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Research article

A framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate

Siyu Li [a], Yaoze Liu [a,*], Anh H. Nguyen [a], Zhuohang Wu [a], Mahmood Z. Al-Farsi [a], Tomi Choi [a], Liming Zhou [b], Younggu Her [c], Fawen Li [d], Dongyang Ren [e,f], Xiaobo Xue Romeiko [g]

[a] Department of Environmental and Sustainable Engineering, University at Albany, State University of New York, 1400 Washington Avenue, Albany, NY, 12222, USA
[b] Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, 1400 Washington Avenue, Albany, NY, 12222, USA
[c] Department of Agricultural and Biological Engineering & Tropical Research and Education Center, University of Florida, 18905 SW 280th St, Homestead, FL, 33031, USA
[d] State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation, Tianjin University, Tianjin, 300072, PR China
[e] Center for Agricultural Water Research, College of Water Resources & Civil Engineering, China Agricultural University, Beijing, 100083, PR China
[f] Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing, 100083, PR China
[g] Department of Environmental Health Sciences, University at Albany, State University of New York, 1 University Place, Rensselaer, NY, 12144, USA

A R T I C L E I N F O

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A B S T R A C T

Rainwater harvesting and reuse with rain barrels/cisterns holds substantial potentials to restore urban hydrology, improve water quality, and provide a resource for landscape irrigation under current and future climates. However, to assist decision-making, a systematic framework needs to be created to develop sustainable rainwater harvesting and reuse strategies for urban landscape irrigation considering their multi-functional impacts in a changing climate. This study created a novel framework for developing sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate with various components, including changes in climate parameters, baselines with/without rainwater harvesting/reuse, potential scenarios with rainwater harvesting/reuse, and identification of sustainable strategies using individual and combined indicators (discharge volume, peak discharge, combined sewer overflow—CSO, freshwater demand, and plant growth). The framework was demonstrated using the Soil and Water Assessment Tool with closed pipe drainage network (SWAT-CPDN) in the Brentwood watershed (Austin, Texas). Compared to the baselines (without rain barrels/cisterns), rainwater harvesting/reuse strategies with the most benefits under historical climate (2000–2014) and future climates (2080–2099 under two Shared Socioeconomic Pathways—SSP2-4.5 and SSP5-8.5) reduced discharge volume by 8.51 %–8.75 %, peak discharge by 4.83 %–5.28 %, CSO by 5.24 %–5.56 %, and freshwater demand by 22.91 %–24.93 %, while maintaining plant biomass. The most sustainable rainwater harvesting/reuse strategy needs to be obtained by evaluating their impacts on combined indicators with well-defined weighting factors and minimum/maximum criteria for individual indicators under each climate condition. The framework created in this study can guide decision-making for sustainable water management in future urban planning initiatives.

1. Introduction

Urbanization, which increases impervious surfaces, causes elevated stormwater runoff volume, heightened peak runoff, increased risk of flooding, more severe combined sewer overflow (CSO) problem, diminished recession time, impeded groundwater recharge and baseflow, and negatively impacted water quality (Li et al., 2019a; Tang et al., 2024; Xu et al., 2018). In addition, rapid urbanization leads to a surge in municipal water consumption (Luo et al., 2024). To mitigate the detrimental water quantity and quality impacts of urbanization, there has been a growing embrace of sustainable urban stormwater management through green infrastructure (GI) practices, e.g., rain barrels/cisterns, porous pavement, green roofs, and rain gardens (Liu et al., 2017a; Rinchumphu et al., 2024; Petreje et al., 2023).

Climate change is expected to have substantial impacts on urban water cycle through altering weather patterns that may cause prolonged

* Corresponding author.
E-mail address: yliu46@albany.edu (Y. Liu).

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flood risks, CSOs, or droughts (Allan et al., 2020; Mo et al., 2023; Zia et al., 2023). Increased rainfall and more intense storms can overwhelm urban drainage systems, causing more frequent flooding and CSOs. Conversely, some regions may experience reduced precipitation and higher temperature, resulting in prolonged droughts and increased evaporation rates, which deplete water sources. These changes can strain water supply, damage infrastructure, and affect urban ecosystems. To mitigate these impacts, cities need to invest in GI practices, promote water conservation, and develop integrated water management plans to ensure a sustainable and resilient water future under a changing climate.

Rain barrels, often in residential areas, and cisterns, typically in commercial or industrial settings, are popular GI practices that can assist urban hydrological and water quality restoration (Boongaling et al., 2024); in addition, rain barrels/cisterns, which can capture and store runoff from roof, provide a beneficial resource for irrigating landscapes and various non-drinking purposes—reducing municipal water usage that can alleviate local to global freshwater stress (Villarreal and Dixon, 2005; Jacque et al., 2023). The demand for irrigation water has been rising since the 1960s (Wada et al., 2011). Irrigation plays a crucial role in the urban water cycle (Johnson and Belitz, 2012), with residential irrigation being the highest water usage in urban areas (Mayer et al., 1999). Thus, rainwater harvesting/reuse for landscape irrigation with rain barrels/cisterns, which can assist urban hydrological/water quality restoration and provide a beneficial resource for irrigating landscape, holds significant potentials in urban areas under current and future climates.

Employing mathematical models to evaluate the performance of GI practices is vital for improving urban stormwater management planning (Liu et al., 2016a, 2018; Guo et al., 2021; Wang et al., 2023; Hou et al., 2023; Gulshad et al., 2024). A number of simulation models have been developed or applied that can evaluate the impacts of rain barrels/cisterns (Rossman, 2015; Liu et al., 2015a, 2015b, 2016b, 2016c, 2017b; Her et al., 2017). However, they only focused on one or a few aspects (e.g., a subset of discharge volume, peak discharge, and CSO) of the impacts of rainwater harvesting/reuse strategies, which cannot comprehensively support decision-making. For example, Steffen et al. (2013) quantified for 23 cities in the US in seven climatic regions about (a) water supply provided from rainwater harvested at a residential parcel using a water-balance approach for a range of rainwater cistern sizes, and (b) stormwater runoff reduction from a residential drainage catchment using the U.S. Environmental Protection Agency Storm Water Management Model (SWMM). The results showed that performance was affected by cistern size and climatic pattern. Jia et al. (2025) investigated the accuracy of the SWMM for modeling the impacts of rain barrels on long-term runoff capture efficiency when water is consumed only in dry periods using three methods, including the SWMM-LID method, a method representing a rain barrel as an equivalent subcatchment in SWMM (SWMM-SC) and a method using a self-coded simulation with water balance equations (Self-Coded Simulation). The SWMM-SC provided more accurate results than the SWMM-LID in Atlanta and Billings, US, indicating that SWMM's LID module for rain barrels may be improved to represent when water is only used during dry periods, or the method of SWMM-SC may be used. Ghodsi et al. (2023) used SWMM to optimally site rainwater harvesting cisterns for reducing CSOs in potential subcatchments of Buffalo, New York. Seven design storm events and a one-month historical rainfall time series were used. The results showed that the strategies obtained using event-based scenarios were less computationally expensive, but did not perform well for continuous rainfall scenarios.

In addition, most of the previous models are unable to fully capture the intricacies of rainwater harvesting/reuse for landscape irrigation with rain barrels/cisterns, such as the lack of plant growth and irrigation in the SWMM model (Rossman, 2015; Liu et al., 2015a, 2015b, 2016b, 2016c, 2017b; Her et al., 2017). Additionally, most large watersheds include both urban and agricultural regions. Effectively managing these varied land uses together is crucial for developing the most cost-efficient watershed management plans, but current computer models lack this capability (Rossman, 2015; Liu et al., 2015a, 2015b, 2016b, 2016c, 2017b; Her et al., 2017). Therefore, a simulation model that can (1) fully capture the intricacies of rainwater harvesting/reuse for landscape irrigation with rain barrels/cisterns, and (2) manage both urban and agricultural aspects needs to be used in decision support systems to support comprehensive decision-making.

Therefore, to assist decision-making: (1) a systematic framework needs to be created to develop sustainable rainwater harvesting and reuse strategies for urban landscape irrigation considering their multi-functional impacts (discharge volume, peak discharge, CSO, freshwater demand, and plant growth) in a changing climate; and (2) a hydrologic model, which has the strengths of fully representing the processes of urban hydrology and rainwater harvesting/reuse strategies, needs to be incorporated in the framework to demonstrate the use of the framework.

The objectives of the study were to: (1) create a novel framework for developing sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate with various components, including changes in climate parameters, baselines without rainwater harvesting/reuse or with existing rainwater harvesting/reuse, potential scenarios with rainwater harvesting/reuse, and identification of sustainable rainwater harvesting/reuse strategies using individual and combined indicators (discharge volume, peak discharge, CSO, freshwater demand, and plant growth); and (2) demonstrate the framework using a hydrologic model, which has the strengths of fully representing the processes of urban hydrology and rainwater harvesting/reuse strategies, to create sustainable rainwater harvesting/reuse strategies in a representative urban area facing significant water challenges under a changing climate. The novel framework created and the findings of the case study demonstrating the framework are expected to provide critical insights into sustainable rainwater harvesting and reuse strategies for urban water management under a changing climate, offering valuable guidance for developing adaptive strategies and informed decision-making in urban planning.

2. Development of a novel framework

A novel framework (Fig. 1) for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate was developed with various components, including changes in climate parameters, baselines without rainwater harvesting/reuse or with existing rainwater harvesting/reuse, potential scenarios with rainwater harvesting/reuse, and identification of sustainable rainwater harvesting/reuse strategies using individual and combined indicators. To create sustainable rainwater harvesting and reuse strategies for urban landscape irrigation considering their multi-functional impacts, various watershed-scale indicators are incorporated in the framework, including (1) urban stormwater (discharge volume, peak discharge, and CSO), (2) freshwater demand, and (3) plant growth (lawn management). Rainwater harvesting/reuse strategies, which are unique combinations of rain barrel/cistern sizes, percentages of suitable areas with rain barrels/cisterns implemented, auto landscape irrigation rates, and landscape irrigation starting times, are included in the framework to create sustainable rainwater harvesting and reuse strategies for urban landscape irrigation.

(1) **Changes in climate parameters.** Changes in climate parameters due to climate change would be compared for different SSPs over historical and future periods. These climate parameters include precipitation, temperature, solar radiation, relative humidity, and wind speed. Insights on how climate change would affect climate parameters, watershed-scale indicators for baselines (without rainwater harvesting/reuse or with existing rainwater harvesting/reuse), and watershed-scale indicators for potential scenarios with rainwater harvesting/reuse in a study area are

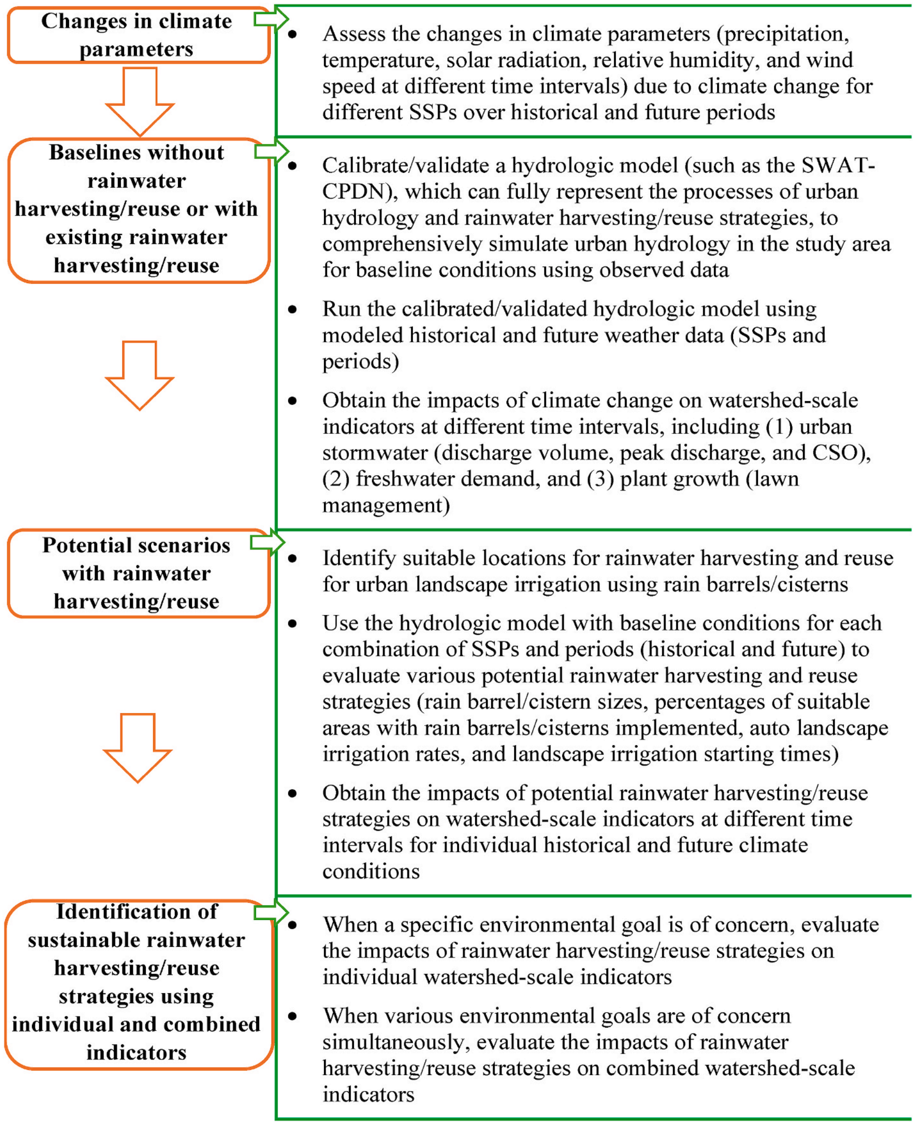

Fig. 1. A novel framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate.

aimed to be provided. To provide these insights, climate parameters in a changing climate can be analyzed using different methods as follows. (i) The ensemble mean of climate parameters for historical and future climates can be evaluated to provide long-term multi-year insights, including average annual precipitation, average annual mean of daily maximum temperature, average annual mean of daily minimum temperature, average annual mean of daily wind speed, average annual mean of daily relative humidity, and average annual mean of daily solar radiation. (ii) Climate parameters for historical and future climates (precipitation, temperature, solar radiation, relative humidity, and wind speed) can also be evaluated at daily, monthly, seasonal, and yearly intervals to provide daily to yearly insights. (iii) Precipitation pattens for historical and future climates can be evaluated for individual storm events considering storm event characteristics (starting time, depth, antecedent dry period, intensity, and duration) to provide short-term insights. All the climate parameters at different time intervals synergistically affect the performance of rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate.

(2) **Baselines without rainwater harvesting/reuse or with existing rainwater harvesting/reuse.** A hydrologic model, which can fully represent the processes of urban hydrology and rainwater harvesting/reuse strategies, would be calibrated/validated for comprehensively simulating urban hydrology in the study area for baseline conditions (without rainwater harvesting/reuse or with existing rainwater harvesting/reuse) using observed weather and hydrological data. The calibrated/validated hydrologic model would be run using modeled weather data for each combination of SSPs and periods (historical and future) to obtain the baseline discharge volume, peak discharge, CSO, freshwater demand, and plant growth for historical and future climate conditions. Discharge volume, peak discharge, CSO, and freshwater demand can be evaluated at the storm event, sub-daily, daily, monthly, seasonal, yearly, and/or average annual intervals to obtain the impacts of climate change on these watershed-scale indicators. And plant growth can be evaluated at the daily, monthly, seasonal, yearly, and/or average annual intervals to obtain the impacts of climate change on watershed-scale plant growth.

(3) **Potential scenarios with rainwater harvesting/reuse.** Suitable locations for rainwater harvesting and reuse for urban landscape irrigation using rain barrels/cisterns would be identified in the study area. The suitable locations for landscape

irrigation would be vegetated areas, and the suitable locations for implementing rain barrels/cisterns would be near rooftop areas that collect roof runoff. The hydrologic model with baseline conditions for each combination of SSPs and periods (historical and future) would be used to evaluate various rainwater harvesting and reuse strategies (rain barrel/cistern sizes, percentages of suitable areas with rain barrels/cisterns implemented, auto landscape irrigation rates, and landscape irrigation starting times), which are main factors affecting the performance of these strategies. The impacts of rainwater harvesting/reuse strategies on watershed-scale indicators would be obtained for individual historical and future climate conditions by comparing the discharge volume, peak discharge, CSO, freshwater demand, and plant growth of the baselines (without rainwater harvesting/reuse or with existing rainwater harvesting/reuse) to those of the potential scenarios with rainwater harvesting/reuse. Similar to the different time intervals of indicators that can be analyzed for baselines without rainwater harvesting/reuse or with existing rainwater harvesting/reuse, these indicators can be evaluated to obtain the impacts of potential rainwater harvesting/reuse strategies on watershed-scale indicators at different time intervals for individual historical and future climate conditions.

(4) **Identification of sustainable rainwater harvesting/reuse strategies using individual and combined indicators.** Sustainable rainwater harvesting/reuse strategies need to be identified using criteria that integrate the environmental goals of a study area. When a specific environmental goal is of concern, the impacts of rainwater harvesting/reuse strategies on a specific indicator (discharge volume, peak discharge, CSO, freshwater demand, or plant growth) can be evaluated under each climate condition. When various environmental goals are of concern simultaneously, the impacts of rainwater harvesting/reuse strategies on combined indicators can be evaluated under each climate condition. For each climate condition, the following equation can be used for identifying sustainable rainwater harvesting/reuse strategies using individual and combined indicators.

$$I\_RWHR = f1 \times R\_DV + f2 \times R\_PD + f3 \times R\_CSO + f4 \times R\_FD - f5 \times R\_PG \quad (1)$$

where I_RWHR is the impacts of a rainwater harvesting/reuse strategy; $f1$ to $f5$ represent the weighting factors for individual watershed-scale indicators, which can be determined based on the importance of each indicator in a project; and R_DV, R_PD, R_CSO, R_FD, and R_PG are the percent reductions in discharge volume, peak discharge, combined sewer overflow, freshwater demand (the ratio between the reduction in municipal freshwater usage due to rainwater harvesting/reuse and the baseline municipal freshwater usage without rainwater harvesting/reuse), and plant growth (rainwater harvesting/reuse strategies should have small or no negative impacts on plant growth), respectively, due to the rainwater harvesting/reuse strategy. To select sustainable rainwater harvesting/reuse strategies by comparing the values of I_RWHR, minimum or maximum criteria would be set for each environmental goal to represent minimum or maximum percent changes in individual watershed-scale indicators.

An example of watershed-scale indicators in the framework. As an example, the individual watershed-scale indicators of the long-term multi-functional impacts of rainwater harvesting for landscape irrigation with rain barrels/cisterns are in Table 1. These indicators can be used to evaluate baselines (without rainwater harvesting/reuse or with existing rainwater harvesting/reuse) and potential scenarios with rainwater harvesting/reuse for historical and future climate conditions.

An ideal hydrologic model that can be used in the framework. The Soil and Water Assessment Tool (SWAT), which has strong capacity to model hydrology and water quality in agricultural regions (Ren et al., 2022; Guo et al., 2022; Liu et al., 2017c, 2024; Wang et al., 2012), has been enhanced and applied to simulate urban areas and integrate GI practices (Glick et al., 2023; Her et al., 2017; Li et al., 2021, 2024; Seo et al., 2017). To assist in creating efficient strategies of rainwater harvesting/reuse for landscape irrigation with rain barrels/cisterns, the SWAT with closed pipe drainage network simulation (SWAT-CPDN) was created and demonstrated to better simulate the sub-daily and long-term processes in urban areas (Li et al., 2021, 2024), including closed pipe drainage network (simulation of conduit links, junctions, and flow divider nodes), rain barrels/cisterns (sizes, suitable areas implemented, harvested water reuse, and bypass flow redistribution), auto landscape irrigation (irrigation starting/ending criteria, irrigation rates, and suitable areas for irrigation), soil profile (improved infiltration equation, soil moisture changes, and sub-daily time steps), initial abstraction (sub-daily time steps), evapotranspiration (sub-daily time steps), lawn management operation (mowing criteria according to grass heights), pervious area, and impervious area (directly/indirectly connected impervious areas and roof runoff). With the strengths of fully representing the processes of urban hydrology and rainwater harvesting/reuse strategies, the SWAT-CPDN serves as an ideal hydrologic model to be used in the framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate with multi-functional indicators of discharge volume, peak discharge, CSO, freshwater demand, and plant growth.

Table 1
The individual watershed-scale indicators of the long-term multi-functional impacts of rainwater harvesting for landscape irrigation with rain barrels/cisterns. "AA_", "Av_", and "EM_" denote average annual, average, and ensemble mean, respectively.

Indicator names	Acronyms	Units
Ensemble mean of average annual discharge volume	EM_AA_DV	m^3
Percent reductions in ensemble mean of average annual discharge volume	EM_AA_DVR	%
Ensemble mean of average peak discharges	EM_Av_PD	m^3/hr
Percent reductions in ensemble mean of average peak discharges	EM_Av_PDR	%
Ensemble mean of average combined sewer overflows	EM_Av_CSO	m^3
Percent reductions in ensemble mean of average combined sewer overflows	EM_Av_CSOR	%
Ensemble mean of average annual municipal freshwater usages	EM_AA_MFWU	m^3
Percent reductions in ensemble mean of average annual municipal freshwater usages	EM_AA_MFWUR	%
Ensemble mean of average annual plant biomasses	EM_AA_PB	ton/ha
Percent reductions in ensemble mean of average annual plant biomasses	EM_AA_PBR	%

The novel framework created in this study can be applied to any urban watersheds to support decision-making. The above framework is dynamic and can be used as a guidance for creating other sustainable water management strategies under a changing climate with additional types of strategies and indicators. The following sections provide a demonstration of applying the framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate.

3. Case study—demonstration of the framework

3.1. Study area

The Brentwood watershed in Austin, Texas was chosen to demonstrate the application of the framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate (Fig. 2), due to its a representative urban watershed facing significant water challenges, such as urbanization, climate change, flooding, CSOs, and drought (City of Austin, 2024; Austin Texas

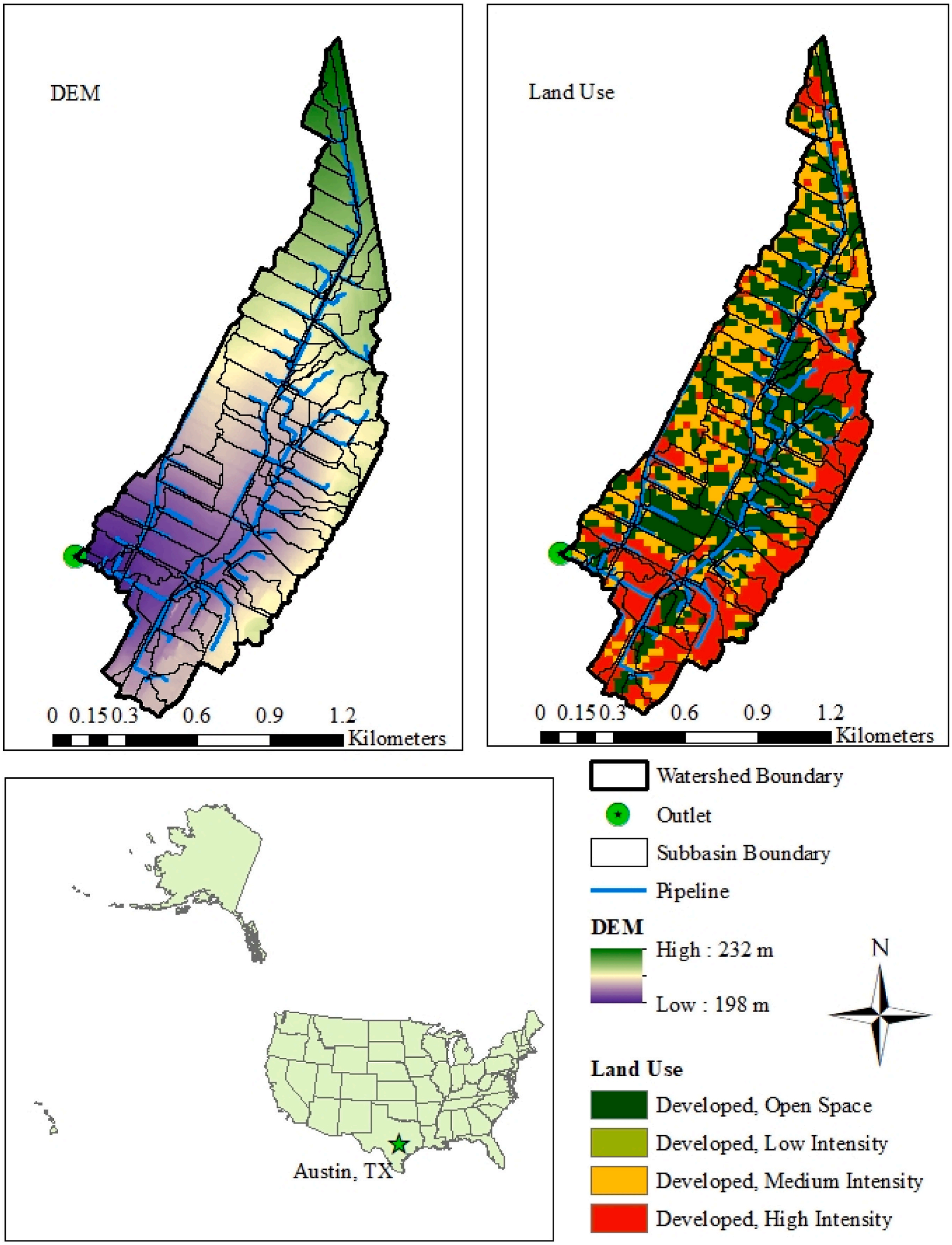

Fig. 2. The Brentwood watershed in Austin, Texas.

flooding; Koehler and Koch, 2019). The area of the watershed is 149.8 ha, with land uses of open space (45 %), low intensity (28 %), medium intensity (11 %), and high intensity (16 %) (Homer et al., 2015).

3.2. Data availability

3.2.1. Observed data for setting up and calibrating/validating SWAT-CPDN

The City of Austin supplied the observed data for 15-min intervals of streamflow and precipitation, daily temperature, and Digital Elevation Model (DEM) data with a resolution of 0.6 m. The details regarding land cover and imperviousness were extracted from the National Land Cover

Database (NLCD) 2011 (Homer et al., 2015). The data of soil properties and building footprints were obtained from the Soil Survey Geographic Database (SSURGO) (United States Department of Agriculture, 2015) and Official City of Austin Open Data Portal (City of Austin, 2013), respectively.

3.2.2. Climate change data

Climate change data were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). Five climate models were chosen, including Euro-Mediterranean Centre on Climate Change Earth System Model Version 2 (CMCC-ESM2) (Lovato et al., 2022), Institut Pierre-Simon Laplace Climate Model Version 6A-LR (IPSL-CM6A-LR) (Boucher et al., 2020), Max Planck Institute Earth System Model Version 1.2-HR (MPI-ESM1.2-HR) (Müller et al., 2018), Max Planck Institute Earth System Model Version 1.2-LR (MPI-ESM1.2-LR) (Mauritsen et al., 2019), and Meteorological Research Institute Earth System Model Version 2.0 (MRI-ESM2.0) (Yukimoto et al., 2019). For each of the five climate models, the climate data (3-h precipitation, daily maximum/minimum temperature, daily solar radiation, daily relative humidity, and daily wind speed) in the study area for historical simulations (2000–2014) and future climates (end of the century [2080–2099] with two Shared Socioeconomic Pathways—SSP2-4.5 and SSP5-8.5]) were accessed through the Earth System Grid Federation (ESGF) website (Earth System Grid Federation). Among the ensemble members, only the first member r1i1p1f1 (indicating the indices for realization, initialization, physics, and forcing) from each model was selected as done in many studies (CMIP).

Observed data of 3-h precipitation, daily maximum/minimum temperature, daily solar radiation, daily relative humidity, and daily wind speed (2000–2014) were obtained from Climate Data Online (City of Austin, 2024) for applying bias correction. Precipitation data were converted from 3-h to 15-min intervals (Zhang et al., 2020). Bias correction using the quantile mapping method (Cannon et al., 2015) was applied to the climate data based on the observed weather data and corresponding CMIP6 historical simulations.

3.3. SWAT-CPDN model setup and calibration/validation

The Brentwood watershed was segmented into 137 subbasins using a stream threshold of 5 % of watershed area. The slopes were categorized into three groups: 0–1.5 %, 1.5–3 %, and over 3 %. Hydrologic Response Units (HRUs) were established with the criteria of 0 % for land use, soil, and slope, which was done to account for all potential combinations. The configuration of closed pipe drainage network was established by Drainage Criteria Manual (DeWitt County Drainage District No. 1, 2019). Rooftop areas were determined based on building's footprint. The proportion of directly connected impervious area to mean total impervious area for each land use category was determined (Sutherland, 2000). Lawn was regularly managed (Li et al., 2021).

The observed weather data were used to set up SWAT-CPDN for calibration/validation. The sensitive parameters utilized for calibrating (03/2012 to 02/2013) and validating (03/2013 to 12/2014) watershed-scale discharges (15-min, daily, and monthly) modeled by SWAT-CPDN under current condition without rain barrels/cisterns are in Table S.1 (supplementary material) (Her et al., 2017; Li et al., 2021, 2024; Liu et al., 2019a, 2019b). A warm-up period (01/2010 to 02/2012) was incorporated to stabilize the initial conditions of SWAT-CPDN. A group of parameters was obtained with a multi-objective calibration/validation approach using AMALGAM (A Multi-Algorithm Genetically Adaptive Multiobjective) optimization method (Vrugt and Robinson, 2007) to simultaneously maximize coefficient of determination (R^2), maximize Nash-Sutcliffe efficiency (NSE) coefficient, and minimize the absolute value of Percent Bias (PBIAS).

3.4. Evaluation of baselines and potential scenarios to identify sustainable strategies

The novel framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate was applied to comprehensively and simultaneously evaluate multi-dimensional aspects of rainwater harvesting/reuse strategies under a changing climate. The climate change data (historical simulations and future climates) after bias correction were used to set up the calibrated/validated SWAT-CPDN. Various scenarios (Table 2) were evaluated for each set of climate change data, including baseline (auto landscape irrigation with a rate of 5.08 mm/h and starting time at 6 a.m. without rain barrels/cisterns, which represented typical landscape irrigation practices in the study area), 1a-1d (sizes of rain barrels/cisterns), 2a-2d (percentages of rooftops with rain barrels/cisterns), 3a-3d (auto landscape irrigation rates), and 4a-4d (auto landscape irrigation starting times). Common parameter values across scenarios were highlighted. Detailed justifications of the scenarios were in previous publications (Li et al., 2021, 2024).

These scenarios were evaluated using the watershed-scale indicators of the long-term multi-functional impacts of rainwater harvesting for landscape irrigation with rain barrels/cisterns (Table 1). Sustainable rainwater harvesting/reuse strategies were identified using Equation (1) for individual and combined indicators (Table 3) to demonstrate the possible application and insights of the framework. Other weighting factors can be used depending on the importance of each indicator in a project. When evaluating the impacts on peak discharges, all storm events that resulted in peak discharges above 0.63 m^3/s at the watershed outlet under individual historical and future climates were chosen. When assessing the impacts on CSOs, all storm events that resulted in discharge volume above 1250 m^3 at the watershed outlet (assuming these storm events caused CSOs) under individual historical and future climates were chosen. In addition, when using combined indicators to identify sustainable rainwater harvesting/reuse strategies, minimum or maximum criteria were set for individual environmental goals, including a minimum of 4 % for EM_AA_DVR, a minimum of 2 % for EM_Av_PDR, a minimum of 2 % for EM_Av_CSOR, a minimum of 3 % for EM_AA_MFWUR, and a maximum of 0 % for EM_AA_PBR.

4. Results and discussion

4.1. Results of calibrating/validating SWAT-CPDN

The results of parameters after calibration and validation are in Table S.1 (supplementary material). Prior research (Engel et al., 2007; Moriasi et al., 2007) demonstrated that when comparing monthly simulated and observed flow results, a very good model performance is achieved if $R^2 \geq 0.75$, NSE ≥ 0.75, and $|\text{PBIAS}| \leq 10$ %. Because model performance tends to deteriorate when simulating shorter time intervals, the results of goodness-of-fit indicators (Table S.2 in supplementary material) for calibrating (03/2012 to 02/2013) and validating (03/2013 to 12/2014) the SWAT-CPDN in simulating 15 min discharges

Table 2
Rainwater harvesting and reuse scenarios (common parameter values across scenarios highlighted).

Main scenarios	Scenarios			
	a	b	c	d
0. Baseline: calibrated/validated SWAT-CPDN without rain barrels/cisterns	/	/	/	/
1. Sizes of rain barrels/cisterns (design runoff depth from treated roof area, mm)	2.5	5.0	7.5	**10.0**
2. Percentages of suitable areas implemented (%)	10	25	50	**100**
3. Auto landscape irrigation rates (mm/hr)	**5.08**	12.70	25.40	50.80
4. Landscape irrigation starting times	0:00	**6:00**	12:00	18:00

Table 3
Individual and combined indicators used to identify sustainable rainwater harvesting/reuse strategies (parameters in Equation (1)).

Indicators	*I_RWHR*	*f1*	*f2*	*f3*	*f4*	*f5*
Individual indicators	EM_AA_DVR	1	0	0	0	0
	EM_Av_PDR	0	1	0	0	0
	EM_Av_CSOR	0	0	1	0	0
	EM_AA_MFWUR	0	0	0	1	0
	EM_AA_PBR	0	0	0	0	1
Combined indicators	Combined-1	1	1	1	1	1
	Combined-2	1	10	10	1	1

(calibration: R^2 = 0.920, NSE = 0.891, PBIAS = 2.87 %; validation: R^2 = 0.792, NSE = 0.783, PBIAS = −4.53 %), daily discharges (calibration: R^2 = 0.962, NSE = 0.901, PBIAS = 2.87 %; validation: R^2 = 0.901, NSE = 0.898, PBIAS = −4.53 %), and monthly discharges (calibration: R^2 = 0.965, NSE = 0.950, PBIAS = 2.87 %; validation: R^2 = 0.917, NSE = 0.913, PBIAS = −4.53 %) indicated very good model performance. The observed and simulated results of discharges were compared in Figure S.1 of supplementary material. Figures S.1a to S.1e show the observed and simulated daily discharge hydrograph, monthly discharge hydrograph, monthly discharge volume, 15 min discharge rate (scatter plot), and 15 min discharge exceedance probability (flow duration curve), respectively. These figures indicate that the simulated results of discharges at 15 min, daily, and monthly intervals corresponded very well with the observed data (supported by the results in Table S.2).

4.2. Changes in climate parameters under different climate conditions

Fig. 3 shows the ensemble mean of climate parameters for historical (2000–2014) and future (SSP2-4.5 and SSP5-8.5 during 2080–2099) climates.

Compared to that of the historical climate, precipitation under future climate during 2080–2099 changed by −0.45 % for SSP2-4.5 and −5.57 % for SSP5-8.5; maximum temperature changed by 10.73 % for SSP2-4.5 and 18.65 % for SSP5-8.5; minimum temperature changed by 23.33 % for SSP2-4.5 and 35.13 % for SSP5-8.5; wind speed changed by 19.02 % for SSP2-4.5 and 11.11 % for SSP5-8.5; relative humidity changed by −3.74 % for SSP2-4.5 and −8.35 % for SSP5-8.5; and solar radiation changed by −0.02 % for SSP2-4.5 or SSP5-8.5.

Among the historical (2000–2014) and future climates (SSP2-4.5 and SSP5-8.5 during 2080–2099), future climate with SSP5-8.5 and historical climate had the lowest and highest precipitation, respectively; historical climate and future climate with SSP5-8.5 had the lowest and highest maximum temperature or minimum temperature, respectively; historical climate and future climate with SSP2-4.5 had the lowest and highest wind speed, respectively; historical climate and future climate with SSP5-8.5 had the highest and lowest relative humidity, respectively; and future climates (both SSPs) had the same solar radiation, which were slightly lower than that of the historical climate.

Similar patterns were projected for 2080–2099, with nearly unchanged precipitation under SSP2-4.5 but a pronounced decline under SSP5-8.5 in the study area (Almazroui et al., 2021; Swain and Hayhoe,

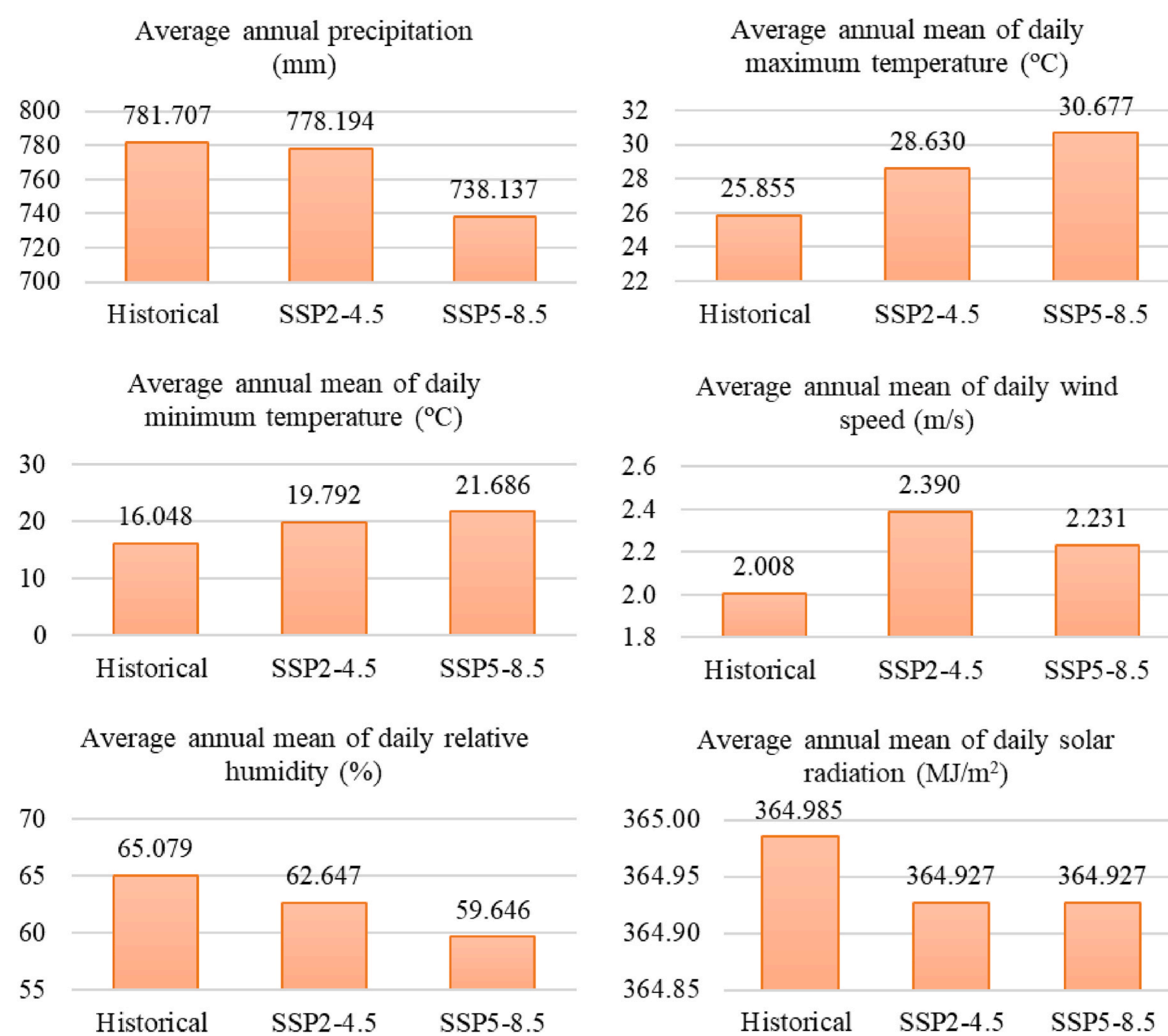

Fig. 3. Ensemble mean of climate parameters for historical (2000–2014) and future (SSP2-4.5 and SSP5-8.5 during 2080–2099) climates.

2015). Warming trends forecasted for this period suggested annual mean temperature increases of 2–3 °C under SSP2-4.5 and 5–6 °C under SSP5-8.5 (Almazroui et al., 2021). Moreover, CMIP6-based drought projections indicated that under both SSP2-4.5 and SSP5-8.5 scenarios, regions across central and western North America—including parts of the central United States—would likely experience increases of up to 100 % in meteorological drought frequency and intensified drought severity under SSP2-4.5 and increases of up to 200 % under SSP5-8.5 (Zhao and Dai, 2022). Solar irradiance projections indicated only minor changes, typically 1 W/m^2 (0.07 %)—reflecting a slight net decrease in surface radiation by the end of the century (Sedlacek et al., 2023). Collectively, these findings highlighted the need for adaptable water strategies under future climate, particularly given the combination of potentially warmer temperatures, reduced precipitation, increased drought risk, and modest shifts in solar energy input.

The differences in historical and future climate parameters (precipitation, temperature, wind speed, relative humidity, and solar radiation) were primarily driven by different levels of greenhouse gas emissions, climate feedback mechanisms, and shifts in atmospheric circulation patterns (Eyring et al., 2016; O'Neill et al., 2016). Historical climate conditions were shaped by past greenhouse gas emissions and natural climate variability, whereas future scenarios (SSPs) predicted different outcomes depending on potential emission trajectories (Eyring et al., 2016; O'Neill et al., 2016). During 2080–2099, the full impacts of the SSPs were realized, with significant differences between low and high emissions scenarios (Eyring et al., 2016; O'Neill et al., 2016).

4.3. Discharge volume

Compared to that of the historical climate (117,695 m^3), the ensemble mean of average annual discharge volume (EM_AA_DV, baseline without rain barrels/cisterns) of future climates increased by 4.80 % for SSP2-4.5 (123,350 m^3) and 4.08 % for SSP5-8.5 (122,493 m^3).

As shown in Fig. 4, for all the historical and future climates, the percent reductions in ensemble mean of average annual discharge volume (EM_AA_DVR) increased as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d) or as the auto landscape irrigation rates increased (3a-3d). For example, under SSP5-8.5 (2080–2099), the percent reductions in ensemble mean of average annual discharge volume were 6.213 %, 8.659 %, 8.727 %, and 8.754 % for scenarios 3a, 3b, 3c, and 3d, respectively. For different auto landscape irrigation starting times (4a-4d), the rankings of EM_AA_DVR were 4a>4d > 4b > 4c for all historical and future climates.

For all the historical and future climates, scenario 3d (sizes of rain barrels/cisterns: 10 mm; percentages of suitable areas implemented: 100 %; auto landscape irrigation rates: 50.80 mm/h; and landscape irrigation starting times: 6 a.m.) had the highest EM_AA_DVR. These rainwater harvesting/reuse strategies with the highest impacts could reduce 8.51 %–8.75 % of discharge volume under historical and future climates.

Factors affecting the discharge volume reductions. The variations in the impacts of different combinations of climate conditions and rainwater harvesting/reuse strategies on discharge volume were caused by the following factors (Jia et al., 2025; Li et al., 2019b, 2020, 2021, 2024; Jennings et al., 2013; Litofsky and Jennings, 2014; Chen et al., 2019; Wright et al., 2016): (1) The Brentwood watershed was segmented into subbasins and subsequently into HRUs in SWAT-CPDN, which resulted in numerous HRUs, each characterized by varied features such as pervious areas, impervious areas (directly or indirectly connected), soil type, rooftop areas, and slope. (2) Variations in the initial and temporal changes in HRU conditions (soil moisture levels, potential initial abstraction depth, evapotranspiration, cumulative infiltration depth, etc.) under different combinations of climate conditions and rainwater harvesting/reuse strategies. (3) Differences in the total capacities of rain barrels/cisterns across various scenarios (scenarios 1–2) and HRUs; and in general, larger rain barrels/cisterns would provide greater storage capacity for roof runoff, which can be utilized for irrigation. (4) Different irrigation rates (scenario 3) would result in varied irrigation amounts, HRU conditions, and available storage capacity of rain barrels/cisterns before and after a storm event ended. The auto irrigation would stop when (a) the soil moisture in the pervious area reached field capacity of the soil, or (b) storm occurred during irrigation (irrigation would stop when storm started). However, after water was released from the rain barrels or cisterns before a storm event because of irrigation (with different irrigation rates for scenarios 3a-3d), additional storage capacity became available to capture roof runoff. If a storm occurred during the irrigation period, scenarios with higher irrigation rates would allow more storage capacity for capturing runoff. However, in this study area, the irrigation demand was relatively low, and increasing the irrigation rate did not significantly shorten the irrigation period for 3b-3d. Moreover, storm events with varied starting times did not happen during potential irrigation periods for many cases (Figure S.2 in supplementary material). (5) Under different irrigation starting times (scenario 4), storms may happen before or after the auto landscape irrigation, causing different initial moisture contents, available storage capacities of rain barrels/cisterns, and cumulative infiltration depths before the storm events. (6) The initial and ending conditions (storage volume availability) of rain barrels/cisterns differed among various HRUs for each storm event due to the unique attributes of each HRU, impacting the watershed-scale discharge. (7) Temporal and/or spatial differences in storm event characteristics (starting time, depth, antecedent dry period, intensity, and duration) and other

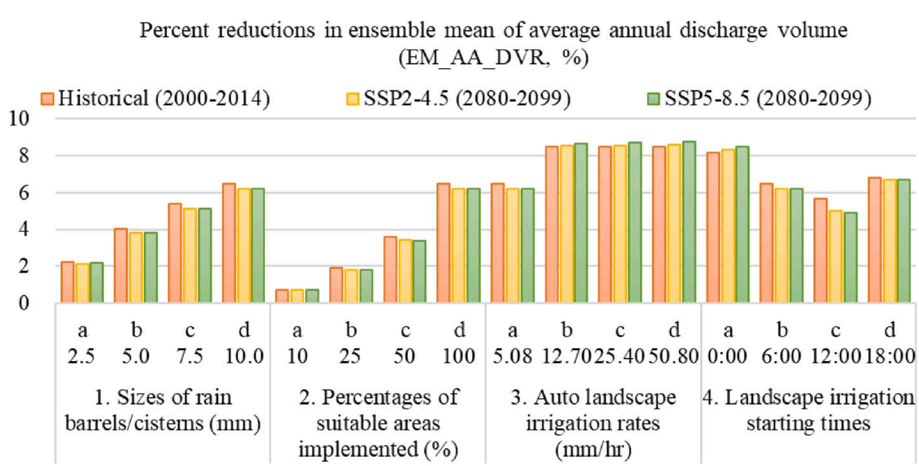

Fig. 4. Percent reductions in ensemble mean of average annual discharge volume (EM_AA_DVR, %; scenarios 1–4) for historical and future climates.

weather conditions (temperature, wind, solar radiation, and relative humidity) under different climate conditions (SSPs), along with vegetation growth in the watershed.

Similar studies have demonstrated that rain barrels/cisterns can help mitigate urban flooding and CSOs by effectively reducing peak flow and discharge volume (Dietz, 2007; Hood et al., 2007). By intercepting and temporarily storing rooftop runoff during rainfall events, these systems can significantly delay and reduce stormwater volume entering urban drainage networks, thereby decreasing the intensity and frequency of flooding events. Furthermore, by retaining stormwater at the source, rain barrels/cisterns can increase infiltration and promote evapotranspiration, thus supporting a more natural hydrological cycle within urbanized areas. Studies have shown that widespread adoption of rainwater harvesting systems can significantly reduce urban runoff during storm events, particularly when combined with other green infrastructure practices (Jennings et al., 2013; Campisano and Modica, 2012; Jia et al., 2013; Fu et al., 2019). For example, a case study showed that large-scale adoption of rain barrels/cisterns combined with permeable pavements and green roofs could reduce runoff volume by 41 % (Fu et al., 2019).

4.4. Peak discharge

Compared to that of the historical climate (4568.57 m^3/h), the ensemble mean of average peak discharges (EM_Av_PD, baseline without rain barrels/cisterns) of future climates increased by 9.64 % for SSP2-4.5 (5008.82 m^3/h) and 19.00 % for SSP5-8.5 (5436.82 m^3/h).

As shown in Fig. 5, for all the historical and future climates, the percent reductions in ensemble mean of average peak discharges (EM_Av_PDR) increased as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d). For different auto landscape irrigation rates (3a-3d), EM_Av_PDR increased as the auto landscape irrigation rates increased for historical climate and future climate with SSP2-4.5; and varied rankings of EM_Av_PDR were found under SSP5-8.5. For different auto landscape irrigation starting times (4a-4d), the rankings of EM_Av_PDR were 4a>4b > 4d > 4c under future climates; and 4a>4b > 4c > 4d under historical climate.

For historical climate and future climate with SSP2-4.5, scenario 3d had the highest EM_Av_PDR. For SSP5-8.5, scenario 3c (sizes of rain barrels/cisterns: 10 mm; percentages of suitable areas implemented: 100 %; auto landscape irrigation rates: 25.40 mm/h; and landscape irrigation starting times: 6 a.m.) had the highest EM_Av_PDR. These rainwater harvesting/reuse strategies with the highest impacts could reduce 4.83 %–5.28 % of peak discharge under historical and future climates.

Factors affecting the peak discharge reductions. In addition to the factors that affected the impacts of different combinations of climate conditions and rainwater harvesting/reuse strategies on discharge volume (discussed in Section 4.3), other factors affected the peak discharge included (Li et al., 2021, 2024; Nilsen et al., 2011; Zhou et al., 2019): (1) The available storages in the rain barrels/cisterns in individual HRUs when peak runoff happened in each HRU for each storm event; for example, when considering different climate conditions, storm events included in the analysis varied and the available storages in the rain barrels/cisterns differed. (2) The characteristics of peak runoff in individual HRUs for different storm events; for example, peak runoff close to the beginning of the storm event would be more likely to be reduced compared to peak runoff close to the end of the storm event due to the process of filling up rain barrels/cisterns during the storm event. (3) HRU conditions (soil moisture levels, potential initial abstraction depth, cumulative infiltration depth, etc.) when peak runoff happened in individual HRUs. (4) The cumulative effects of peak runoffs from different HRUs on the watershed-scale peak discharges following routing processes.

Modeling studies indicated that widespread deployment of rain barrels/cisterns can significantly lower stormwater peaks—by up to 28 % for a 2-year storm event and 13.6 % for a 100-year storm event—in urban areas with constrained drainage capacity (Jokowinarno and Kusumastuti, 2020). In smaller-scale systems, rain barrels/cisterns have been shown to attenuate peak discharge rates during moderate storms by temporarily retaining runoff and gradually releasing it post-event (Campisano et al., 2014). A case study in urban Japan simulated a dense residential neighborhood with integrated rain barrels and rain gardens, showing notable reduction in the first peak of discharge during long-duration events (Lin et al., 2023). Additionally, rain barrels/cisterns that are pre-emptively drained and actively managed in real time—demonstrated peak flow reductions of 39–48 % during simulated 100-year, 24-h storms compared to passive retention tanks (Di Matteo et al., 2019). Further, a study found that rain barrels/cisterns alone controlled peak flows for storms up to a 2-year return period and when combined with detention ponds, achieved hydrograph attenuation comparable to traditional infrastructure (Lyu, 2018).

4.5. Combined sewer overflow (CSO)

Compared to that of the historical climate (2812.98 m^3), the ensemble mean of average CSO (EM_Av_CSO, baseline without rain barrels/cisterns) of future climates increased by 12.10 % for SSP2-4.5 (3153.26 m^3) and 24.00 % for SSP5-8.5 (3487.97 m^3).

As shown in Fig. 6, for all the historical and future climates, the percent reductions in ensemble mean of average CSO (EM_Av_CSOR) increased as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d). For

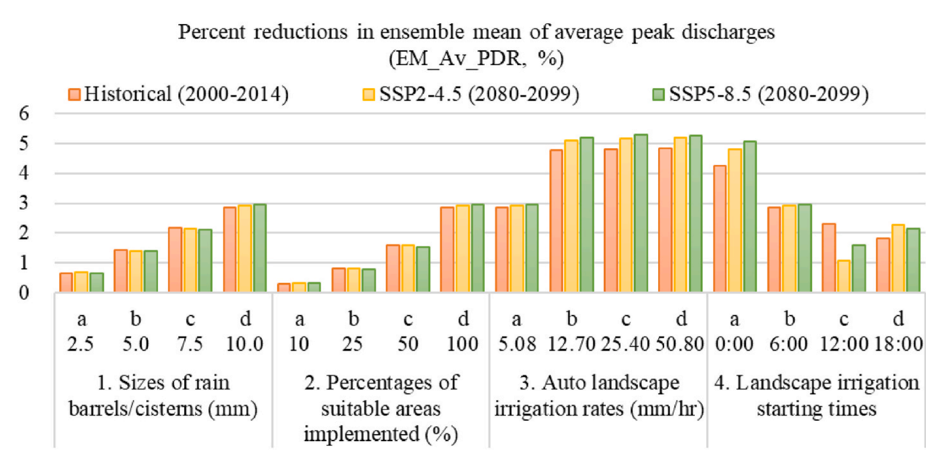

Fig. 5. Percent reductions in ensemble mean of average peak discharges (EM_Av_PDR, %; scenarios 1–4) for historical and future climates.

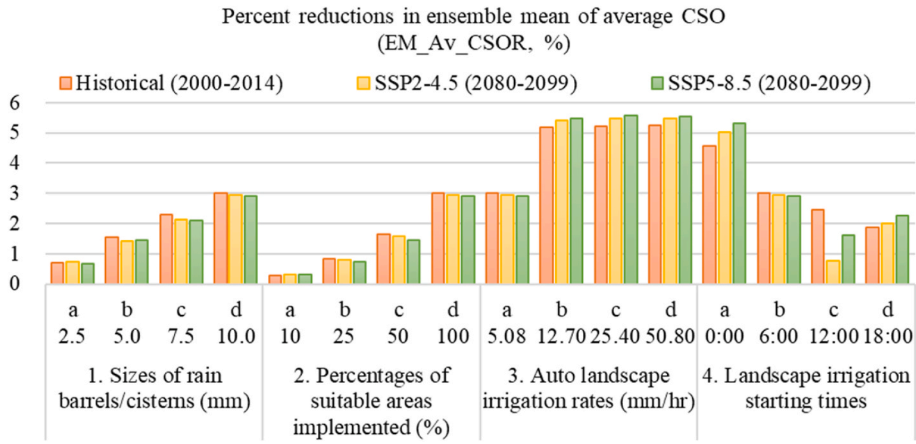

Fig. 6. Percent reductions in ensemble mean of average CSO (EM_Av_CSOR, %; scenarios 1–4) for historical and future climates.

different auto landscape irrigation rates (3a-3d), EM_Av_CSOR increased as the auto landscape irrigation rates increased for historical climate and future climate with SSP2-4.5; and varied rankings of EM_Av_CSOR were found under SSP5-8.5. For different auto landscape irrigation starting times (4a-4d), the rankings of EM_Av_CSOR were 4a>4b > 4d > 4c for future climates and 4a>4b > 4c > 4d for historical climate.

For historical climate and future climate with SSP2-4.5, scenario 3d had the highest EM_Av_CSOR. For SSP5-8.5, scenario 3c had the highest EM_Av_CSOR. These rainwater harvesting/reuse strategies with the highest impacts could reduce 5.24 %–5.56 % of CSO under historical and future climates.

Factors affecting the CSO reductions. In addition to the factors that affected the impacts of different combinations of climate conditions and rainwater harvesting/reuse strategies on discharge volume (discussed in Section 4.3), other factors affected the CSOs included (Ghodsi et al., 2023; Li et al., 2021, 2024; Nilsen et al., 2011): (1) differences in the storages of rain barrels/cisterns in individual HRUs at the beginning of intense storm events that caused CSOs; (2) different HRU conditions (soil moisture levels, potential initial abstraction depth, cumulative infiltration depth, etc.) at the beginning of these intense storm events; and (3) the cumulative effects of runoff from different HRUs on the watershed-scale discharge volume following routing processes for these intense storm events.

Community-scale modeling in Buffalo, NY using the SWMM model has demonstrated that deploying rain barrels (≈1000 gal) across residential rooftops can reduce CSO volumes by up to 12 %, and the addition of large commercial-roof cisterns (≈5000 gal) can contribute an additional 12 % reduction (Ghodsi et al., 2021). Other studies found similar results showing that widespread adoption of rain barrels/cisterns across residential properties could cost-effectively reduce runoff and attenuate the magnitude of CSO events within combined-sewer catchments (Chaosakul et al., 2013; Abi Aad et al., 2009). A review of global water-sensitive urban design (WSUD) strategies reinforced the role of rain barrels/cisterns among top-performing practices (Muttil et al., 2023). Their findings highlighted that rain barrels/cisterns effectively reduce CSO events, especially when integrated with other green infrastructures.

4.6. Freshwater demand

Compared to that of the historical climate (1.407×10^6 m^3), the ensemble mean of average annual municipal freshwater usages (EM_AA_MFWU, baseline without rain barrels/cisterns) of future climates increased by 11.49 % for SSP2-4.5 (1.568×10^6 m^3) and 18.53 % for SSP5-8.5 (1.667×10^6 m^3).

As shown in Fig. 7, for all the historical and future climates, the percent reductions in ensemble mean of average annual municipal freshwater usages (EM_AA_MFWUR) increased as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d) or as the auto landscape irrigation rates increased (3a-3d). For example, under SSP5-8.5 (2080–2099), the percent reductions in ensemble mean of average annual municipal freshwater usages were 3.064 %, 23.952 %, 24.803 %, and 24.929 % for scenarios 3a, 3b, 3c, and 3d, respectively. For different auto landscape irrigation starting times (4a-4d), the rankings of EM_AA_MFWUR were 4a>4d > 4b > 4c for all historical and future climates; and negative EM_AA_MFWUR values for scenario 4c were found for all historical and future climates.

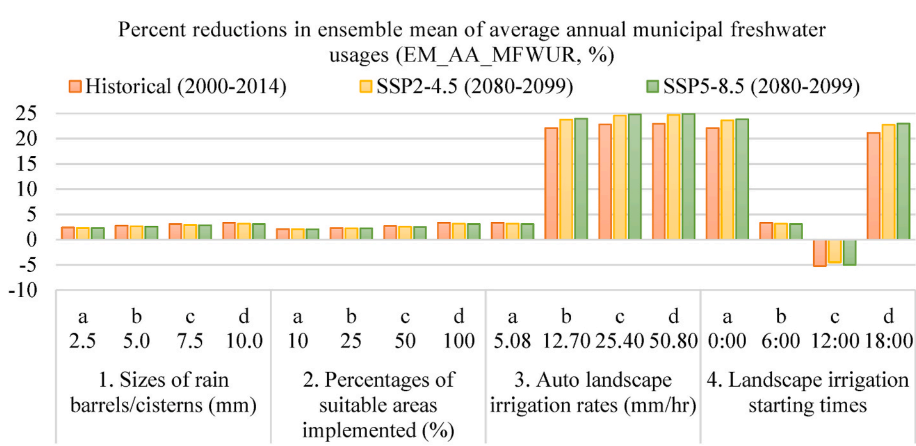

Fig. 7. Percent reductions in ensemble mean of average annual municipal freshwater usages (EM_AA_MFWUR, %; scenarios 1–4) for historical and future climates.

The total water usages for irrigation (combining municipal freshwater usages and water usages from rain barrels/cisterns) under scenarios 1a-4d were different from the total water usages of baseline without rain barrels/cisterns. For all the historical and future climates, scenario 3d (the scenario with the highest auto landscape irrigation rate) had the highest EM_AA_MFWUR. These rainwater harvesting/reuse strategies with the highest impacts could reduce 22.91 %–24.93 % of freshwater demand under historical and future climates.

Factors affecting the freshwater demand. The variations of freshwater demand and total water demand for landscape irrigation under different combinations of historical/future climates and rainwater harvesting/reuse strategies were caused by the following factors (Li et al., 2021, 2024; Litofsky and Jennings, 2014; Doll et al., 2022): (1) larger rain barrels/cisterns or higher implementation levels of rain barrels/cisterns can store more rainwater that can be used for irrigation and reduce the need to use municipal freshwater supplies; (2) variations in rainwater harvesting/reuse strategies can lead to varying soil water cycles and evapotranspiration amounts, which in turn affected when irrigation should start or stop and how much irrigation water was needed; (3) the watershed with large numbers of HRUs with different characteristics, including HRU areas, impervious areas (both directly and indirectly connected), and pervious areas, would influence the amount of irrigation needed for lawns; and (4) temporal and/or spatial differences in storm event characteristics (starting time, depth, antecedent dry period, intensity, and duration) and other weather conditions (temperature, wind, solar radiation, and relative humidity) under different climates, along with vegetation growth in the watershed would affect the municipal freshwater usages and water usages from rain barrels/cisterns.

Scenario 4c increased municipal freshwater demand, mainly due to starting irrigation at 12:00 p.m. resulted in higher evaporation rates compared to the baseline irrigation time of 6:00 a.m. Irrigation at noon required more water to bring soil moisture to field capacity because evapotranspiration rates were typically higher during this period compared to other times of the day. Therefore, the water demand was higher when irrigating at 12:00 p.m. Although the harvested water was used, the freshwater demand was still higher than that of the baseline.

To irrigate the same amount of irrigation water, scenario 3a needed 2.5 times, 5 times, and 10 times of the length of irrigation periods needed for scenarios 3b, 3c, and 3d, respectively. Therefore, the extended irrigation duration for scenario 3a increased the likelihood of storm events occurring during the irrigation periods, and it had much fewer chances for storm events to happen during potential irrigation periods for scenarios 3b-3d. The auto irrigation would stop when (a) the soil moisture in the pervious area reached field capacity of the soil, or (b) storm occurred during irrigation (irrigation would stop when storm started). However, in this study area, the irrigation demand was relatively low, and increasing the irrigation rate did not significantly shorten the irrigation period for 3b-3d. Moreover, storm events with varied starting times did not happen during potential irrigation periods for many cases (Figure S2 in supplementary material). Scenario 3a had a much longer irrigation period compared to scenarios 3b, 3c, and 3d. This extended duration increased the likelihood of storm events occurring during the irrigation period, leaving less storage capacity in the rain barrels/cisterns. As a result, the system's ability to capture additional rainwater during storm events was reduced and the percent reductions in ensemble mean of average annual municipal freshwater usages of 3a was lower than 3b-3d.

Multiple studies have confirmed that rain barrels/cisterns can significantly reduce municipal freshwater demand for urban irrigation. For example, Litofsky and Jennings (2014) reported that a standard 235 L rain barrel can supply between 5 % and 73 % of garden irrigation needs, depending on regional climate conditions. Wurthmann (2019) highlighted its potential to sustainably meet residential landscape irrigation needs in Florida, given adequate storage. Another study showed city-scale rainwater harvesting in Arizona could offset approximately one-third of outdoor irrigation water demand during wet years, generating substantial cost savings of approximately US $13.8 million (Zhong et al., 2022). In addition, another study found rainwater harvesting can significantly supplement irrigation for landscape and public gardens, reducing drought vulnerability, though its effectiveness varies with site characteristics and climate, and could be improved by passive collection or additional storage in local waterbodies (Jacque et al., 2023). Modeling for the campus of a University quantified that roof runoff collection could supply approximately 10,927 m^3 for irrigation, substantially reducing reliance on municipal water (Saeedi and Goodarzi, 2020).

4.7. Plant growth

Compared to that of the historical climate (7.788 ton/ha), the ensemble mean of average annual plant biomasses (EM_AA_PB) of baselines without rain barrels/cisterns under future climates changed by 2.07 % for SSP2-4.5 (7.949 ton/ha) and −3.85 % for SSP5-8.5 (7.488 ton/ha).

As shown in Fig. 8, for all the historical and future climates, the percent reductions in ensemble mean of average annual plant biomasses (EM_AA_PBR) did not change as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d). For different auto landscape irrigation rates (3a-3d) under all historical and future climates, scenario 3a provided the lowest EM_AA_PBR, while scenario 3b had the highest EM_AA_PBR. For different auto landscape irrigation starting times (4a-4d) under all historical and future climates, scenario 4b provided the lowest EM_AA_PBR, while scenario 4a or scenario 4d had the highest EM_AA_PBR.

For all the historical and future climates, the lowest EM_AA_PBR were found in baseline, scenarios 1a-1d, scenarios 2a-2d, scenario 3a, and scenario 4b.

Factors affecting the plant growth. The variations in plant biomasses under different combinations of historical/future climates and rainwater harvesting/reuse strategies were caused by the following factors (Li et al., 2021, 2024; Kisvarga et al., 2023; Li and Xiaoyi, 2021): (1) it was assumed that there were not any stresses of nitrogen and phosphorus for plant growth; (2) long-term water stresses did not occur due to the simulation of auto landscape irrigation; (3) larger rain barrels/cisterns or higher implementation levels of rain barrels/cisterns did not change the water stresses of plant growth due to municipal freshwater was supplied when needed; (4) different auto landscape irrigation rates and varied auto landscape irrigation starting times would (a) affect the lengths and degrees of water stresses for plant growth due to the irrigation starting times and lengths of time needed to complete the irrigation processes were different, and (b) affect the irrigation amount and soil water cycle given irrigation stops when storm events start; (5) the watershed with large numbers of HRUs with different characteristics, including HRU areas, impervious areas (both directly and indirectly connected), and pervious areas, would influence the water stresses for plant growth; and (6) temporal and/or spatial differences in storm event characteristics (starting time, depth, antecedent dry period, intensity, and duration) and other weather conditions (temperature, wind, solar radiation, and relative humidity) under different climates would affect plant growth/biomasses. As an example, Figure S.3 in supplementary material shows the percent reductions in plant biomass (%) and water stress (1 represents no water stress) for scenarios 3a-3d and 4a-4d in a typical medium intensity HRU of the watershed under SSP5-8.5 (2080–2099) using the climate outputs of MPI-ESM1.2-HR model. The HRU has an area of 1022.7 m^2 with 64.8 % imperviousness and 35.2 % of impervious areas as rooftops. Results indicated the variation in soil moisture content that led to water stress due to changes in the timing and rate of auto landscape irrigation.

Previous studies also demonstrated the benefits of rainwater harvesting for irrigation focusing on plant growth. For example, rainwater harvesting systems can fully meet the water needs of various crops, such

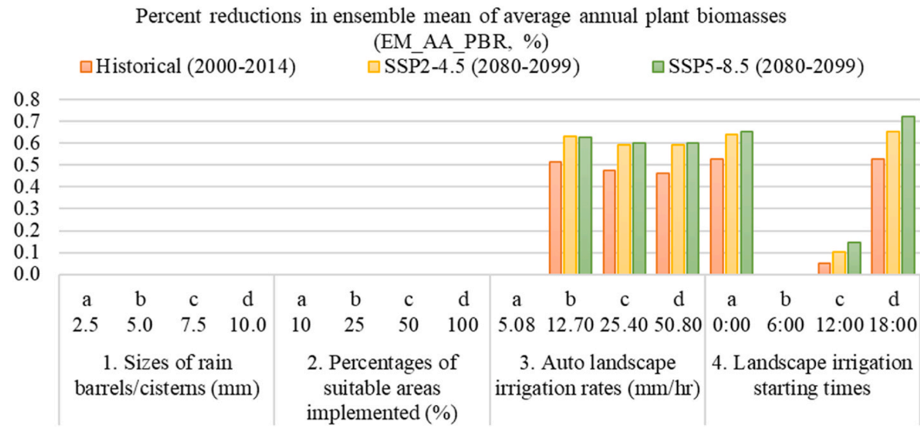

Fig. 8. Percent reductions in ensemble mean of average annual plant biomasses (EM_AA_PBR, %; scenarios 1–4) for historical and future climates.

as vegetables and fruits in greenhouses, ensuring optimal growth and production (Sirait et al., 2024). In rain-fed orchards, rainwater harvesting systems can improve soil water storage and temperature, enhancing the growth and water use efficiency of apricot trees (Feng et al., 2024). In India, a study demonstrated that low-tech rainwater harvesting structures can substantially improve soil moisture and vegetation establishment (Singh et al., 2013).

4.8. Combined indicators

Fig. 9 shows the impacts of rainwater harvesting/reuse strategies (I_RWHR) for combined indicators with different weighting factors. Combined indicator 1 included equal weights for discharge volume, peak discharge, CSO, freshwater demand, and plant growth. Combined indicator 2 included higher weights for peak discharge and CSO (representing heavy storm events caused the major challenges) compared to the weights of other individual indicators. When using combined indicator 1 to identify sustainable rainwater harvesting/reuse strategy, scenario 3d provided the highest I_RWHR for all the historical (2000–2014) and future (SSP2-4.5 and SSP5-8.5 during 2080–2099) climates. When using combined indicator 2 to identify sustainable rainwater harvesting/reuse strategy, scenario 3c provided the highest I_RWHR for future climate with SSP5-8.5 (2080–2099), while scenario 3d provided the highest I_RWHR for other climate conditions.

When identifying sustainable rainwater harvesting/reuse strategy including minimum or maximum criteria for individual environmental

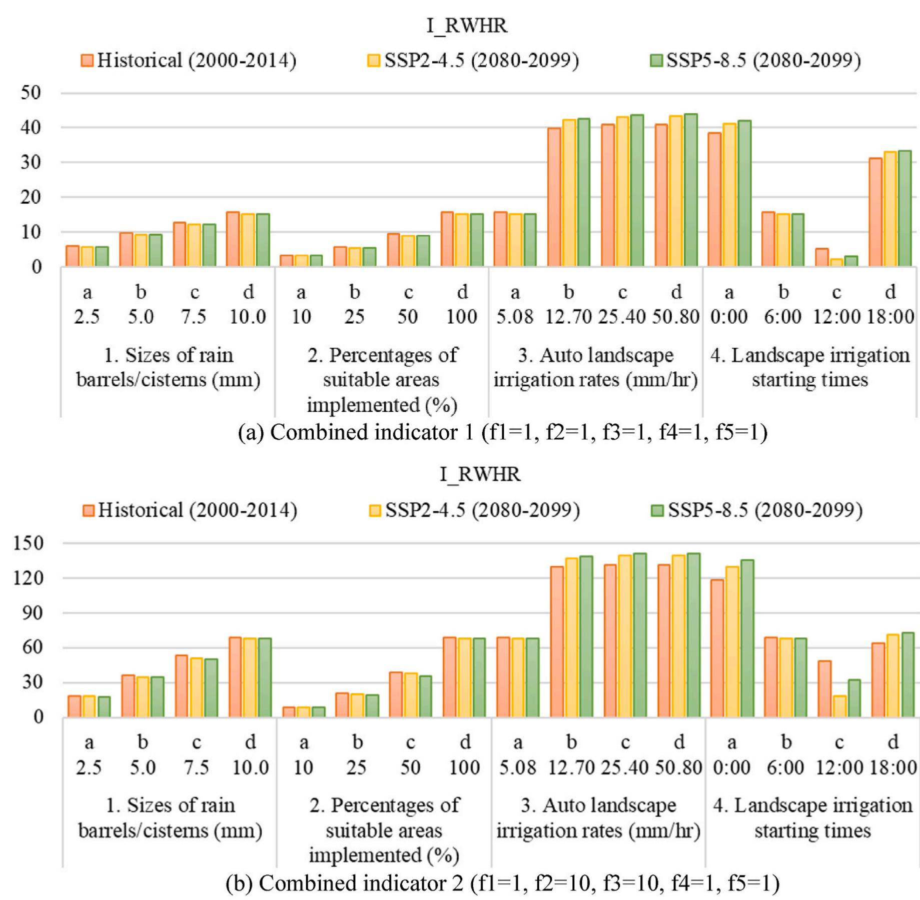

Fig. 9. The impacts of rainwater harvesting/reuse strategies (I_RWHR, %) for combined indicators with different weighting factors.

goals (a minimum of 4 % for EM_AA_DVR, a minimum of 2 % for EM_Av_PDR, a minimum of 2 % for EM_Av_CSOR, a minimum of 3 % for EM_AA_MFWUR, and a maximum of 0 % for EM_AA_PBR), scenarios 3c and 3d were excluded because they reduced plant biomasses compared to the baseline conditions. Under these criteria, scenarios 1d, 2d, 3a, and 4b provided the highest I_RWHR for all historical and future climate conditions, representing the most sustainable rainwater harvesting/reuse strategy among the scenarios.

4.9. Major results and insights obtained

A novel framework for creating sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate was developed. The novel framework can be applied in any urban watersheds to support decision-making. And the framework was demonstrated in a case study area. The results and insights obtained in the case study are applicable to other areas with similar conditions.

Compared to the ensemble mean of historical climate, future climates (2080–2099 under SSP2-4.5 and SSP5-8.5) exhibited large changes in precipitation (−5.57 % to −0.45 %), maximum temperature (10.73 %–18.65 %), minimum temperature (23.33 %–35.13 %), wind speed (11.11 %–19.02 %), and relative humidity (−8.35 % to −3.74 %), while solar radiation remained relatively stable (−0.02 %). These suggest that the effects of climate change on hydrology and water quality due to changes in solar radiation would be small compared to the impacts resulting from alterations in other climate parameters (precipitation, maximum/minimum temperature, wind speed, and relative humidity).

Compared to those of the historical climate, for baselines without rain barrels/cisterns under future climates, EM_AA_DV increased by 4.08 %–4.80 %; EM_Av_PD increased by 9.64 %–19.00 %; EM_Av_CSO increased by 12.10 %–24.00 %; EM_AA_MFWU increased by 11.49 %–18.53 %; and EM_AA_PB changed by −3.85 %–2.07 %. The rankings of EM_AA_DV and EM_AA_PB under different SSPs were SSP2-4.5>SSP5-8.5. The rankings of EM_Av_PD, EM_Av_CSO, and EM_AA_MFWU under different SSPs were SSP2-4.5<SSP5-8.5. These indicate that climate change adversely affected discharge volume, peak discharge, CSO, and municipal freshwater usage; however, the impacts of climate change on plant growth were not always negative, depending on the specific future climate conditions. In addition, when compared to those of SSP2-4.5, SSP5-8.5 had increased adverse impacts on the indicators evaluated except discharge volume.

For all the historical and future climates, 4 indicators (EM_AA_DVR, EM_Av_PDR, EM_Av_CSOR, and EM_AA_MFWUR) increased and one indicator (EM_AA_PBR) stayed unchanged as the sizes of rain barrels/cisterns increased (1a-1d) or as the percentages of suitable areas implemented increased (2a-2d); EM_AA_DVR and EM_AA_MFWUR increased as the auto landscape irrigation rates increased (3a-3d); and the rankings of EM_AA_DVR and EM_AA_MFWUR were 4a>4d > 4b > 4c (different auto landscape irrigation starting times). For different auto landscape irrigation rates (3a-3d) or different auto landscape irrigation starting times (4a-4d), EM_Av_PDR, EM_Av_CSOR, and EM_AA_PBR did not have consistent trends under individual historical and future climates. These indicate that the trends in the multi-functional impacts of different rainwater harvesting/reuse strategies on discharge volume, peak discharge, CSO, freshwater demand, and plant growth were not always consistent under individual historical and future climates.

For all the historical and future climates, scenario 3d (the scenario with the highest auto landscape irrigation rate) had the highest EM_AA_DVR and EM_AA_MFWUR; and baseline, scenarios 1a-1d, scenarios 2a-2d, scenario 3a, and scenario 4b had the lowest EM_AA_PBR. The highest EM_Av_PDR and EM_Av_CSOR were found in scenario 3d under historical climate and future climate with SSP2-4.5; and in scenario 3c under SSP5-8.5. Compared to the baselines (without rain barrels/cisterns), rainwater harvesting/reuse strategies with the most benefits under historical and future climates could reduce discharge volume by 8.51 %–8.75 %, peak discharge by 4.83 %–5.28 %, CSO by 5.24 %–5.56 %, and freshwater demand by 22.91 %–24.93 %, while maintaining plant biomass. The most sustainable rainwater harvesting/reuse strategy identified using combined indicators varied under different climates, different weighting factors of individual indicators, and different minimum/maximum criteria for individual indicators. These indicate that: (1) The percent reductions in freshwater demand were much higher than the percent reductions in discharge volume, peak discharge, and CSO, due to the rainwater harvesting/reuse strategies were designed to efficiently use the water harvested and only irrigate when plants need water. The rainwater harvesting/reuse strategies can be redesigned to release more water during dry periods, which would reduce additional discharge volume, peak discharge, and CSO with higher freshwater demand. (2) Rainwater harvesting and reuse has high potentials to be a sustainable solution to mitigate the adverse impacts of urbanization and climate change on water resources. (3) No single rainwater harvesting/reuse strategy can maximize benefits across all individual indicators under varying climates, emphasizing the need for tailored approaches based on specific goals and climate conditions. (4) The most sustainable rainwater harvesting/reuse strategy needs to be obtained by evaluating the impacts on combined indicators with well-defined weighting factors and minimum/maximum criteria for individual indicators under each climate condition. (5) Adaptive water management strategies capable of evolving with changing climate conditions are needed to address the uncertainties of climate change.

5. Conclusions

This study created a novel framework for developing sustainable rainwater harvesting and reuse strategies for urban landscape irrigation in a changing climate. And the framework was demonstrated in a case study area. Climate change and rainwater harvesting/reuse had significant impacts on discharge volume, peak discharge, CSO, freshwater demand, and plant growth. No single strategy can maximize benefits across all individual indicators under varying climates, emphasizing the need for tailored approaches based on specific goals and climate conditions. The most sustainable rainwater harvesting/reuse strategy needs to be obtained by evaluating the impacts on combined indicators with well-defined weighting factors and minimum/maximum criteria for individual indicators under each climate condition. The framework created in this study can guide decision-making for sustainable water management in future urban planning initiatives. In future studies, the novel framework could be applied using longer periods of future climate data (e.g., 2026–2099) that cover the fluctuations of climate conditions during different periods.

CRediT authorship contribution statement

Siyu Li: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Yaoze Liu:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Anh H. Nguyen:** Writing – review & editing, Software, Formal analysis. **Zhuohang Wu:** Writing – review & editing, Software, Formal analysis. **Mahmood Z. Al-Farsi:** Writing – review & editing, Software, Formal analysis. **Tomi Choi:** Writing – review & editing, Software, Formal analysis. **Liming Zhou:** Writing – review & editing, Methodology. **Younggu Her:** Writing – review & editing, Methodology, Data curation. **Fawen Li:** Writing – review & editing, Methodology. **Dongyang Ren:** Writing – review & editing, Methodology. **Xiaobo Xue Romeiko:** Writing – review & editing, Methodology.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126852.

Data availability

Data will be made available on request.

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