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THE ROLE OF GREEN ROOFS IN CLIMATE CHANGE MITIGATION AND ADAPTATION: ANALYZING PERFORMANCE DURING EXTREME RAINFALL EVENTS

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ABSTRACT. This study evaluated the water storage and runoff capacities of an extensive green roof simulator in Bahía Blanca, Argentina, during the region's most extreme precipitation event in 47 years. The analysis involved a time series of daily precipitation from 1961 to 2022. A Green Roof model was applied using daily precipitation data, potential evapotranspiration, and field-measured water storage capacity data from 2022. The model was based on a 1 m² green roof simulator, with 50 % of its surface covered by native species. The substrate depth was set at 15 cm, with a soil water storage capacity of 58.7 mm. Precipitation in Bahía Blanca showed considerable variability across temporal scales. The most frequent events (89 %) involved less than 20 mm of rainfall, followed by events between 20.1 mm and 40 mm (8 %). Eight events with precipitation between 80.1 mm and 100 mm were recorded, with March 24, 2022, marking the highest daily rainfall in 15 years (90.3 mm). However, when examining three-day accumulated rainfall, the period from March 23 to 25, 2022, accumulated 150.3 mm, making it the most extreme event in the last 47 years and the second highest in the 62 years analyzed. During this event, total runoff amounted to 83.4 mm, indicating a substantial water storage of 44.6 % by the green roof simulator. Given the projected increase in the frequency and intensity of extreme rainfall events, green roofs offer a sustainable and innovative solution for mitigating and adapting to climate change impacts. Additionally, they serve as crucial urban green infrastructures for managing runoff, particularly in regions prone to intense precipitation events like Bahía Blanca.

El papel de los techos verdes en la mitigación y adaptación al cambio climático: análisis de su efectividad durante eventos de lluvia extrema

RESUMEN. En este estudio se evaluó la capacidad de almacenamiento de agua y escorrentía de un simulador de techo verde extensivo en la ciudad de Bahía Blanca (Argentina), durante el evento de precipitación más extremo de los últimos 47 años. Para ello, se analizó la serie temporal de precipitación diaria del período 1961-2022. Se utilizó el modelo Green Roof con datos de precipitación y evapotranspiración potencial diaria y de capacidad de campo medidas *in situ* durante el año 2022 y se seleccionó el período más extremo en términos de precipitación. El modelo se aplicó considerando un simulador de techo verde con una superficie de 1 m^2, cubierto al 50 % por especies nativas. La profundidad del sustrato fue 15 cm y la capacidad máxima de almacenamiento de agua del suelo fue 58,7 mm. Bahía Blanca presentó una marcada variabilidad de las precipitaciones a diferentes escalas temporales. Las precipitaciones más frecuentes fueron las menores de 20 mm (89 %), seguidas de las de entre 20,1 y 40 mm (8 %). Se detectaron ocho eventos entre 80,1 mm y 100 mm, entre los que destaca el de 24 de marzo de 2022 por ser el evento de mayor precipitación diaria de los últimos 15 años (90,3 mm). Sin embargo, al analizar las precipitaciones acumuladas en tres días consecutivos, se observó que la cantidad registrada durante el período 23-25 de marzo (150,3 mm) fue la más extremo de los últimos 47 años y la segunda más importante de los 62 años analizados. Durante este evento se generó una escorrentía total de 83,4 mm, lo que indica que el simulador de techo verde tuvo una buena capacidad de almacenamiento de agua, alcanzando un 44,6 %. Considerando que se prevé un aumento en la frecuencia e intensidad de eventos pluviométricos extremos, los techos verdes representan una alternativa innovadora y sostenible para mitigar y adaptarse a los efectos del cambio climático, permitiendo además gestionar la escorrentía en entornos urbanos, particularmente en regiones con eventos pluviométricos extremos frecuentes, como Bahía Blanca.

Keywords: Green roof, water balance model, runoff, extreme precipitation events, native species, sustainable cities.

Palabras clave: techo verde, modelo de balance hídrico, escorrentía, eventos extremos de precipitación, especies nativas, ciudades sostenibles.

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1. Introduction

Urban expansion has transformed natural areas into impermeable surfaces, altering their hydrological patterns and flow regimes (Zhang *et al.,* 2018). Among the most significant changes resulting from this process are the increase in peak flows, the reduction in water concentration times, the modification of the water balance, and the increase in surface runoff volume (Li *et al.,* 2018; Paule-Mercado *et al.,* 2017). Additionally, climate change has caused a significant increase in the frequency and intensity of extreme precipitation events, directly affecting the recurrence and magnitude of flooding in numerous cities (Berggren *et al.,* 2012; Pour *et al.,* 2020). Therefore, rapid urbanization and climate change are expected further to increase the risk of flooding in the near future (Yin *et al.,* 2015; Zhou *et al.,* 2019). Among the mitigation measures implemented worldwide, green roofs are one of the most adopted, as they can be easily installed on existing buildings without requiring additional land space (Carter and Jackson, 2007). Moreover, these green infrastructures provide multiple environmental benefits, such as water quality purification (Rowe, 2011), reduction of building temperatures and the urban heat island effect (He *et al.,* 2020), as well as contributing to the decrease of air pollution (Speak *et al.,* 2012). Furthermore, they mitigate greenhouse gas emissions by promoting carbon absorption and retention, which aids in reducing CO_2 levels in the atmosphere (Perillo *et al.,* 2023).

Green roofs can mitigate stormwater runoff by collecting and retaining precipitation, reducing the flow volume to conventional stormwater infrastructure (Driscoll *et al*., 2015). The water storage capacity depends on several factors, including the construction conditions of the green roof, such as substrate type and vegetation, slope, and drainage system, among others. Studies on the capacity of these infrastructures to store precipitation and manage urban runoff are becoming increasingly common worldwide, but in Argentine cities, they remain scarce. Mentens *et al*. (2006) analyzed 18 extensive green roofs with different growing media and vegetation coverage in Central Europe and found an average runoff reduction of 50 %. In New York, it was demonstrated that a green roof on a commercial building retains 89 % of water during intense rains (> 25 mm/event) (Todorov *et al.,* 2018), while in a semi-arid region of China with an annual precipitation of 425 mm/year, green roofs showed water storage ranging from 34.7 % to 48.5 %, depending on the substrate moisture level before the precipitation event (Liu *et al.,* 2020). A study in Lisboa (Portugal), which shares a climate comparable to the study area, revealed a 73 % rainwater storage capacity rate in green roofs (Brandão *et al*., 2017). Despite this, studies on how green roofs manage water storage and runoff during extreme precipitation events have not yet been conducted in Bahía Blanca, Argentina.

This study investigates the hydrological dynamics of a green roof system in Bahía Blanca city, Argentina, by applying a water balance model to a green roof simulator (Figs. 1 and 2). The approach combines physical measurements from the simulator with hydrological modeling to evaluate performance during extreme precipitation events. While the simulator provided essential data on substrate and vegetation characteristics, the model enabled the assessment of water storage and runoff dynamics under various precipitation conditions. The green roof simulator is located in Bahía Blanca city (Argentina) (Fig. 1), in the lower basin of the Napostá Grande stream, whose course crosses the city and originates from the Ventania mountain system (Fig. 1). This lower basin location makes the city vulnerable to accumulated upstream runoff, increasing flood risk during intense precipitation events (Mastrandrea and Pérez, 2022). The region has a sub-humid climate, with average annual precipitation and temperature of 627.4 mm and 15.6 °C, respectively (1961-2022). The area is characterized by the most severe extreme precipitation events in the Pampas Region (Aliaga *et al.,* 2017). These phenomena are considered the most representative and have the most significant adverse effects, mainly due to the alteration of socioeconomic activities in rural areas and the emergence of socio-environmental problems in urban settings (Bohn *et al.,* 2011). The city is situated in a flat environment, with different terrace levels in the north and northeast and low, flood-prone lands in the south, influencing normal runoff conditions. As a consequence, during extreme precipitation, flooding occurs, especially in neighborhoods located in the southern sector and over the floodplain of the Napostá stream toward the north of the city (Mastrandrea and Pérez, 2022). Given that precipitation events in the region are expected to become more frequent and intense in the near future (Brendel, 2023), it is essential to understand the capacity of green roofs to reduce runoff during precipitation of varying magnitudes.

This study evaluated the water storage and runoff capacities of an extensive green roof simulator in Bahía Blanca, Argentina, during the region's most extreme precipitation event in 47 years. The specific objectives were to:

- Analyze precipitation patterns and identify extreme events in Bahía Blanca from 1961-2022,
- Evaluate the hydrological performance of a green roof simulator during the most extreme precipitation event of the last 47 years using the Green Roof Water Balance Model,
- Compare the model results with international literature and discuss their implications for urban planning in Bahía Blanca.

The relevance of these results is reflected in providing specific and applicable data to the climatic and geographical conditions of Bahía Blanca, which will serve as a basis for designing green infrastructure strategies adapted to the region. It is expected that the results will not only improve water management in the city but also serve as a model for implementing nature-based solutions in other urban areas with similar characteristics worldwide.

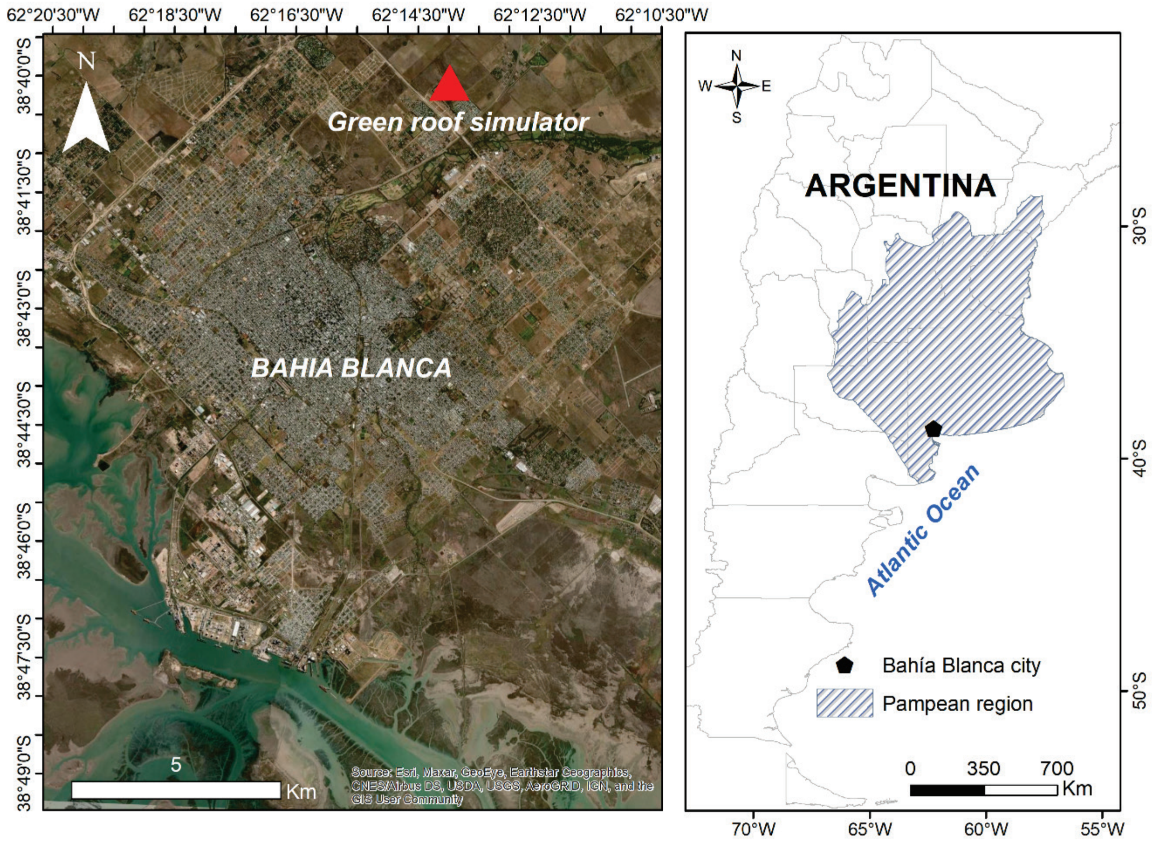

Figure 1. Location of the green roof simulator in Bahía Blanca city (Argentina).

2. Material and methods

2.1. Structure and characteristic of green roof simulator

This study analyzed one extensive green roof simulator (1 m²) vegetated with native species selected from an experimental setup of eight simulators installed in April 2021 at the Argentine Institute of Oceanography (IADO, CONICET-UNS) experimental site (Fig. 2a). This simulator was chosen because it was designed explicitly with drought-resistant native species and a substrate composition optimized for local climatic conditions. In contrast, the other seven simulators tested different combinations of exotic species and substrate compositions for other research purposes. The selected simulator was specifically designed to evaluate the performance of locally-adapted species under extreme precipitation conditions. It was divided into nine cells following a completely randomized design, with three replicates of each native species distributed randomly (Fig. 3). The green roof simulator was constructed following the guidelines of Barbaro *et al*. (2017), as follows: a waterproof membrane to prevent moisture penetration; a drainage layer to facilitate the flow of excess water toward the drains, avoiding waterlogging and oxygen deficiency in the soil; a geotextile filter layer to contain the plant roots, protect the drainage layer, and prevent the leaching of organic matter; and finally, the substrate layer composed of 80 % inorganic material (70 % pumice and 10 % perlite) and 20 % organic matter (15 % peat and 5 % compost) with a height of 15 cm (Fig. 3). The planted species were herbaceous and native (S*phaeralcea bonariensis, Aloysia gratissima, Atriplex undulata, Senecio pampeanus*), as they utilize water more efficiently and exhibit greater drought tolerance than their non-native counterparts (Butler *et al.*, 2012; Paço *et al.*, 2019), thereby ensuring better vegetation survival rates and overall green roof performance under the region's semi-arid conditions (Figs. 2 and 3).

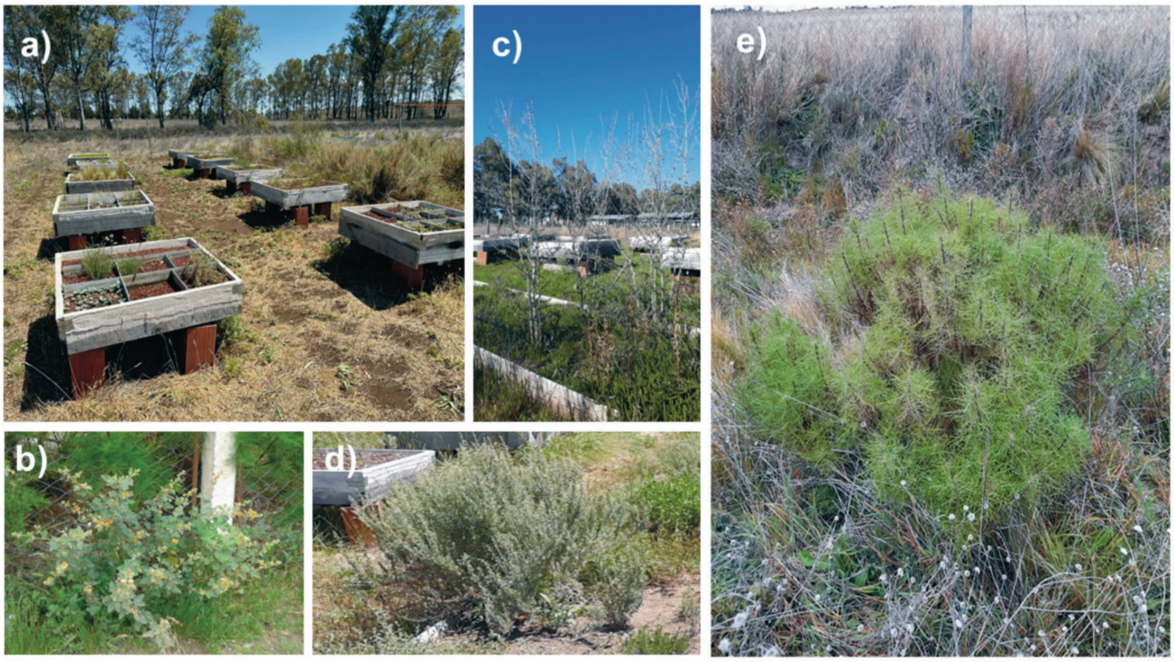

Figure 2. Experimental setup of green roof simulators at IADO experimental site and species used in this study. a) General view of simulator setup showing the eight 1m² simulators with different substrate and vegetation treatments, b) Sphaeralcea bonariensis*, c)* Aloysia gratissima*, d)* Atriplex undulata*, and e)* Senecio pampeanus.

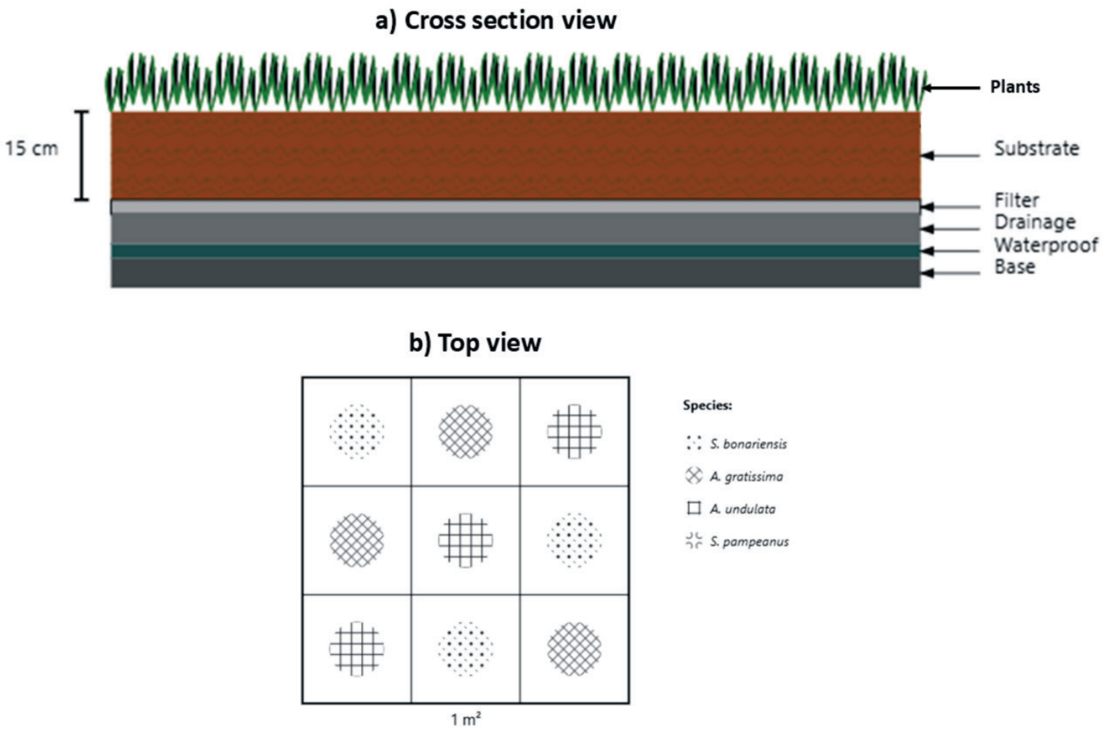

Figure 3. Schematic representation of the green roof simulator design. a) Cross section view showing the different layers, b) top view illustrating the randomized distribution of native species.

2.2. Green roof model

2.2.1. Model Overview

In this study, the GreenRoof Water Balance Model (Raes *et al*., 2006) was applied to a green roof simulator (see section 2.1.) located in Bahía Blanca city (Figs. 1 and 2). This model has been widely used in numerous urban green roofs around the world, such as in Belgium (Vanuytrecht *et al*., 2014), Poland (Burszta-Adamiak and Mrowiec, 2013), and Maryland (Starry *et al*., 2016), but it has not yet been explored in Argentina, characterized by significant climate variability and increasing extreme precipitation events in urban areas (Pérez *et al*., 2015; Ferrelli *et al*., 2019; Brendel *et al*., 2021).

The model calculates the water retained in a green roof and the amount discharged as runoff, based on precipitation and potential or reference evapotranspiration (ETo). Calculations can be performed for user-specified roofs, with or without vegetation cover. Additionally, factors affecting the balance between runoff, evaporation, and water storage can be specified: (i) roof characterization (type, area, orientation, slope, from completely protected from wind and sun to extremely windy and sun-exposed) and (ii) vegetation characterization (type of vegetation, degree of vegetation cover, substrate depth, presence of a drainage or reservoir layer) (Table 1).

The model parameters (Table 1) were based on the physical characteristics of the previously described simulator, incorporating its dimensions, vegetation coverage, orientation, slope, and field-measured water storage capacity. While direct runoff measurements were not performed, the model provides reliable estimates of hydrological performance when incorporating high-quality local measurements. Therefore, the runoff values presented in this study represent model outputs based on field-measured substrate properties and local meteorological data during the extreme precipitation event of March 23-25, 2022.

Table 1. Green roof simulator parameters and characteristics included in the model. W_{max} represents the maximum water storage capacity (mm); a_{rain} is a dimensionless program parameter related to rainfall interception based on roof orientation; Kc is the crop coefficient that accounts for vegetation characteristics; p is the threshold fraction of maximum water storage capacity below which vegetation experiences water stress.

	Parameters	Characteristics
Field-measured parameters	Vegetation	Herbaceous. Species: *Sphaeralcea bonariensis*, *Aloysia gratissima*, *Atriplex undulata*, *Senecio pampeanus*.
	Coverage (%)	75 %
	Area (m^2)	1 m^2
	Substrate Depth (cm)	15 cm
	$\boldsymbol{Ws_{max}}$	58.7 mm
Model input parameters	a_{rain}	0.0003
	Slope (°)	5°
	Orientation	North
	Kc	1.0
	p	0.5

2.2.2. Maximum water storage capacity (W_{smax})

To determine W_{Smax} (maximum water storage capacity), the substrate's field capacity (FC) and bulk density were measured *in situ*. Following the method of Cassel and Nielsen (1986), three undisturbed substrate samples were collected from the green roof simulator using metal cylinders. These samples were saturated with water and allowed to drain gravitationally until reaching field capacity. Subsequently, bulk density and volumetric water content at field capacity were determined for each sample. The obtained W_{Smax} value was 58.7 mm.

2.2.3. Daily water balance components

Incoming Water

The model determines the daily water balance, considering incoming (W_{in}) and outgoing water flows (W_{ro} and W_{ET}). Where W_{in} is the daily precipitation (mm), modified by the cosine of the slope and orientation of the roof to correct for the effect of wind on rain capture:

$$W_{in} = R_{obs} \times \Omega \times \cos\left(\frac{X \times \pi}{180}\right) \times (1 + a_{rain} \times X) \quad (1)$$

where R_{obs} is the daily precipitation (mm), Ω is the area of the green roof (m²), a_{rain} is a dimensionless program parameter, and X is the slope of the roof (in degrees). The value of a_{rain} depends on the orientation of the roof, the local wind and rainfall characteristics, as roofs oriented towards a dominant wind direction receive more precipitation than flat roofs or those oriented in other directions (Raes *et al.,* 2006). For this study, since our green roof is north-oriented, we used $a_{rain} = 0.0003$, which accounts for the influence of dominant northern winds on rainfall capture, indicating a slight increase in capture with slope for this orientation. This value was obtained from the Green Roof Water Balance Model standard correction factors for different roof orientations.

Water Storage Update

W_{Sact} (actual water storage) is calculated using a daily water balance. W_{Sact} is initialized at 0 or at a measured initial value for the first day. For each subsequent day, W_{Sact} is updated using the following equation:

$$W_{sact} = W_{sact\,(t-1)} + W_{in} - W_{ET} - W_{ro} \quad (2)$$

where $W_{sact\,(t-1)}$ is the water stored from the previous day, W_{in} is the incoming rainfall, W_{ET} is the water lost through evapotranspiration, and W_{ro} is water lost as runoff. The daily calculation follows this sequence: first, incoming rainfall (W_{in}) is added to the previous day's storage; if this sum exceeds W_{Smax} (here, 58.7 mm), the excess water becomes runoff (W_{ro}); finally, evapotranspiration losses (W_{ET}) are subtracted. W_{sact} is constrained between 0 (completely dry roof) and W_{Smax} (saturated roof).

Evapotranspiration

W_{ET} is the amount of water lost from the green roof through evapotranspiration (ET, mm), which depends on the atmospheric evaporative demand (ETo) and the characteristics of the roof.

$$W_{ET} = \Omega \times K_s \times K_c \times ETo^{*} \quad (3)$$

Where Ω is the roof area (m^2), K_s is the water stress coefficient, K_c is the crop coefficient, and ETo* is the adjusted ETo (mm/day). ETo* is the ETo adjusted for slope, orientation, and position. The slope and orientation of the roof determine the amount of radiation received and, consequently, the ETo. Additionally, the ETo is influenced by the position of the roof to prevailing winds. K_s is a water stress coefficient that modifies evapotranspiration from the roof (Kc × ETo*) and varies linearly between 0 (complete stress) when W_{Sact} is equal to zero (empty root reservoir) and 1 (no stress) above a threshold value when the vegetation on the green roof does not experience water stress. The threshold, which depends on the characteristics of the roof or vegetation, is specified as the fraction p of W_{Smax}.

The Green Roof Water Balance Model provides standard crop coefficient (Kc) values for different roof surface conditions and vegetation types (Allen *et al.*, 1998). Kc is set to 1.10 for a bare substrate layer, reflecting the high initial evaporation rate from exposed substrate surfaces. When considering vegetation, Kc values vary according to plant type: succulent-mosses have the lowest value (Kc = 0.40) due to their water-conservative nature and reduced transpiration rates; both mosses-succulents and succulent-grasses combinations show intermediate values (Kc = 0.70), while grass-herb combinations exhibit the highest coefficient (Kc = 1.00) due to their greater transpiration rates.

In our study, we selected Kc = 1.0 following these guidelines for grass-herb combinations, despite using drought-tolerant native species. This value was chosen because: (i) our green roof simulator contained a diverse mix of herbaceous species rather than solely succulents; (ii) the vegetation coverage was relatively high (75%), resulting in greater total transpiration surface area; and (iii) while these native species are efficient in water use during drought conditions, they can exhibit opportunistic water consumption during wet periods, a common adaptation in semi-arid environments with irregular precipitation patterns. This approach also allowed us to avoid underestimating potential evapotranspiration during periods when water was abundantly available, such as during the extreme rainfall event analyzed. The Kc value is then used to estimate the actual evapotranspiration rate of the green roof by multiplying it by the reference evapotranspiration (ETo).

Runoff generation

When the sum of incoming rainfall and existing stored water exceeds W_{Smax}, runoff occurs:

$$W_{ro} = W_{in} - (W_{Smax} - W_{Sact}) \quad (4)$$

where W_{ro} is the amount of water lost due to runoff (mm) when W_{in} exceeds the roof's storage capacity. W_{Sact} is the water effectively retained on the roof (mm). W_{Smax} depends on the type of roof and surface, while W_{Sact} depends on precipitation and evapotranspiration from the green roof and is updated daily. W_{Sact} varies from zero when the roof is completely dry to W_{Smax} when the roof is saturated with rain.

Vegetation Water Stress

When the water content stored in the substrate drops below the threshold fraction *p* of W_{Smax}, the stress level (S in %) for the green roof vegetation is calculated using:

$$S = 100 \times \left(1 - \frac{W_{Sact}}{p \times W_{Smax}}\right) \quad (5)$$

where *p* is the threshold for vegetation water stress, W_{Smax} is the maximum and W_{Sact} is the actual amount of water retained on the roof (mm). The threshold for vegetation water stress (*p*) was set to 0.5, indicating that plants experience water stress when water storage drops below 50 % of maximum capacity (W_{smax}). This value was selected based on the drought-tolerant characteristics of our native species, consistent with validated green roof models (Vanuytrecht *et al*., 2014; Starry *et al*., 2016; Liu *et al*., 2021; Zhang *et al*., 2021) and particularly suitable for extensive green roofs in regions with frequent water deficits.

2.2.4. Model Application and Data Input

Users can customize the roofs simulated by the Green Roof Model to site-specific conditions by adjusting the program parameters that describe the processes mentioned above. In this case, the model parameters were applied to a green roof simulator in Bahía Blanca (Fig. 2a). The values of the parameters used to apply the model are shown in Table 1. The effect of orientation, slope, and position on precipitation interception and evapotranspiration from the roof was modeled using empirical equations based on observations from the calibration site. Daily data on precipitation and potential evapotranspiration were obtained for the year 2022 from a weather station of the National Meteorological Service (SMN, Argentina), located in the peripheral area of the city. The behavior of daily precipitation was analyzed as suggested by the Expert Group on Climate Change Detection and Indices (ETCCDI; http://etccdi.pacificclimate.org). Therefore, daily precipitation exceeding 50 mm was considered extreme (Brendel *et al.,* 2021).

3. Results

3.1. Annual and Monthly Characterization of Precipitation from 1961 to 2022

Bahía Blanca has an average annual precipitation of 627.4 mm (± 145.4 mm) (Fig. 4). Additionally, it shows notable interannual variability, with a minimum of 306 mm in 2019 and a maximum of 1,086 mm in 1976 (Fig. 4a). Summer is the season with the highest precipitation (192 mm), followed by autumn and spring, which have similar values (175 mm and 173 mm, respectively) (Fig. 4b). On the other hand, winter is the season with the lowest precipitation, with an average total of 86 mm. March is the wettest month, 78.3 mm, while June has the lowest recorded precipitation levels (26.2 mm) (Fig. 4b).

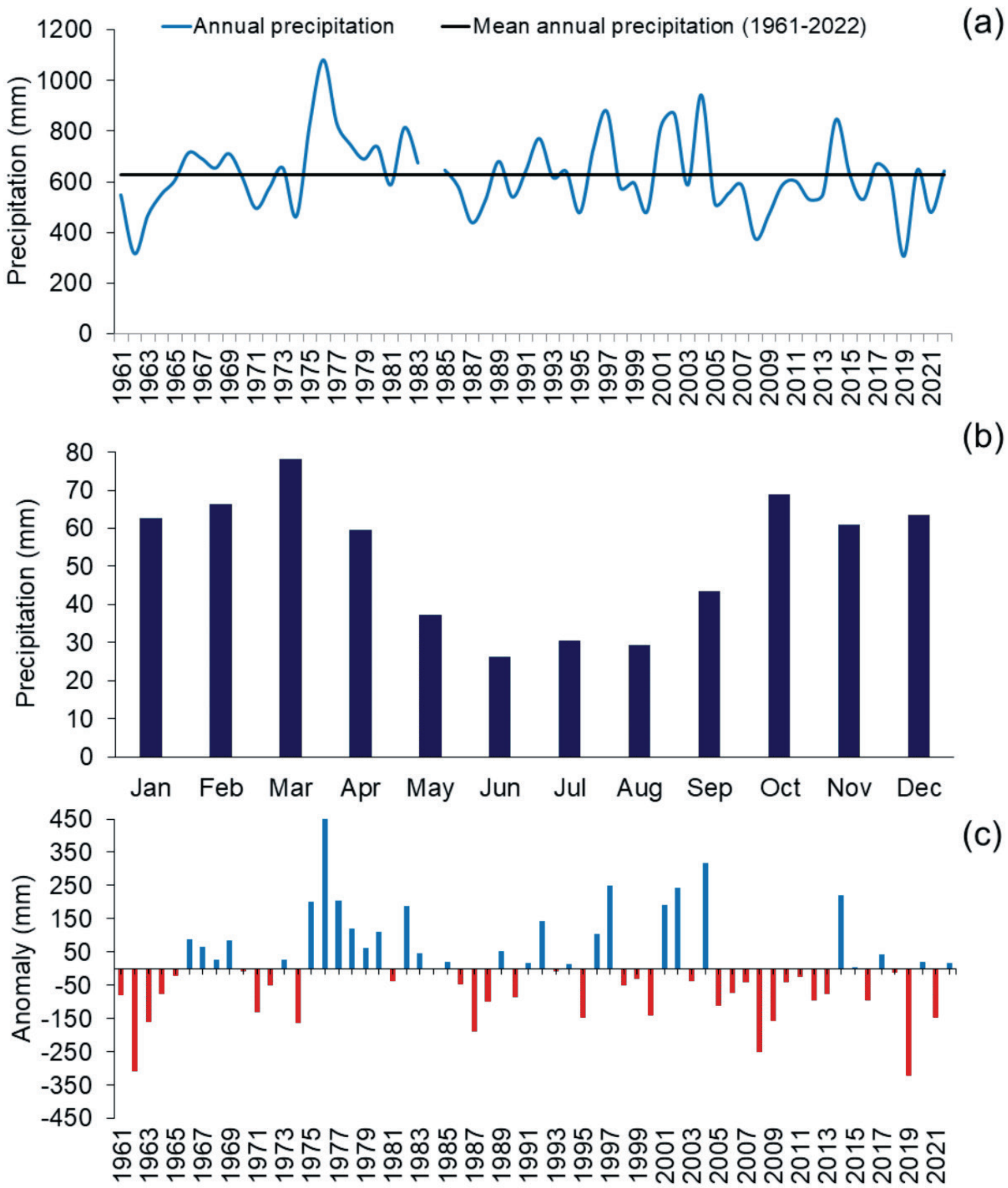

Figure 4. a) annual precipitation, b) monthly precipitation, and c) interannual precipitation anomalies in Bahía Blanca, Argentina (1961-2022).

Four well-defined periods of positive and negative anomalies were observed in the rainfall time series, demonstrating the significant interannual precipitation variability. The first period, characterized by a higher percentage of negative anomalies, extended from 1961 to 1974 (-10.1 to -310 mm), while the second occurred between 1975 and 1985, exhibiting positive anomalies (47.6 to 454.8 mm) (Fig. 4c). During this interval, six consecutive years with positive anomalies were recorded, including the year with the highest recorded precipitation (1082.2 mm, anomaly = 454.8 mm) (Fig. 4c). The third and most prolonged period was characterized by alternating positive and negative anomalies from 1986 to 2004. The fourth period (2005 to 2022) predominantly featured dry conditions (-5.4 to -286.5 mm), with the exceptions of 2014 (220 mm), 2017 (25 mm), and 2020 and 2021, which had positive anomalies of approximately 20 mm. It is noteworthy that during this period, negative anomalies were more significant than positive ones (-321 mm and 220.7 mm, respectively), and the most extreme negative anomaly over the 61 years studied was recorded (-321 mm in 2019) (Fig. 4c).

3.2. Characterization of Daily Precipitation from 1961 to 2022

Daily precipitation from 1961 to 2022 is shown in Figure 5. The most frequent occurrences are those less than 20 mm (89 %), while those between 20.1 and 40 mm represent 8 %. Precipitation events between 40.1 and 60 mm account for 2 %, and those between 60.1 and 80 mm comprise 0.5 % (Fig. 5a). Events exceeding 80.1 mm occurred only 11 times in the 62 years analyzed, with a total of eight events between 80.1 mm and 100 mm, highlighting the event on March 24, 2022, as the highest daily precipitation in the last 15 years (90.3 mm) (Fig. 5b). However, when analyzing the accumulated precipitation over three consecutive days, it was observed that the amount recorded from March 23 to 25 was the most extreme rainfall event in the last 47 years and the second most significant in the 62 years analyzed (Fig. 6). This event was characterized by a total precipitation of 150.3 mm, of which 51 mm occurred on March 23, 90.3 mm on March 24, and 9 mm on March 25 (Fig. 6).

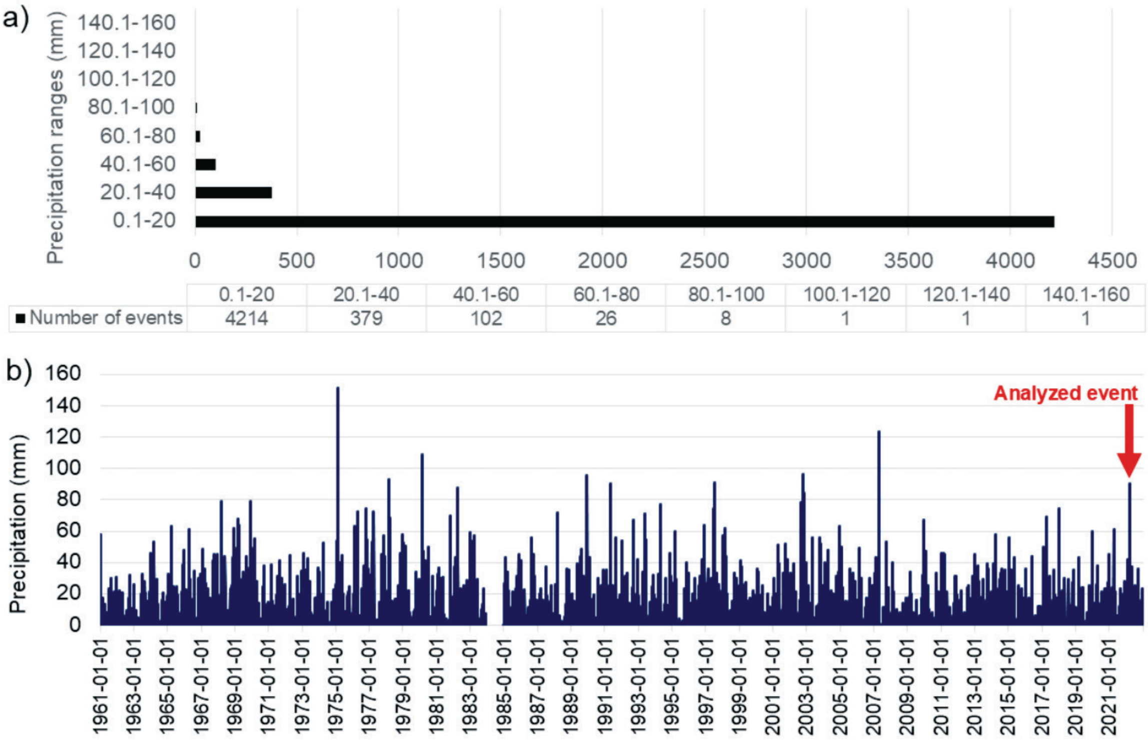

Figure 5. a) Number of events by precipitation ranges and b) daily precipitation during 1961-2022 period.

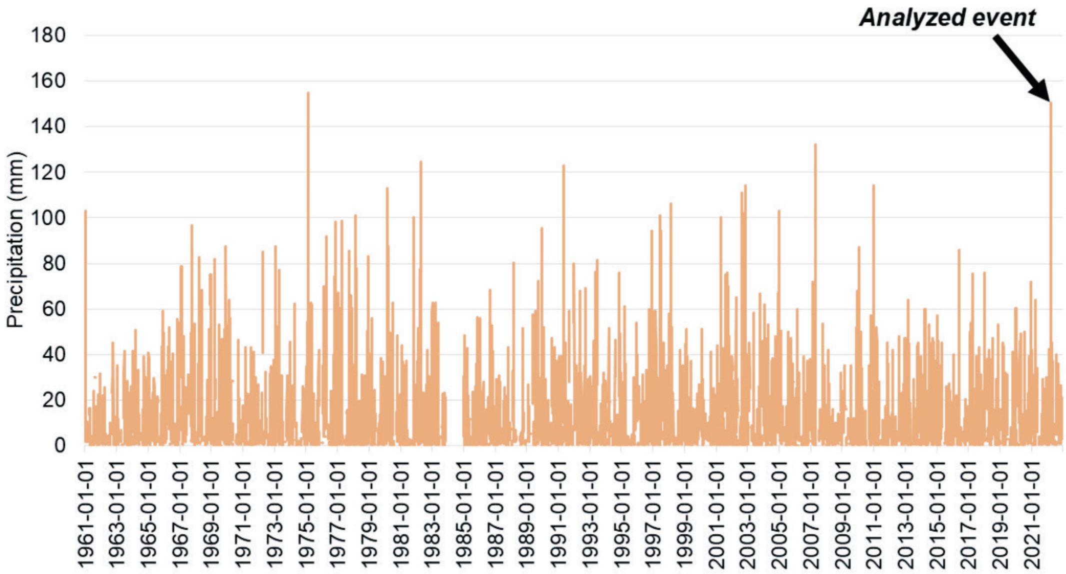

Figure 6. Accumulated precipitation over three consecutive days during 1961-2022 period.

3.3. Hydrological Response of the Green Roof to Precipitation in 2022 and During March 23 to 25

In 2022, Bahía Blanca recorded 74 precipitation events (days with precipitation > 0.1 mm), with most events (54 events, 73 %) involving less than 5 mm of rainfall, 13 events (18 %) between 5-20 mm, 4 events (5 %) between 20-40 mm, and only 3 events (4 %) exceeding 40 mm (Fig. 7a) Several periods exhibited precipitation values exceeding PET, suggesting elevated water availability, specifically during March 23-25, April 7-12, and October 23-24, 2022 (Fig. 7a). Among all precipitation events, only two generated runoffs when W_{Smax} (58.7 mm) was exceeded, representing less than 3 % of the total events (Fig. 7b). It is essential to highlight that during precipitation episodes, part of the water is retained in the soil matrix, while vegetation reduces water outflow through both canopy interception (water caught on leaves and stems) and transpiration processes, and the rest is lost through surface and subsurface runoff. A clear relationship between precipitation and evapotranspiration (PET) was observed throughout 2022 (Fig. 7a). PET, representing atmospheric water demand, exceeded precipitation for most of the year, which indicates the high annual water deficit characteristic of the regional climate (643 mm of rainfall versus 1740 mm of PET) (Fig. 7a).

The most significant runoff generation was estimated by the model during March 23-25, 2022 (Fig. 7c). Despite receiving 51 mm of precipitation on March 23, no runoff was generated during this event. Subsequently, on March 24, with rainfall of 90.3 mm, W_{Sact} reached 11.5 mm, while Wro amounted to 78.8 mm, indicating that the green roof stored 12.7 % of the incoming rain, with the remaining 87.3 % lost as runoff. This lower storage value can be attributed to elevated soil moisture content from the previous day's precipitation, which reduced the available storage capacity. On March 25, of the 9 mm of rainfall received, 4.6 mm resulted in runoff, corresponding to a storage of 48.9 %. Therefore, during the three-day event (total precipitation 150.3 mm), the green roof generated a total runoff of 83.4 mm, resulting in a cumulative storage of 44.6 % (Fig. 7c).

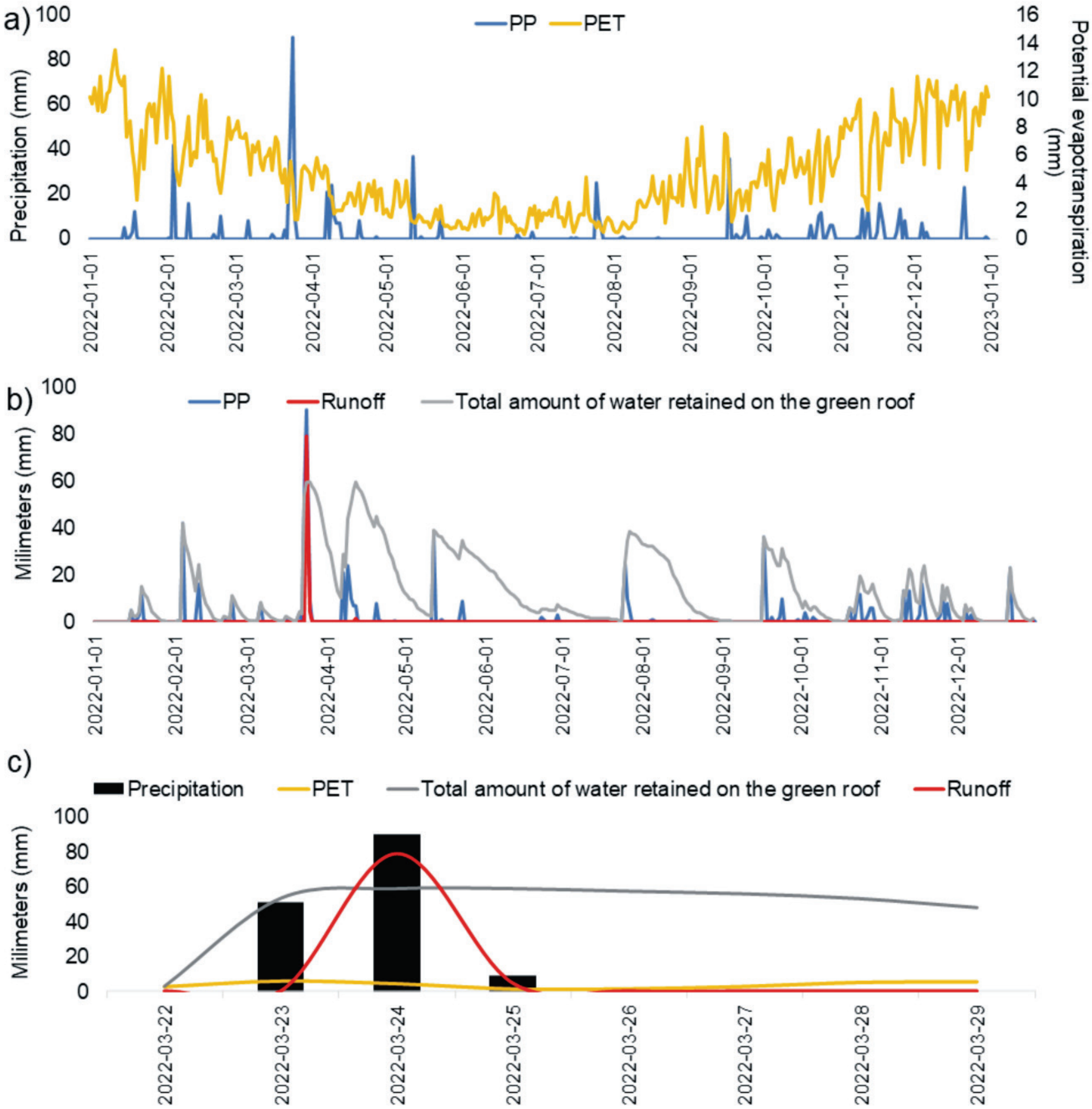

Figure 7. Hydrological dynamics of the green roof simulator. a) Daily precipitation (PP) and potential evapotranspiration (PET) during 2022; b) precipitation, runoff, and the amount of water stored in the roof in 2022 and c) precipitation, potential evapotranspiration, runoff and the amount of water stored in the roof during 22-29 March 2022

4. Discussion

The study of precipitation, particularly during extreme events, is a fundamental element in understanding climate due to the various environmental and social consequences they generate, such as flooding, soil erosion, and biodiversity loss (Brendel *et al.,* 2017). Precipitation is a highly variable parameter across different temporal scales: annual, seasonal, and daily (Bekele *et al.,* 2017; Ferrelli *et al.,* 2019). In Bahía Blanca, significant variability in precipitation has been observed over the last 62 years due to its location in a transitional zone between temperate and arid climates (Aliaga *et al.,* 2017). This variability significantly influences plant species' survival and performance on green roofs, particularly in climates with high water deficit and irregular precipitation patterns, such as Bahía Blanca (Perillo *et al*., 2023). The high variability necessitates substrate compositions and native plant selections that can rapidly adapt to sudden changes between prolonged dry periods and intense precipitation events. This ensures water storage capacity and runoff management even under extreme climatic conditions (Perillo *et al*., 2023).

The analyzed precipitation event was the most extreme in the last 47 years and the second most significant from 1960 to 2022. This situation is associated with global warming, the main cause of climate change (Padhiary *et al.,* 2018). According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021), the last four decades have been successively warmer than any other since 1850. The average air temperature in the previous two decades of the 21st century (2000-2020) was 1°C higher than in the 1850-1900 period and 1.1°C higher in 2011-2020 compared to 1850-1900. This temperature increase has primarily been driven by greenhouse gas emissions from human activities, especially CO_2 (Padhiary *et al.,* 2018), whose concentration reached peak levels in at least two million years in 2019 (IPCC, 2021). Consequently, the increase in atmospheric water vapor has modified precipitation patterns worldwide (Bekele *et al*., 2017; Muthuwatta *et al*., 2018), manifesting in Bahía Blanca with an increase in precipitation intensity over the last six decades (Ferrelli *et al.,* 2021). Looking forward, precipitation variability and extremes are projected to intensify globally (IPCC, 2021), with regional variations depending on local conditions and emission scenarios. For Bahía Blanca specifically, projections indicate increased precipitation toward the end of the 21st century, particularly under high emission scenarios (RCP 8.5) (Brendel, 2023). This trend is particularly concerning as climate change exacerbates flooding risks through increased frequency and intensity of extreme events (Avashia and Garg, 2020; Leandro *et al*., 2020). The city's vulnerability is further heightened by its location in the lower basin of the Napostá Grande stream and urban infrastructure limitations (Zapperi, 2014; Mastrandrea and Pérez, 2022), making the implementation of green infrastructure solutions increasingly critical. Given these local challenges and future climate projections, it is essential to evaluate green roof performance through reliable methodologies. Model simulations have emerged as a valuable tool to assess the hydrological performance of green roofs (Busker *et al*., 2022). Several models have been developed for this purpose, each addressing different aspects of green roof hydrology. Liu *et al*. (2021) used HYDRUS-1D to simulate runoff response under different substrate designs, while Zhang *et al.* (2021) employed a physically based model to evaluate stormwater storage during intense rainfall events. Hamouz *et al*. (2020) analyzed single events runoff from extensive green roofs in cold climates, and Shafique *et al*. (2018) proposed a comprehensive model considering different substrate compositions and rainfall intensities. In Bahía Blanca, our application of the Green Roof Water Balance Model represents the first attempt to evaluate extensive green roof performance during extreme precipitation events in this region. While the model has not undergone formal validation locally, its implementation provides valuable insights due to the incorporation of high-quality local measurements, including daily precipitation, potential evapotranspiration, and field-measured water storage capacity obtained through rigorous soil sampling and laboratory analysis.

The water storage capacity of green roofs fundamentally depends on substrate properties, vegetation types, and local climatic conditions (Akther *et al.,* 2018; Peng *et al.,* 2019). Studies have shown that climatic factors such as rainfall intensity, antecedent dry period, solar radiation, air temperature, relative humidity, and evapotranspiration rate significantly influence the hydrological performance of green roofs (Wong and Jim, 2015; Zhang *et al.,* 2021). However, in climates with significant water deficits, runoff variability is primarily attributed to precipitation, evapotranspiration, substrate water storage capacity, and initial water content before a rain event (Liu *et al.,* 2021; Todorov *et al.,* 2018). In this context, and considering the climate of Bahía Blanca, the daily variability of runoff analyzed and water storage could be linked to these factors. The variation in water storage capacity observed during the three-day extreme event (March 23-25, 2022) clearly demonstrates the influence of antecedent moisture conditions on the green roof's hydrological performance. On March 23, the green roof showed maximum storage capacity with no runoff generation despite receiving 51 mm of precipitation. This optimal performance can be attributed to initially dry substrate conditions, resulting from the characteristic high evapotranspiration rates of the warm season (PET values around 4-5 mm/day in March). However, this precipitation event significantly increased the substrate moisture content, thereby reducing its storage capacity for subsequent rainfall. Consequently, on March 24, when 90.3 mm of rain fell on the already moistened substrate, the storage capacity decreased substantially to 12.7 %, with most of the precipitation (87.3 %) converting to runoff. This behavior aligns with findings from Liu *et al*. (2021), who reported that water storage capacity in green roofs varies from 34.7 % to 48.5 % depending on initial moisture conditions, with dry substrates showing significantly higher storage capacities. While direct measurements of initial substrate moisture were not available in our study, the daily water balance calculations through the model provide valuable insights into the substrate's moisture status and its influence on storage performance. This moisture-dependent behavior is particularly relevant in Bahía Blanca's climate, where the typically dry substrate conditions favor high initial storage capacities, but consecutive rain events can rapidly reduce this effectiveness.

The green roof simulator analyzed showed optimal performance in retaining precipitation and reducing runoff generated during the most extreme precipitation event in the last 47 years, with an average water storage capacity of 44.6 % and 55.5 % runoff. These values align with those reported in numerous experimental green roof plots worldwide using validated models (Gong *et al*., 2019; Harper *et al*., 2015; Lee *et al*., 2015; Liu *et al*., 2019; Stovin *et al*., 2012; Zhang *et al*., 2021). For example, Palla *et al*. (2009) using SWMS_2D found water storage of 51.5 % during a 153.2 mm event, remarkably similar to our water storage of 44.6% during a 150.3 mm event. Similarly, Villarreal and Bengtsson (2005) reported values of 20-40 % during intense short-duration events. More recent studies have further validated these water storage ranges under various conditions. Zhang *et al*. (2021) documented values of 42.8-56.7 % during extreme events exceeding 100 mm in China, while Liu *et al*. (2021) found comparable results (34.7-48.5 %) in semi-arid conditions, emphasizing the critical role of initial substrate moisture in determining storage capacity. These findings align closely with our results, particularly considering our use of field-measured water storage capacity and local meteorological data. Additionally, Hamouz *et al*. (2020) reported similar ranges (30-45 %) during extreme events, noting decreased efficiency near substrate saturation, while Shafique *et al*. (2018) found values of 40-60 % during intense rainfall events, emphasizing substrate characteristics' importance. The consistency between our model's predictions and these validated studies, especially those conducted under similar rainfall intensities or climatic conditions, suggests that despite lacking formal validation, the Green Roof model provides reliable estimates of hydrological performance under local conditions. This alignment with international findings strengthens confidence in the model's utility for urban planning in Bahía Blanca, though future local validation would further enhance its applicability.

The hydrological performance of green roofs varies according to local climate. For instance, in a dry climate in southern Australia, water storage capacity was observed to range from 51 % to 96 % (Beecham and Razzaghmanesh, 2015), while in a humid tropical climate in Hong Kong, it varied between 24.3 % and 36.3 % (Wong and Jim, 2014). Additionally, average runoff retention is significantly higher in extensive green roofs in dry subhumid climates (75.2 %) compared to maritime climates (43.4 %) (Sims *et al.,* 2019). This corroborates that the use of green roofs in Bahía Blanca, a city with significant water deficits but intense and frequent wet events, is crucial for controlling urban runoff. On the other hand, substrate selection is fundamental as it can affect both the hydrological performance of the system and the quality of the drained water (Shafique *et al.,* 2018). The substrate significantly influences water storage capacity more than vegetation type and cover (Berndtsson, 2010; Liu *et al.,* 2019; Stovin *et al.,* 2012; Zhang *et al.,* 2019).

In this study, the substrate used is lightweight with high porosity, composed of 80% inorganic material (70 % pumice and 10 % perlite) and 20 % organic matter (15 % peat and 5 % compost), which provides high water storage capacity and good drainage properties, essential for the hydraulic dynamics of a green roof (Hachoumi *et al.,* 2021). Furthermore, the local climate, characterized by significant annual water deficits and high evapotranspiration rates in the warm season, produces a substrate with low moisture content. This characteristic is important, as studies have shown that dry substrates can store more water due to a larger water storage volume during precipitation events (Liu *et al.,* 2020). Regarding the appropriate vegetation type for extensive green roofs, the selection of species with short roots that exhibit rapid growth, low maintenance, and high tolerance to extreme climatic conditions, especially to water deficits, is suggested (Shafique *et al.,* 2018). Thus, native species selected for their drought tolerance were used in the green roof simulator (Perillo *et al.,* 2023). Furthermore, it has been shown that these species possess a remarkable ability to retain precipitation, especially during intense rainfall events (Todorov *et al.,* 2018). Therefore, considering that the study area projects an increase in the severity of rainfall in the near future, using native species is essential to mitigate the effects of climate change (Brendel, 2023).

Finally, the simulation provides robust evidence of green roof hydrological performance during extreme events, strengthened by integrating locally-adapted native vegetation and optimally selected substrate composition. This comprehensive approach generates valuable data precisely calibrated for Bahía Blanca's context, establishing a strong foundation for green infrastructure implementation in the region. Future research on full-scale installations will build upon these findings by incorporating continuous runoff monitoring systems and examining additional aspects such as edge effects, root development dynamics, and long-term maintenance. Direct runoff measurements in future studies will complement our modeling approach, providing additional insights into the temporal dynamics of water movement through the green roof system during extreme events. This combination of modeling and empirical measurements will further advance our understanding of green roof behavior in the region, ultimately enhancing their effectiveness as a climate change adaptation strategy.

5. Conclusion

This study represents the first assessment of green roof performance in Bahía Blanca. It demonstrates their effectiveness as an innovative and sustainable solution for mitigating the effects of climate change and managing urban runoff, particularly in regions experiencing frequent extreme rainfall events. The results showed that during the most extreme precipitation event recorded in the last 47 years, the green roof successfully retained an average of 44.6 % of the rainfall, significantly reducing surface runoff volume and mitigating the risk of flooding within the city.

In the context of climate change, where an increase in the frequency and intensity of extreme rainfall events is expected, adopting green infrastructure is not only a mitigation measure but also an essential strategy for urban adaptation. The information generated by this study is crucial for developing policies and strategies for green infrastructure development in Bahía Blanca and other regions with similar climatic conditions. Integrating green roofs into urban planning can significantly enhance the sustainability and resilience of cities in the face of future climate challenges.

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References

Akther, M., He, J., Chu, A., Huang, J., Van Duin, B. 2018. A review of green roof applications for managing urban stormwater in different climatic zones. *Sustainability, 10*(8), 2864. https://doi.org/10.3390/su10082864

Aliaga, V. S., Ferrelli, F., Piccolo, M. C. 2017. Regionalization of climate over the Argentine Pampas. *International Journal of Climatology, 37*(S1), 1237-1247. https://doi.org/10.1002/joc.4765

Allen, R.G., Pereira, L. S., Raes, D., Smith, M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper, 56*, FAO Rome, 300(9), D05109.

Avashia, V., Garg, A. 2020. Implications of land use transitions and climate change on local flooding in urban areas: An assessment of 42 Indian cities. *Land Use Policy, 95*, 104571. https://doi.org/10.1016/j.landusepol.2020.104571

Barbaro, L.A., Soto, M.S., Sisaro, D., Karlanian, M., Stancanelli, S. 2017. Sustratos para techos verdes sustentables (extensivos). *Ediciones INTA*.

Bekele, F., Mosisa, N., Terefe, D. 2017. Analysis of current rainfall variability and trends over Bale-Zone SouthEastern highland of Ethiopia. *Climate Change, 3*(12), 889-902. https://doi.org/10.4172/2157-7617.1000417

Beecham, S., Razzaghmanesh, M. 2015. Water quality and quantity investigation of green roofs in a dry climate. *Water Research, 70*, 370-384. https://doi.org/10.1016/j.watres.2014.12.015

Berggren, K., Olofsson, M., Viklander, M., Svensson, G., Gustafsson, A.M. 2012. Hydraulic impacts on urban drainage systems due to changes in rainfall caused by climatic change. *Journal of Hydrologic Engineering, 17*(1), 92-98. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000406

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering, 36*(4), 351-360. https://doi.org/10.1016/j.ecoleng.2009.12.014

Bohn, V.Y., Piccolo, M.C., Perillo, G.M.E. 2011. Análisis de los períodos secos y húmedos en el sudoeste de la provincia de Buenos Aires (Argentina). *Revista de Climatología, 11*, 31-44.

Brandão, C., do Rosário Cameira, M., Valente, F., de Carvalho, R.C., Paço, T.A. 2017. Wet season hydrological performance of green roofs using native species under Mediterranean climate. Ecological Engineering, 102, 596-611. https://doi.org/10.1016/j.ecoleng.2017.02.025

Brendel, A.S., Bohn, V.Y., Piccolo, M.C. 2017. Variabilidad de la precipitación y su relación con los rendimientos agrícolas en una región semiárida de la llanura pampeana (Argentina). *Estudios Geográficos, 78*(282), 7-29. https://doi.org/10.3989/estgeogr.201723

Brendel, A., Ferrelli, F., Piccolo, M.C., Perillo, G.M.E. 2021. Impacto de eventos pluviométricos sobre el caudal diario de un río de la región Pampeana (Argentina). *Interespaço: Revista de Geografía e Interdisciplinaridade, 7*(e202112), 1-22. http://doi.org/10.18764/2446-6549.e202112

Brendel, A.S. 2023. Impacto del cambio climático: Un análisis espacial del riesgo futuro al cambio climático en el sur de la Región Pampeana (Argentina). *Papeles de Geografía, 69*, 155-168. https://doi.org/10.6018/geografia.563951

Burszta-Adamiak, E., Mrowiec, M. 2013. Modelling of green roofs' hydrologic performance using EPA's SWMM. *Water Science and Technology, 68*(1), 36-42. https://doi.org/10.2166/wst.2013.238

Busker, T., de Moel, H., Haer, T., Schmeits, M., van den Hurk, B., Myers, K., ... & Aerts, J. 2022. Blue-green roofs with forecast-based operation to reduce the impact of weather extremes. *Journal of Environmental Management*, 301, 113750. https://doi.org/10.1016/j.jenvman.2021.113750

Butler, C., Butler, E., Orians, C. M. 2012. Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. *Urban forestry & urban greening*, *11*(1), 1-10. https://doi.org/10.1016/j.ufug.2011.11.002

Carter, T., Jackson, C.R. 2007. Vegetated roofs for stormwater management at multiple spatial scales. *Landscape and Urban Planning, 80*(1-2), 84-94. https://doi.org/10.1016/j.landurbplan.2006.06.005

Cassel, D.K., Nielsen, D.R. 1986. Chapter 36: Field Capacity and Available Water Capacity. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*. Soil Science Society of America. Madison, WI, USA. 2nd edition.

Driscoll, C.T., Eger, C.G., Chandler, D.G., Davidson, C.I., Roodsari, B.K., Flynn, C.D., ... & Groffman, P.M. 2015. Green infrastructure: Lessons from science and practice. A publication of the *Science Policy Exchange, 32.*

Ferrelli, F., Brendel, A.S., Aliaga, V.S., Piccolo, M.C., Perillo, G.M.E. 2019. Climate regionalization and trends based on daily temperature and precipitation extremes in the south of the Pampas (Argentina). *Cuadernos de Investigación Geográfica: Geographical Research Letters, 45*(1), 393-416. https://doi.org/10.18172/cig.3622

Ferrelli, F., Brendel, A.S., Piccolo, M.C., Perillo, G.M.E. 2021. Evaluación de la tendencia de la precipitación en la región Pampeana (Argentina) durante el período 1960-2018. *Raega-O Espaço Geográfico em Análise*, 51, 41-57. http://dx.doi.org/10.5380/raega.v51i0.69962

Gong, Y., Yin, D., Li, J., Zhang, X., Wang, W., Fang, X., Wang, Q. 2019. Performance assessment of extensive green roof runoff flow and quality control capacity based on pilot experiments. *Science of the Total Environment, 687*, 505-515. https://doi.org/10.1016/j.scitotenv.2019.06.063

Hachoumi, I., Pucher, B., Vito-Francesco, D., Prenner, F., Ertl, T., Langergraber, G., Allabashi, R. 2021. Impact of green roofs and vertical greenery systems on surface runoff quality. *Water, 13*(19), 2609. https://doi.org/10.3390/w13192609

Hamouz, V., Pons, V., Sivertsen, E., Raspati, G.S., Bertrand-Krajewski, J.L., Muthanna, T.M. 2020. Detention-based green roofs for stormwater management under extreme precipitation due to climate change. *Blue-Green Systems,* 2(1), 250-266. https://doi.org/10.2166/bgs.2020.101

Harper, G.E., Limmer, M.A., Showalter, W.E., Burken, J.G. 2015. Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. *Ecological Engineering, 78*, 127-133. https://doi.org/10.1016/j.ecoleng.2014.06.013

He, Y., Yu, H., Ozaki, A., Dong, N. 2020. Thermal and energy performance of green roof and cool roof: A comparison study in Shanghai area. *Journal of Cleaner Production, 267*, 122205. https://doi.org/10.1016/j.jclepro.2020.122205

Intergovernmental Panel on Climate Change (IPCC). 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, *et al.,* Eds.). *Cambridge University Press*. https://doi.org/10.1017/9781009157896

Leandro, J., Chen, K.F., Wood, R.R., Ludwig, R. 2020. A scalable flood-resilience-index for measuring climate change adaptation: Munich city. *Water Research, 173*, 115502. https://doi.org/10.1016/j.watres.2020.115502

Lee, J. Y., Lee, M. J., Han, M. 2015. A pilot study to evaluate runoff quantity from green roofs. *Journal of Environmental Management, 152*, 171-176. https://doi.org/10.1016/j.jenvman.2015.01.049

Li, C., Liu, M., Hu, Y., Shi, T., Qu, X. 2018. Effects of urbanization on direct runoff characteristics in urban functional zones. *Science of the Total Environment, 643*, 301-311. https://doi.org/10.1016/j.scitotenv.2018.06.211

Liu, W., Feng, Q., Chen, W., Wei, W., Deo, R.C. 2019. The influence of structural factors on stormwater runoff retention of extensive green roofs: New evidence from scale-based models and real experiments. *Journal of Hydrology, 569*, 230-238. https://doi.org/10.1016/j.jhydrol.2018.12.037

Liu, W., Feng, Q., Deo, R.C., Yao, L., Wei, W. 2020. Experimental study on the rainfall-runoff responses of typical urban surfaces and two green infrastructures using scale-based models. *Environmental Management, 66*(4), 683-693. https://doi.org/10.1007/s00267-020-01339-9

Liu, W., Engel, B. A., Feng, Q. 2021. Modelling the hydrological responses of green roofs under different substrate designs and rainfall characteristics using a simple water balance model. *Journal of Hydrology, 602*, 126786. https://doi.org/10.1016/j.jhydrol.2021.126786

Mastrandrea, A., Pérez, M.I. 2022. Representaciones sociales del riesgo hídrico: Análisis crítico del discurso periodístico en la cuenca del arroyo Napostá Grande (Bahía Blanca, Argentina). *Revista Universitaria de Geografía, 31*(1), 19-22. https://doi.org/10.52292/j.rug.2022.31.1.0039

Mentens, J., Raes, D., Hermy, M. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning, 77*(3), 217-226. https://doi.org/10.1016/j.landurbplan.2005.02.010

Muthuwatta, L., Sood, A., McCartney, M., Silva, N.S., Opere, A. 2018. Understanding the impacts of climate change in the Tana River Basin, Kenya. *Proceedings of the International Association of Hydrological Sciences, 379*, 37-42. https://doi.org/10.5194/piahs-379-37-2018

Paço, T.A., Cruz de Carvalho, R., Arsénio, P., Martins, D. 2019. Green roof design techniques to improve water use under Mediterranean conditions. *Urban science*, *3*(1), 14. https://doi.org/10.3390/urbansci3010014

Padhiary, J., Patra, K.C., Das, D.M., Sahoo, B.C., Singh, K.K. 2018. Prediction of climate change impact on streamflow and evapotranspiration in Baitarani basin using SWAT model. *Journal of Agrometeorology,* 20(4), 325-328. https://doi.org/10.54386/jam.v20i4.576

Palla, A., Gnecco, I., Laurenti, A. 2009. Hydrologic restoration in the urban environment using green roofs. *Water and Environmental Journal*, 23(3), 209-220. https://doi.org/10.1111/j.1747-6593.2008.00133.x

Paule-Mercado, M.A., Lee, B.Y., Memon, S.A., Umer, S.R., Salim, I., Lee, C.H. 2017. Influence of land development on stormwater runoff from a mixed land use and land cover catchment. *Science of the Total Environment, 599*, 2142-2155. https://doi.org/10.1016/j.scitotenv.2017.05.081

Peng, Z., Smith, C., Stovin, V. 2019. Internal fluctuations in green roof substrate moisture content during storm events: Monitored data and model simulations. *Journal of Hydrology, 573*, 872-884. https://doi.org/10.1016/j.jhydrol.2019.03.051

Pérez, S., Sierra, E., Momo, F., Massobrio, M. 2015. Changes in average annual precipitation in Argentina's Pampa region and their possible causes. *Climate, 3*(1), 150-167. https://doi.org/10.3390/cli3010150

Perillo, V.L., Brendel, A.S., Ferrelli, F., Gutiérrez, A., Vitale, A.J., Marinangeli, P., Piccolo, M.C. 2023. CO2 flux dynamics of exotic and native species in an extensive green roof simulator with hydric deficit. *Urban Climate, 49*, 101567. https://doi.org/10.1016/j.uclim.2023.101567

Pour, S.H., Abd Wahab, A.K., Shahid, S., Asaduzzaman, M., Dewan, A. 2020. Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustainable Cities and Society, 62*, 102373. https://doi.org/10.1016/j.scs.2020.102373

Raes, D., Timmerman, A., Hermy, M., Mentens, J. 2006. GreenRoof – water balance model. *K.U.Leuven University Faculty of Bioscience Engineering Division of Soil and Water Management*, Leuven, Belgium.

Rowe, D.B. 2011. Green roofs as a means of pollution abatement. *Environmental Pollution, 159*(8-9), 2100-2110. https://doi.org/10.1016/j.envpol.2010.10.029

Shafique, M., Kim, R., Rafiq, M. 2018. Green roof benefits, opportunities, and challenges–A review. *Renewable and Sustainable Energy Reviews, 90*, 757-773. https://doi.org/10.1016/j.rser.2018.03.060

Sims, A.W., Robinson, C.E., Smart, C.C., O'Carroll, D.M. 2019. Mechanisms controlling green roof peak flow rate attenuation. *Journal of Hydrology, 577*, 123972. https://doi.org/10.1016/j.jhydrol.2019.123972

Speak, A.F., Rothwell, J.J., Lindley, S.J., Smith, C.L. 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment, 61*, 283-293. https://doi.org/10.1016/j.atmosenv.2012.07.043

Starry, O., Lea-Cox, J., Ristvey, A., Cohan, S. 2016. Parameterizing a water-balance model for predicting stormwater runoff from green roofs. *Journal of Hydrologic Engineering, 21*(12), 04016046. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001451

Stovin, V., Vesuviano, G., Kasmin, H. 2012. The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology, 414*, 148-161. https://doi.org/10.1016/j.jhydrol.2011.10.022

Todorov, D., Driscoll, C.T., Todorova, S. 2018. Long-term and seasonal hydrologic performance of an extensive green roof. *Hydrological Processes, 32*(16), 2471-2482. https://doi.org/10.1002/hyp.13155

Vanuytrecht, E., Van Mechelen, C., Van Meerbeek, K., Willems, P., Hermy, M., Raes, D. 2014. Runoff and vegetation stress of green roofs under different climate change scenarios. *Landscape and Urban Planning, 122*, 68-77. https://doi.org/10.1016/j.landurbplan.2013.11.001

Villarreal, E.L., Bengtsson, L. 2005. Response of a Sedum green-roof to individual rain events. *Ecological Engineering*, 25(1), 1-7. https://doi.org/10.1016/j.ecoleng.2004.11.008

Wong, G.K., Jim, C.Y. 2015. Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning. *Landscape and Urban Planning, 143*, 173-182. https://doi.org/10.1016/j.landurbplan.2015.07.010

Yin, J., Ye, M., Yin, Z., Xu, S. 2015. A review of advances in urban flood risk analysis over China. *Stochastic Environmental Research and Risk Assessment, 29*(3), 1063-1070. https://doi.org/10.1007/s00477-014-0939-7

Zapperi, P.A. (2014). Caracterización del escurrimiento urbano en la ciudad de Bahía Blanca. *Revista Universitaria de Geografía, 23*(2), 125-150.

Zhang, Y., Xia, J., Yu, J., Randall, M., Zhang, Y., Zhao, T., Shao, Q. 2018. Simulation and assessment of urbanization impacts on runoff metrics: Insights from land use changes. *Journal of Hydrology, 560*, 247-258. https://doi.org/10.1016/j.jhydrol.2018.03.031

Zhang, Z., Szota, C., Fletcher, T.D., Williams, N.S., Farrell, C. 2019. Green roof storage capacity can be more important than evapotranspiration for retention performance. *Journal of Environmental Management, 232*, 404-412. https://doi.org/10.1016/j.jenvman.2018.11.077

Zhang, S., Lin, Z., Zhang, S., Ge, D. 2021. Stormwater retention and detention performance of green roofs with different substrates: Observational data and hydrological simulations. *Journal of Environmental Management, 291*, 112682. https://doi.org/10.1016/j.jenvman.2021.112682

Zhou, Q., Leng, G., Su, J., Ren, Y. 2019. Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. *Science of the Total Environment, 658*, 24-33. https://doi.org/10.1016/j.scitotenv.2018.12.184