvial flooding and non-point source pollution compared to natural landscapes [5]. Nature-based solutions are described as “actions to protect, sustainably manage and restore natural and modified ecosystems in way that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits” [6]. Implementing nature-based solutions in infrastructure is a practical strategy for mitigating flood risks and enhancing urban resilience [7]. Among these solutions, green roofs are widely adopted in urban areas as an effective measure for mitigating urban runoff [8–12]. As a nature-based solution,

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green roofs can be implemented at both large scales (e.g., communities and districts) and small scales (e.g., individual households), providing a holistic and flexible approach to flood risk management across multiple scales [13]. However, global climate change is anticipated to intensify in the coming decades, leading to more frequent and severe extreme rainfall events (e.g., intense rainfall) [14,15], which will further heighten the risk of urban flooding [16,17]. Therefore, assessing and quantifying the impact of future climate change on the stormwater retention performance of green roofs is crucial.

The stormwater retention performance of green roofs is affected by multiple factors. Several studies indicate that employing high water-using plants [18,19], substrate with high water-holding capacity [20, 21], deeper substrate [22] and storage layers [23–25] can improve the stormwater retention performance of green roofs. Although optimizing green roof configurations enhances stormwater retention performance, the stormwater volume retained by green roofs is primarily constrained by climatic characteristics [26]. This is because local rainfall and evapotranspiration predominantly impact changes in stormwater retention capacity (defined as the difference between the field capacity and substrate moisture content) of green roofs [22]. Under climate change conditions, rainfall frequency and depth, and antecedent dry period (the length of time without rainfall before a rainfall event) vary across climates [27,28]. To adapt to changing rainfall patterns under climate change, green roofs need to be properly designed to ensure long-term benefits in urban runoff mitigation [29,30]. Thus, assessing the long-term stormwater retention performance of green roofs under future climate change conditions is crucial for optimizing climate-resilient green roof designs.

Climate change has accelerated the global hydrological cycle, altering the spatiotemporal patterns of rainfall, runoff and evaporation. Some regions are projected to experience more frequent and intense extreme rainfall events, whereas others are projected to become increasingly arid [14,31]. The stormwater retention performance of green roofs under future non-extreme and extreme rainfall has been examined in previous studies, with most employing a design storm approach for simulations. Liu et al. [32] utilized the SWMM to simulate the stormwater retention performance of green roofs across return periods of storm events projected under SSP2–4.5 and SSP5–8.5 scenarios, assessing the impact of climate change on stormwater retention and peak flow attenuation. Liu et al. [33] applied a conceptual hydrological model to simulate the green roof hydrological processes in Dingxi City, Gansu Province of China, using design storm events with return periods of 10, 20, 50, and 100 years. Similarly, Zhang et al. [34] used the Hydrus-1D model to simulate the hydrologic performance of green roofs in Beijing under design storms with return periods of 3, 5, 10, 20, and 50 years. However, these studies neglected the long-term dynamic hydrological processes of green roofs in the context of climate change. Simulating long-term hydrological dynamics provides critical insights into the green roof hydrological cycle across diverse climate zones. These insights are essential for formulating optimized green roof configurations to adapt to climate change across various scenarios.

Based on the negative impact of climate change for urban environment, this study leveraged long-term historical climate data (1970 to 2018) and projected climate data (2052 to 2100), and quantitively analyzed the impact of climate change on the long-term stormwater retention performance of green roofs. Unlike previous studies, this research focuses on analyzing the long-term stormwater retention performance of green roofs under the combined impact of future non-extreme rainfall, extreme rainfall, and antecedent dry periods. Based on this, specific design directions for future green roofs in different climate zones are proposed. This study is expected to provide scientific reference of stormwater retention performance and configuration choose for future decision making and practicing on green roof construction.

2. Methodology

2.1. Study area

This study focuses on four representative cities from distinct climatic zones in China, i.e., Guangzhou, Guangdong Province (humid climate), Beijing (semi-humid climate), Lanzhou, Gansu Province (semi-arid climate), and Urumqi, Xinjiang Autonomous Region (arid climate) (Fig. 1). Daily meteorological data were obtained for the periods 1970–2018 and 2052–2100, encompassing precipitation, temperature, relative humidity, solar radiation, atmospheric pressure, and wind speed. The 1970–2018 data were sourced from the National Meteorological Science Data Center (http://data.cma.cn/), and the 2052–2100 data were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), as described in detail in Section 2.2.1.

2.2. Patterns of CMIP6 modeling results

The future meteorological data for this study were sourced from the downscaled CMIP6 NC dataset (1979–2100) for rainfall, temperature, and wind speed in China [35], which has been calibrated to accurately simulate China's climate. Historical data were utilized to evaluate the FGOALS-g3 model, developed by the Institute of Atmospheric Physics at the Chinese Academy of Sciences, for its ability to simulate rainfall and temperature. Meteorological data from CMIP6 before 2015 belong to the historical simulation phase, while data from 2015 onward represent the future scenario phase. This phase explores various potential future development pathways under different SSP scenarios. Therefore, NC datasets from two future climate scenarios (SSP2–4.5 and SSP5–8.5) generated by the FGOALS-g3 model were utilized. To evaluate the model's adaptability across various climates, Root Mean Square Error (*RMSE*) and Correlation Coefficient (*R*) were used to evaluate the performance of the FGOALS-g3 model [36,37], and the formulas are listed in Appendix A.

Python was employed in this study to extract daily rainfall, maximum, and minimum temperature data from meteorological NC files for stations in Urumqi, Lanzhou, Beijing, and Guangzhou, covering the periods 1979–2014 and 2052–2100.

The evaluated performance of the FGOALS-g3 model in simulating future climate by analyzing *RMSE* and *R* for daily mean extreme rainfall, annual mean rainfall, daily maximum temperature, and daily minimum temperature. Table 1 displays the *RMSE* and *R* comparing simulated and observed meteorological results from 1979 to 2014.

2.3. Screen extreme rainfall

Taking into account geographical locations and climate impacts [38], this study employed the percentile threshold method [39] to identify extreme rainfall events. This widely adopted method in extreme rainfall research addresses the limitations of selecting extreme events using fixed precipitation grades [40,41]. The 99th percentile of rainfall is used as the threshold for extreme rainfall events in various climatic zones. Extreme rainfall thresholds, derived from daily rainfall data spanning 1970–2018, were used to identify extreme rainfall events under the SSP2–4.5 and SSP5–8.5 scenarios for 2052–2100 across different climate conditions.

2.4. The simulation of stormwater retention performance

The conceptual hydrological model developed by Yan et al. [26] was used to simulate the stormwater retention performance of green roofs. This model is based on daily water balance theory and comprises three modules: the stormwater retention capacity of green roofs, evapotranspiration (ET) from green roofs, and rainfall-runoff processes of green roofs. The model considers both the replenishment of substrate moisture during rainfall events and the depletion of substrate moisture

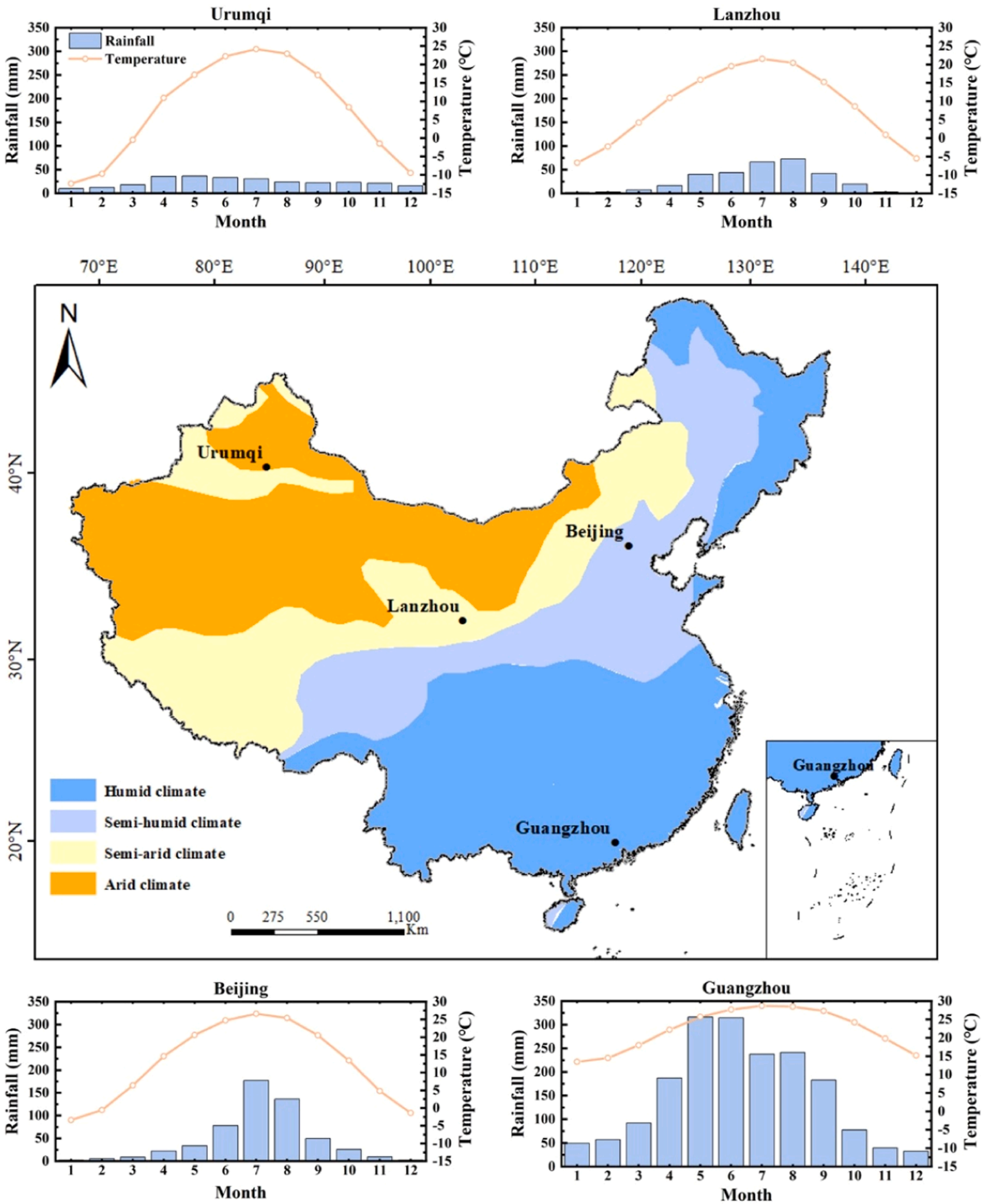

Fig. 1. Location map of the study areas and the climate statistics.

Table 1
RMSE and *R* between the simulated meteorological values by the FGOALS-g3 model and the observed values from 1979 to 2014.

Meteorological elements	*RSME*	*R*
Daily mean extreme rainfall (mm)	10.362	0.995
Annual mean rainfall (mm)	34.751	0.999
Daily maximum temperature (°C)	0.537	0.996
Daily minimum temperature (°C)	0.258	1.000

through ET.

The stormwater retention capacity of green roofs is primarily determined by the vegetation interception capacity and the substrate stormwater retention capacity.

$$S_t = S_v + (\theta_f - \theta_{t-1})h \tag{3}$$

where S_t is the stormwater retention capacity of green roofs at t day (mm); S_v is the vegetation interception capacity (mm); θ_f is the field capacity of the substrate ($cm^3 \cdot cm^{-3}$); $\theta_{t\text{-}1}$ is the substrate moisture content at the end of $t-1$ day ($cm^3 \cdot cm^{-3}$); h is the substrate depth of green roofs (mm).

The maximum retention capacity of a green roof system can be reached as the substrate moisture content decreases to the wilting point.

$$S_{\max} = S_v + (\theta_f - \theta_w)h \tag{4}$$

where $S_{\max}$ is the maximum stormwater retention capacity of green roofs (mm); θ_w is the wilting point moisture content of the substrate ($cm^3 \cdot cm^{-3}$).

The substrate moisture content can be calculated based on the water balance approach:

$$\theta_t = \begin{cases} \theta_f, P_t - AET_t \geq S_t \\ \dfrac{P_t - AET_t}{h} + \theta_{t-1}, AET_t - P_t \leq (\theta_{t-1} - \theta_w)h \\ \theta_w, AET_t - P_t > (\theta_{t-1} - \theta_w)h \end{cases} \tag{5}$$

where P_t is the depth of rainfall at t day (mm); AET_t is the actual ET at t day (mm), and relevant equations are listed in Appendix A.

The runoff generated from green roofs can be determined based on the water balance model.

$$R_t = \begin{cases} 0, P_t - AET_t \leq S_t \\ P_t - AET_t - S_t, P_t - AET_t > S_t \end{cases} \tag{8}$$

where R_t is the depth of runoff at t day (mm).

The stormwater retention rate (SRR) is calculated by:

$$SRR = \frac{P - R}{P} \times 100\% \tag{9}$$

This study summarized and used the types and parameters of green roofs in Table 2 for four climates, which were calibrated and verified in Yan et al. [26]. The green roofs include two types of vegetation (*Sedum lineare* and *Portulaca grandiflora*) and substrate (light growing medium and engineered soil). *S. lineare* and *P. grandiflora* are both commonly used in green roofs, with drought and cold resistance, as well as strong stress resistance. The light growing medium is mixed by pumice, peat soil, zeolite and sawdust (4: 3: 2: 1 by volume) and the engineered soil is mixed by light sandy loam, humus, perlite and vermiculite (2.5: 5: 2: 0.5 by volume). The green roof module in Yan et al. [26] is showed in Appendix A, Fig. A1.

The FAO-56 Penman-Monteith equation was utilized in this study as the evapotranspiration module in the green roof hydrological model. The historical meteorological data contains sufficient parameters to calculate the potential evapotranspiration using the FAO-56 Penman-Monteith equation. However, due to the challenges in obtaining extensive meteorological parameters required by the FAO-56 Penman-Monteith equation, the potential evapotranspiration for future green roofs was estimated using the Hargreaves equation [42]. To estimate the future potential evapotranspiration corresponding to the FAO-56 Penman-Monteith equation, this study used both the FAO-56 Penman--Monteith and Hargreaves equations to simulate potential evapotranspiration from 1970 to 2018, followed by a regression analysis to derive the regression model. Based on the future potential evapotranspiration calculated by the Hargreaves equation and the regression model, we obtained the future potential evapotranspiration corresponding to the FAO-56 Penman-Monteith equation, which were then compared with historical data for analysis.

3. Result

3.1. Climate characteristics under different periods

Fig. 2 and Fig. 3 illustrate changes in annual rainfall and temperature (1970–2018 and 2052–2100) and rainfall distribution across four cities, respectively. Rainfall statistics are summarized in Table 3. Compared to 1970–2018, climate change is projected to increase the distribution or peak values of annual rainfall (Fig. 2) and frequency of 0.01–10 mm rainfall events from 2052 to 2100 across four climates (Fig. 3). In Urumqi and Lanzhou, both historical and future annual rainfall depth are generally concentrated around 300 mm. In Beijing, historical annual rainfall centers around 500 mm, whereas future annual rainfall is projected to concentrate around 600 mm. In Guangzhou, both historical and future annual rainfall distributions are broader compared to the other cities. Additionally, future rainfall distributions under both scenarios exhibit significant increases compared to historical distributions (Fig. 2). This indicates an increase in both small non-extreme rainfall and large extreme rainfall (Fig. 3). Future annual rainfall will primarily concentrate between 1706.9 mm and 1836.5 mm in Guangzhou. Furthermore, future temperatures in all four cities are projected to rise, with a

Table 2
The configurations and parameters of simulated green roofs [26].

Type of Green roofs	Vegetation type	Substrate type	Substrate depth (mm)	Field capacity ($cm^3 \cdot cm^{-3}$)	Wilting point ($cm^3 \cdot cm^{-3}$)	Crop coefficient (-)	Vegetation interception capacity (mm)
100-LS	*Sedum lineare*	Light Growing Medium	100	0.22	0.08	0.45	1.60
100-LP	*Portulaca grandiflora*	Light Growing Medium	100	0.22	0.08	0.60	2.00
100-ES	*Sedum lineare*	Engineered Soil	100	0.39	0.10	0.45	1.60
100-EP	*Portulaca grandiflora*	Engineered Soil	100	0.39	0.10	0.60	2.00
150-LS	*Sedum lineare*	Light Growing Medium	150	0.22	0.08	0.45	1.60

Note: 100-LS means the green roof with 100 mm light growing medium and *S. lineare*. 100-LP means the green roof with 100 mm light growing medium and *P. grandiflora*. 100-ES means the green roof with 100 mm engineered soil and *S. lineare*. 100-EP means the green roof with 100 mm engineered soil and *P. grandiflora*. 150-LS means the green roof with 150 mm light growing medium and *S. lineare*.

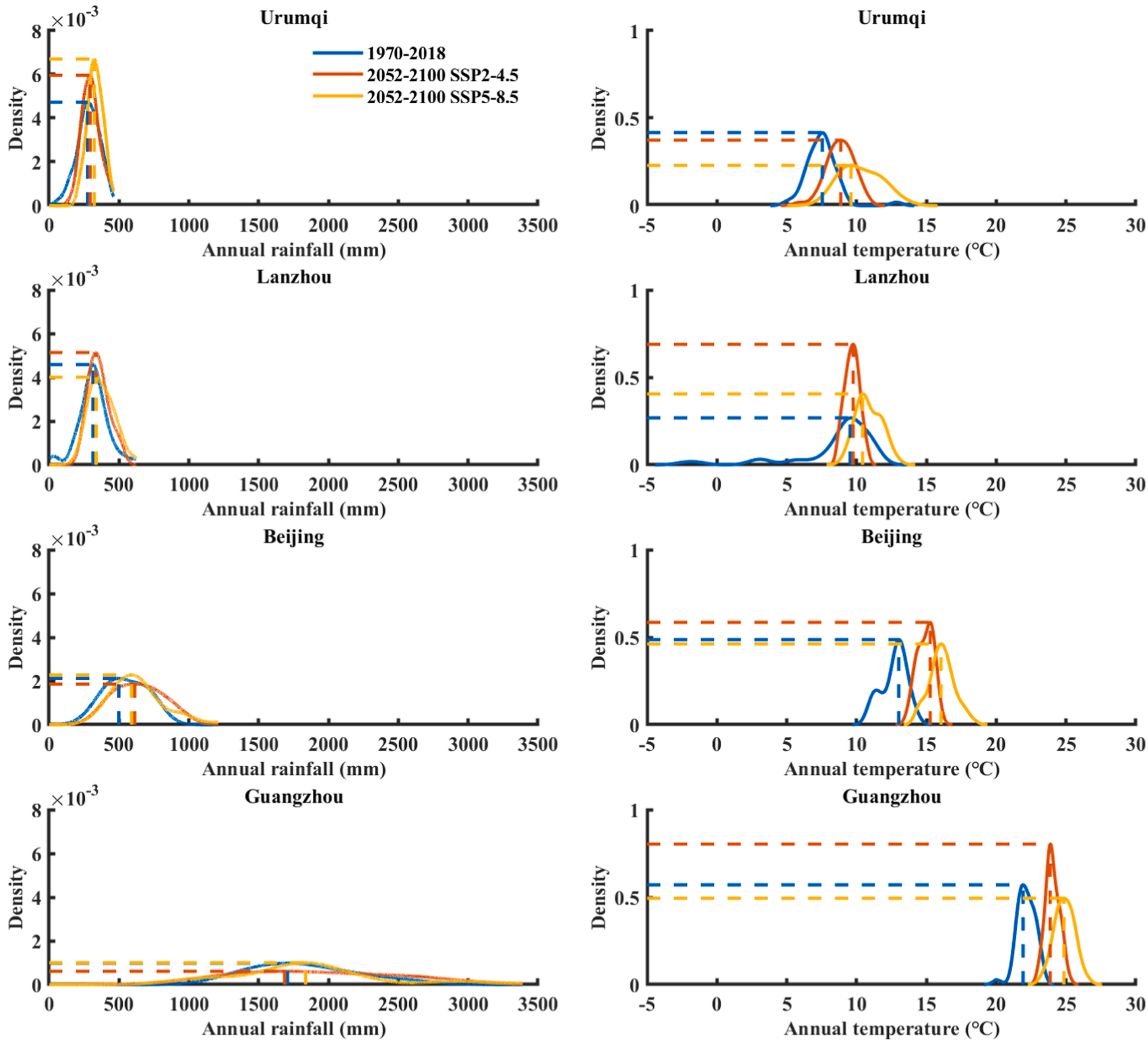

Fig. 2. The kernel density for rainfall and temperature of four cities in 1970–2018 and 2052–2100 with SSP2–4.5 and SSP5–8.5.

relatively narrow range of variation, indicating more frequent occurrences of high temperatures.

Climate change leads to increased rainfall depth and frequency while shortened antecedent dry periods. Table 3 indicates the extreme rainfall thresholds are 25.2 mm, 31.8 mm, 69.4 mm, and 97.8 mm for Urumqi, Lanzhou, Beijing, and Guangzhou, respectively. Between 1970–2018 and 2052–2100, the annual rainfall depth increased across all four cities. In Urumqi and Lanzhou, the increase in future rainfall depth is primarily associated with non-extreme rainfall events, with depths increased by 1790.9–3345.0 mm. Conversely, in Guangzhou, the increase is predominantly due to extreme rainfall events, which rose by 1670.7–4588.3 mm. The frequency and total depth of extreme rainfall are projected to decline in Urumqi from 1970–2018 to 2052–2100. However, the frequency and total depth of extreme rainfall show small differences between 1970–2018 and 2052–2100 in Lanzhou. In Beijing, the rainfall depth for both non-extreme and extreme rainfall is projected to increase. In Guangzhou, although the frequency of non-extreme rainfall increases, its depth is projected to slightly decrease. Table 4 summarizes the total, annual mean, longest and average antecedent dry periods for the four cities during 1970–2018 and 2052–2100. In all four cities, climate change shortens the antecedent dry periods under both SSP2–4.5 or SSP5–8.5 scenarios. This reduction is particularly significant in arid and semi-arid climates like Urumqi and Lanzhou, where annual mean antecedent dry periods decrease by 139.2–151.8 d·year^{-1} and 111.7–114.0 d·year^{-1}, respectively.

3.2. Stormwater retention performance of green roofs under climate change

Fig. 4 illustrates that, from 1970–2018 to 2052–2100, green roofs in arid climate (Urumqi: 70.9–85.7 %) exhibit higher long-term SRRs compared to those in semi-arid (Lanzhou: 66.2–83.3 %), semi-humid (Beijing: 41.4–55.0 %) and humid climates (Guangzhou: 24.7–33.5 %). Across the four climates, 100-LS and 150-LS consistently exhibit the poorest performance, whereas 100-EP achieves the best performance among the five types of green roofs.

In Urumqi, green roofs with engineered soil (100-EP and 100-ES) exhibit the best stormwater retention performance (SRRs: 85.8 % and

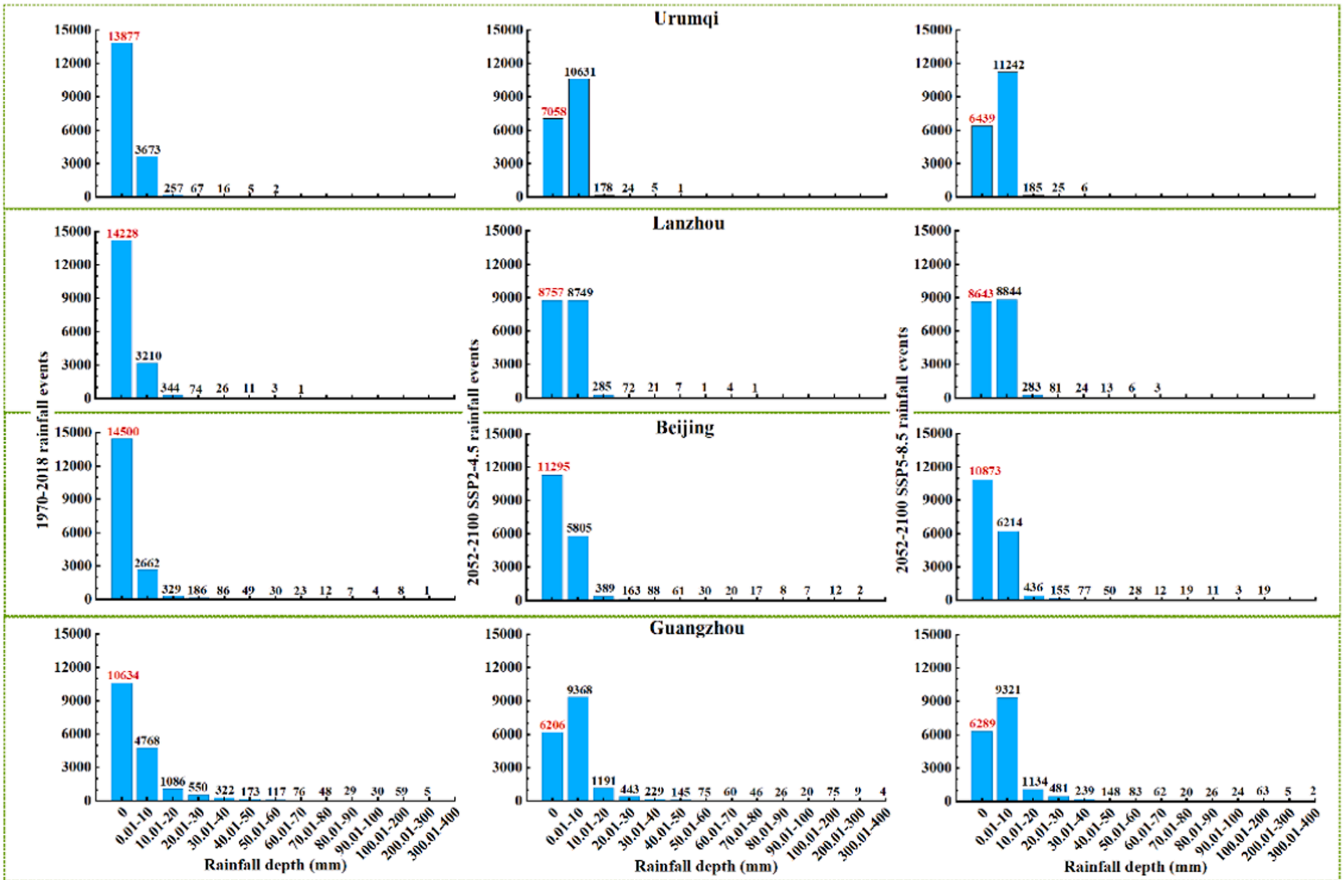

Fig. 3. The rainfall distribution histogram in 1970–2018 and 2052–2100 with SSP2–4.5 and SSP5–8.5.

80.0 %, respectively) from 1970 to 2018. However, from 2052 to 2100, the role of *P. grandiflora* in stormwater retention becomes more prominent, as 100-EP and 100-LP achieve the highest and second-highest SRRs. During 1970–2018, the low rainfall frequency in Urumqi resulted in prolonged mean antecedent dry periods (283.2 d·year^{-1}). Green roofs with engineered soil, offering a higher maximum stormwater retention capacity compared to light growing medium, can store more rainfall. Besides, compared to 2052–2100, they have long antecedent dry periods to recover the stormwater retention capacity in1970–2018 (Fig. 5). As a result, 100-EP and 100-ES have the highest and second-highest SRRs in 1970–2018. Due to water scarcity, the low maximum stormwater retention capacity of light growing medium and the high transpiration of *P. grandiflora*, the vegetation of 100-LP may often experience water stress. As future rainfall frequency and depth increase, water stress on vegetation is alleviated, and the AET of 100-LP increased. Additionally, *P. grandiflora*, a high water-using C4 photosynthetic plant, exhibits higher transpiration capacity than *S. lineare*, a low water-using Crassulacean acid metabolizing (CAM) plant. Consequently, the AET increase of 100-LP surpasses that of 100-ES (Fig. 5). This leads to faster restoration of stormwater retention capacity and higher SRRs for 100-LP compared to 100-ES.

In Lanzhou and Beijing, green roofs with 100 mm engineered soil (100-EP and 100-ES) consistently achieve the highest long-term SRRs during both 1970–2018 and 2052–2100. In Lanzhou, the SRRs of 100-EP and 100-ES range from 73.8 % to 83.3 %, while in Beijing, they vary between 47.4 % and 55.0 %. This indicates that substrate with a high maximum stormwater retention capacity is well-suited for future green roofs in Lanzhou and Beijing. Although rainfall frequency increases (Table 3), numerous antecedent dry periods exceeding 8000 days are still projected for the future (Table 4). Employing engineered soil can store more water and alleviate water stress on vegetation compared to light growing medium. Accordingly, 100-EP and 100-ES in Lanzhou and Beijing consistently exhibit the best stormwater retention performance among the five green roof configurations.

The green roofs with *P. grandiflora* (100-EP and 100-LP), a high water-using plant, achieve the highest long-term SRRs (29.3–33.5 %) among the five green roofs in Guangzhou during both 1970–2018 and 2052–2100. However, the SRRs of 100-LP increase more than 100-EP, narrowing the difference from 3.4 % (1970–2018) to 1.6 % (2051–2100) (Fig. 4). The frequency of non-extreme rainfall increases by over 4300 d from 1970–2018 to 2052–2100, and the average rainfall depth of non-extreme rainfall events decreases from 11.18 mm in 1970–2018 to 6.91 mm (SSP2–4.5) and 6.88 mm (SSP5–8.5) in 2052–2100 (Table 3). Additionally, the antecedent dry periods decrease from 10,634 d (1970–2018) to approximately 6200 d (2052–2100) (Table 4). This results in increased stormwater retained by green roofs and higher substrate moisture content (Fig. 5). In 1970–2018, due to the engineered soil retaining more water than light growing medium, 100-LP is more often to have low substrate moisture content than 100-EP (Fig. 5), and 100-EP has sufficient water for evapotranspiration. Hence, AET in 100-LP is primarily limited by available water, while in 100-EP it is mainly constrained by energy [43]. However, during 2052–2100, 100-LP has higher substrate moisture content compared to 1970–2018 (Fig. 4), reducing the water limitation on evapotranspiration. Therefore, the average AET of 100-LP increases in 2052–2100. For 100-EP, the increasing rainfall frequency reduces the energy input, leading to lower average AET, thereby maintaining consistently high average substrate moisture content (Fig. 4). The increased AET accelerates the recovery of stormwater retention capacity, resulting in a faster SRR increase for 100-LP compared to 100-EP under climate change conditions.

Table 3
Rainfall statistics in four typical cities of China.

City	Threshold of extreme rainfall (mm)	Annual rainfall depth (mm)			Frequency of non-extreme rainfall in entire period (d)			Total depth of non-extreme rainfall (mm)			Frequency of extreme rainfall in entire period (d)			Total depth of extreme rainfall (mm)		
		1970–2018	2052–2100		1970–2018	2052–2100		1970–2018	2052–2100		1970–2018	2052–2100		1970–2018	2052–2100	
			SSP2–4.5	SSP2–8.5		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5
Urumqi	25.2	287.7	306.7	337.4	3981	10,825	11,446	12,484	14,275.2	15,829.3	39	14	12	1326.5	444.4	366.4
Lanzhou	31.8	323.9	363.5	386.0	3632	9113	9216	14,048	16,256.4	16,877.1	37	27	38	1499.6	1190.1	1649.5
Beijing	69.4	562.5	653.9	646.1	3363	6555	6972	23,804	26,711.1	26,097.4	34	47	52	3196.2	4674.2	4913.2
Guangzhou	97.8	1865.4	1956.4	1879.3	7191	11,600	11,531	80,376	80,154	79,370	72	91	77	9164.3	13,753	10,835

Note: The data of 1970–2018 is based on historical record, and the data of 2052–2100 is based on CMIP6 model simulations.

3.3. *Stormwater retention performance of green roofs under non-extreme and extreme rainfall*

From 1970–2018 to 2052–2100, SRRs of green roofs for non-extreme rainfall increase across all four climates (Fig. 6a). This increase is attributed to the higher frequency of non-extreme rainfall, and the declined average depth of rainfall events (Table 3). Therefore, green roofs are able to retain more rainfall. For non-extreme rainfall, the mean SRRs of green roofs exceed 60 % in all four cities (Fig. 6a), demonstrating excellent performance in retaining non-extreme rainfall under future climate change conditions. During 1970–2018 and 2052–2100, 100-EP and 100-LP exhibit the highest and second-highest SRRs for non-extreme rainfall among the five green roofs across four climates. In Urumqi, Lanzhou and Beijing, SSRs of green roofs with various configurations exceed 80 % (Fig. 6a). However, SRRs of 100-EP and 100-LP are significantly higher than those of other green roofs in Guangzhou, with differences ranging from 2.6 % to 6.3 %. This is attributed to the significantly greater non-extreme rainfall depth in Guangzhou compared to the other three cities (Table 3). The total non-extreme rainfall depth in Guangzhou is approximately 80,000 mm. *P. grandiflora* can transpire faster, so green roofs with *P. grandiflora* can restore higher stormwater retention capacity for subsequent rainfall event than *S. lineare*.

Fig. 6b indicates that under climate change conditions, SRRs of green roofs for extreme rainfall generally decline across the four climates. This decline is attributed to the increased total rainfall frequency and depth, which reduces the stormwater retention capacity of green roofs (Fig. 4), limiting their stormwater retention performance for extreme rainfall under climate change. The mean SRRs of green roofs for extreme rainfall vary between 1.8 % and 56.9 % across the four cities. In comparison, green roofs perform moderately in arid and semi-arid climates (SRRs: 15.2–56.9 %) but perform poorly in semi-humid and humid climates (SRRs: 1.8–13.3 %). Between 1970–2018 and 2052–2100, 100-EP and 100-ES exhibit the best stormwater retention performance for extreme rainfall in Urumqi (33.4–56.9 %), Lanzhou (36.2–38.6 %) and Beijing (11.8–13.3 %). In Guangzhou, the stormwater retention performance of the green roof is the poorest among the four cities, primarily due to abundant extreme rainfall, with SRRs below 3.0 % in 2052–2100.

4. Discussion

4.1. *The stormwater retention performance of green roofs under climate change*

This study concludes that rainfall frequency and depth increase in four cities from 1970–2018 to 2052–2100 under climate change conditions, with annual rainfall showing a decreasing trend from the southeast coast to the northwest, consistent with findings by Zhou et al. [35] and Yang et al. [44]. Pan et al. [45] analyzed rainfall trends in Beijing from 2022 to 2121 and concluded that annual rainfall slightly increases, while rainfall frequency and extreme rainfall depth increase significantly. The findings are consistent with the trends observed in this study. Liu et al. [32] simulated rainfall under SSP2–4.5 and SSP5–8.5 scenarios in Guangdong-Hong Kong-Macao Greater Bay Area and found that the annual mean rainfall depth exceeds 1800 mm, aligning with the findings of this study. Furthermore, Ji et al. [46] projected that extreme rainfall will become more frequent in southern and eastern China, whereas the increasing will be less pronounced in northern and western regions. Consistent with these studies, this study finds that although the total rainfall depth increases across all four cities, extreme rainfall depth increases only in Beijing and Guangzhou, but it decreases in Urumqi and Lanzhou from 1970–2018 to 2052–2100.

In the future, green roofs will exhibit excellent stormwater retention performance in response to increasing rainfall, with SRRs ranging from 26.6 % to 85.7 % across four cities. Liu et al. [32] assessed the stormwater retention performance of green roofs for design storms with 1a,

Table 4
Antecedent dry periods in four cities.

City	Total antecedent dry periods (d)			Annual mean antecedent dry periods (d·year^{-1})			Longest continuous antecedent dry periods (d)			Average continuous antecedent dry periods (d)		
	1970–2018	2052–2100		1970–2018	2052–2100		1970–2018	2052–2100		1970–2018	2052–2100	
		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5		SSP2–4.5	SSP5–8.5
Urumqi	13,877	7058	6439	283.2	114	131.4	80	15	19	5.9	2.2	2.3
Lanzhou	14,228	8757	8643	290.4	178.7	176.4	164	48	35	6.8	2.8	2.8
Beijing	14,500	11,295	10,873	295.9	230.5	221.9	145	90	63	7.3	4.4	4.1
Guangzhou	10,634	6206	6289	217	126.7	128.3	58	41	59	4.5	3.9	4.1

Note: The data of 1970–2018 is based on historical record, and the data of 2052–2100 is based on CMIP6 model simulations.

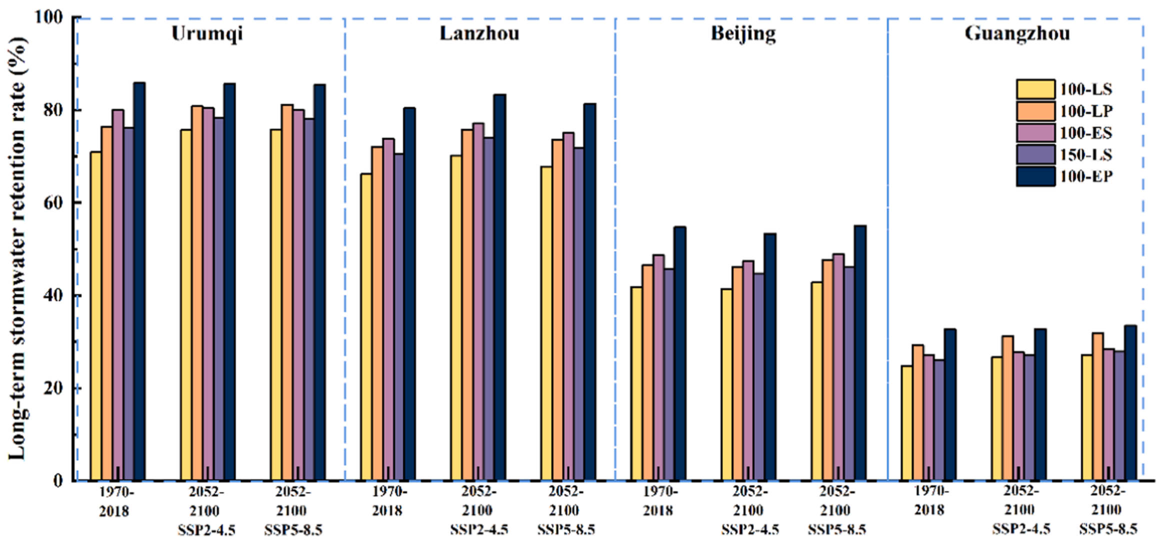

Fig. 4. The long-term stormwater retention rates of various green roofs in four cities.

2a, 10a, and 100a return periods under SSP2–4.5 and SSP5–8.5 scenarios in Lanzhou. The corresponding rainfall depths for these return periods are 14.3 mm, 20.0 mm, 33.3 mm, and 53.3 mm. The SRRs of green roofs vary from 59.5 % to 22.8 % for 1a, 2a, 10a, and 100a storms, demonstrating higher effectiveness in retaining storm events with 1a and 2a return periods. Additionally, SRRs of green roofs under SSP2–4.5 scenarios exceed those under SSP5–8.5 scenarios. The rainfall depth for the 10a return period is close to the extreme rainfall threshold for Lanzhou in this study (31.8 mm). Although the long-term periods used in this study distinct from the design storm method used by Liu et al. [32], both studies highlight that green roofs can mitigate rainfall amplification caused by climate change and exhibit higher SRRs for non-extreme rainfall.

4.2. The configuration selection of green roofs under climate change conditions

The SRRs of green roofs are impacted by multiple factors, such as the antecedent dry periods [47,48], rainfall depth [49], vegetation types [50,51], and substrate depth and types [34]. However, the effectiveness of configurations in enhancing stormwater retention performances is constrained by climate-specific limitations [26]. Hence, achieving large SRRs of green roofs under future climate change requires tailoring configurations of green roofs to the specific climate conditions of each city.

In the arid and semi-arid climates like Urumqi and Lanzhou, although the total antecedent dry periods decreasing from over 13,000 d to 6439–8757 d under the climate change conditions (Table 4), the annual rainfall depth remains low, ranging from 306.7 mm to 386.0 mm for SSP2–4.5 and SSP5–8.5 scenarios. In semi-humid climates like Beijing, the annual rainfall exceeds 600 mm in 2052–2100. However, total antecedent dry periods remain relatively long compared to Urumqi and Lanzhou, reaching 11,295 d under SSP2–4.5 and 10,873 d under SSP5–8.5 scenarios. Employing light growing medium may lead to insufficient water storage on green roofs, hindering vegetation growth. Therefore, substrates with high maximum stormwater retention capacity, such as engineered soil, are recommended for retaining more stormwater to support vegetation growth in arid, semi-arid and semi-humid climates. As shown in Fig. 3, green roofs with engineered soil exhibit excellent stormwater retention performance, regardless of whether low or high water-using plants are used. To maximize stormwater retention performance of green roofs, high water-using plants are preferable. Conversely, to minimize vegetation water stress during antecedent dry periods, low water-using plants are more suitable for green roofs.

In humid climates such as Guangzhou, green roofs with substrates of large maximum stormwater retention capacity and high water-using plants demonstrate optimal stormwater retention performance under future climate conditions. However, as indicated in Section 3.2, the SRRs for 100-LP increase more significantly than those of 100-EP under climate change, with their differences narrowing to approximately 1.6 % by 2052–2100. The ample annual rainfall (> 1800 mm) and high rainfall frequency (> 11,000 d) ensure that plants will not die due to water scarcity. Therefore, to minimize building load, employing substrates with lower maximum stormwater retention capacity and the high water-using plant is recommended for Guangzhou.

4.3. Limitations and prospects

The parameters of the hydrological model in this study were

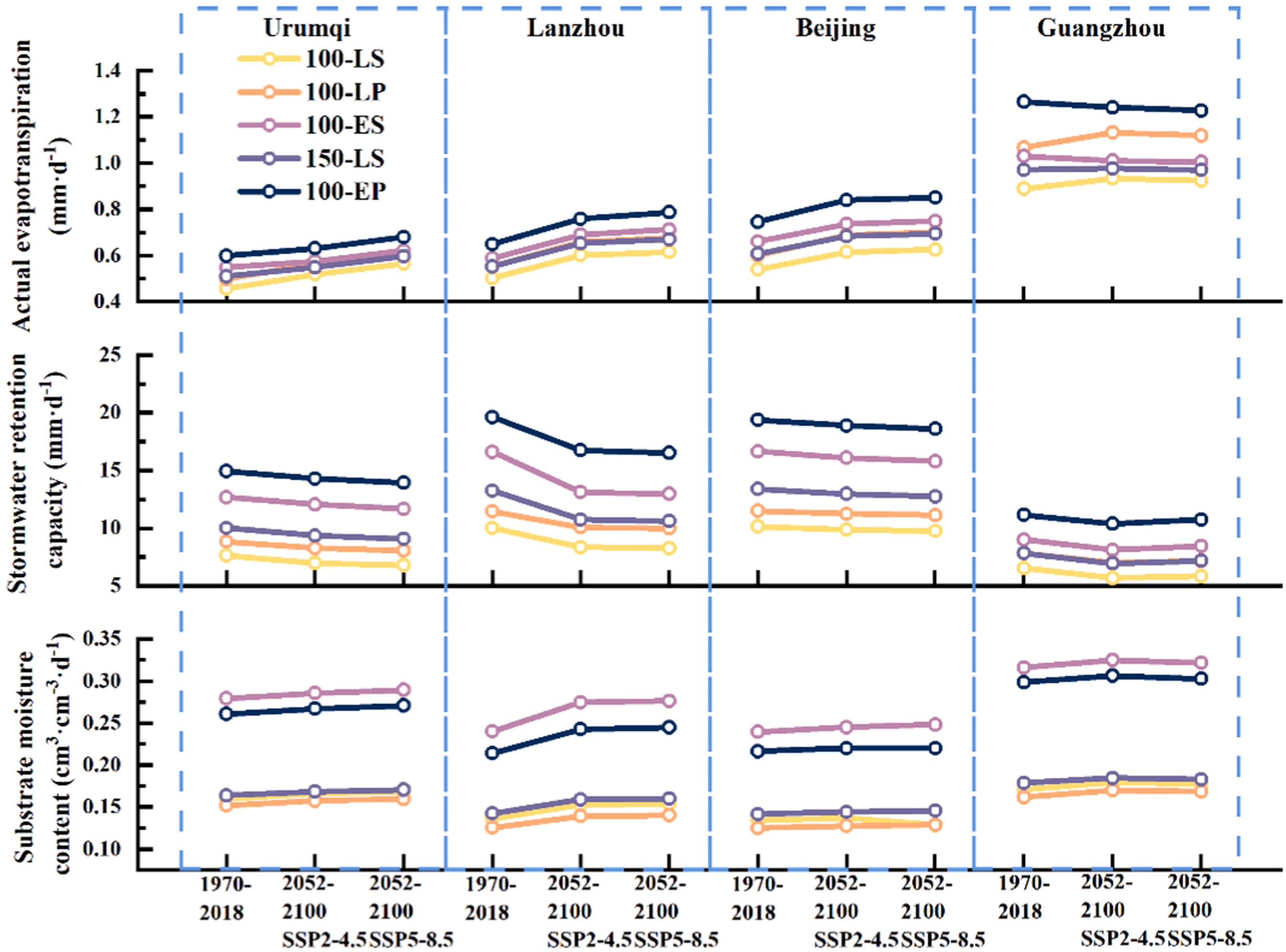

Fig. 5. Daily mean actual evapotranspiration, stormwater retention capacity and substrate moisture content of various green roofs at four cities.

calibrated and validated exclusively using data from experimental green roofs in Beijing [26]. Given climatic variations among cities, green roof parameters are likely to differ across locations. Future research should separately calibrate and validate the conceptual hydrological model using data from green roofs in multiple cities. This would improve the model's accuracy and applicability for simulating long-term stormwater retention performance of green roofs across diverse climatic zones. Moreover, the complexity and diversity of climate change drivers and the persistent uncertainties in future projections necessitate conducting uncertainty analyses on climate models. Such analyses can improve future climate predictability and reduce the uncertainties affecting assessments of green roof stormwater retention performance.

Despite advancements in resolution and physical parameterization of CMIP6 climate models, substantial uncertainties persist in predicting future climate change. Future efforts should prioritize advancing climate model research and development to improve accuracy and reliability. Additionally, intensified research and monitoring of climate change drivers are needed to better understand and predict climate change patterns [52]. Future studies should incorporate extreme rainfall indices and refine the definition of extreme rainfall events to improve simulation accuracy [53]. Furthermore, China's vast area and diverse climatic types, along with complex terrain and anthropogenic factors, complicate future rainfall predictions. This contributes to variations in the simulation results among different climate models. Therefore, employing a multi-model ensemble approach, integrated with data from multiple meteorological stations, could further improve the accuracy of climate predictions [55].

Traditional green roofs face limitations in managing extreme rainfall events, making it imperative to enhance their stormwater retention capacity. This can be achieved by adding a storage layer beneath the substrate layer of green roofs [23,54,56,57]. Integrating green roofs with other LID measures [58,59], such as permeable pavements, bio-retention cells, grassed swales, and infiltration trenches, can systematically address climate change impacts and enhance urban resilience [30,60].

5. Conclusion

This study simulated and analyzed the SRRs of various green roofs in 1970–2018 (49 years) and 2052–2100 (49 years) under SSP2–4.5 and SSP5–8.5 scenarios for Urumqi (arid climate), Lanzhou (semi-arid climate), Beijing (semi-humid climate), and Guangzhou (humid climate) by performing simulations from a conceptual hydrological model. The conclusions can be drawn as follows:

(1) Climate change is expected to increase rainfall depth and frequency and shorten antecedent dry periods in the future. Compared with 1970–2018, the rainfall distribution in 2052–2100 is projected to increase across four climates, particularly for the frequency of rainfall events of 0.01–10 mm. Between 1970–2018 and 2052–2100, the frequency of non-extreme rainfall is projected to increase by 3192–7465 d, while the annual mean antecedent dry periods are projected to decrease by

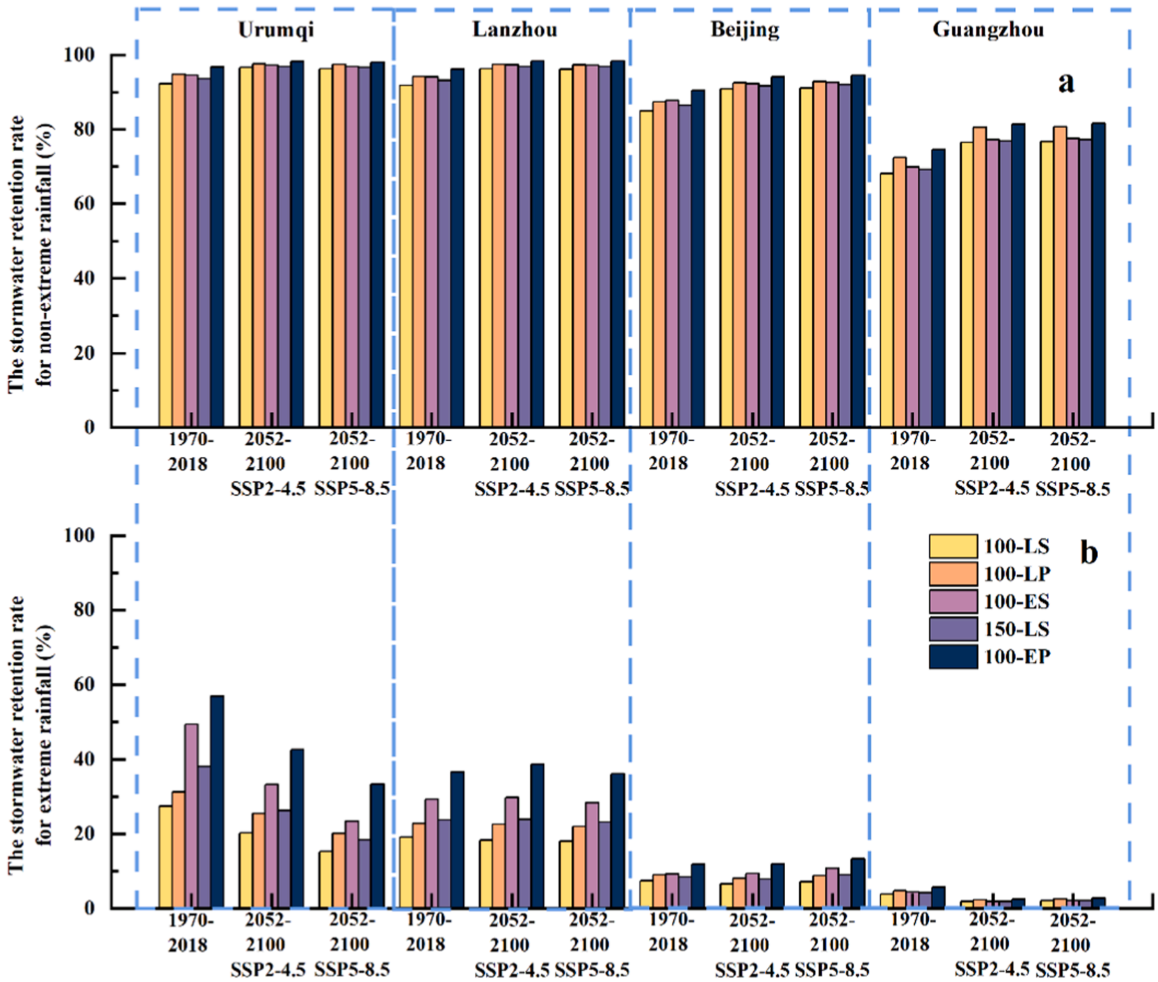

Fig. 6. The stormwater retention rates of green roofs for non-extreme and extreme rainfall at four cities.

65.4–151.8 d·year^{-1} across all four cities under SSP2–4.5 and SSP5–8.5 scenarios.

(2) The stormwater retention performance of green roofs under climate change conditions is influenced by local climatic characteristics. From 1970–2018 to 2052–2100, green roofs with various configurations in arid climate (e.g., Urumqi: 70.9–85.7 %) exhibit larger long-term SRRs compared to those in semi-arid (Lanzhou: 66.2–83.3 %), semi-humid (Beijing: 41.4–55.0 %) and humid climates (Guangzhou: 24.7–33.5 %). Across four climates, the 100-LS and 150-LS consistently perform poorest, while 100-EP demonstrates the best performance among the five types of green roofs. In the future, green roofs are expected to effectively retain non-extreme rainfall across all four climatic zones, achieving SSRs exceeding 60 %. For extreme rainfall events in the future, green roofs in arid and semi-arid climates exhibit moderate SRRs (15.2–42.6 %), but less effective in semi-humid and humid climates (1.8–13.3 %). Therefore, combining green roofs with other LID measures in urban planning and design is highly recommended to mitigate urban flooding under climate change conditions.

(3) Under climate change conditions, green roofs with various configurations demonstrate varying stormwater retention performance across climatic zones. In the future, although the 100-EP achieves the largest long-term SRRs across the four climates, the optimal green roof configuration should be tailored to local climatic conditions. Substrates like engineered soil with higher stormwater retention capacity are more suitable for green roofs in arid, semi-arid and semi-humid climates, such as Urumqi, Lanzhou and Beijing. In humid climates, such as Guangzhou, high water-using plants like *P. grandiflora* and substrate of low stormwater retention capacity like light growing medium are recommended for green roofs to improve the stormwater retention performance and minimizing building load.

CRediT authorship contribution statement

Jing Yan: Writing – original draft, Software, Methodology, Data curation. **Fan Zhang:** Writing – review & editing, Writing – original draft, Data curation. **Faith Ka Shun Chan:** Writing – original draft. **Liang Emlyn Yang:** Writing – original draft. **Yingying He:** Methodology, Data curation. **Shouhong Zhang:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.113477.

Data availability

Data will be made available on request.

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