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Modelling urban stormwater and irrigation management with coupled blue-green infrastructure in the context of climate change

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ABSTRACT

Urban planners must consider stormwater infrastructure to prevent floods, enhance resilience and promote sustainability, ultimately benefiting cities by minimizing damage and fostering sustainable growth. This is leading cities to consider the implementation of urban blue-green infrastructure (BGI) as an integrated approach to stormwater management. An urban irrigation model, blue-green infrastructure irrigation (B-GRIIN), has been developed that incorporates BGI and the possibility of reusing stormwater for irrigation to facilitate the design of zero-runoff urban blocks. Simulations based on rainfall time series, including an extremely dry year, have shown that it is possible to achieve a zero-water balance and provide sufficient water for irrigation by implementing coupled BGI. However, water availability in extremely dry years may limit the full irrigation of all green areas. The results have also shown that the evapotranspiration scaling factor kc has a large influence on the predicted irrigation volume and thus on the overall water balance. The B-GRIIN model makes it possible to couple the rainwater management functions of different BGIs, determine their water requirements and provide sufficient irrigation water. As a result, it can serve as a basis for holistic planning and operation of BGI in order to achieve a zero urban water balance.

Key words: blue-green infrastructure, urban irrigation, urban stormwater management, zero-runoff, zero urban water balance

HIGHLIGHTS

- Blue-green infrastructure irrigation – a new model for urban stormwater management through coupled urban blue-green infrastructure.
- It includes an irrigation module for stormwater reuse and allows the design of a zero-water balance without network discharge.
- A zero-runoff urban block has been designed for new urban development.
- Water availability for irrigation is limited in dry years.
- Evapotranspiration factor kc is critical for predicting the total water balance.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Today, the world is facing rapid global urbanization, climate change and increasing water scarcity, and cities are confronted with the consequences of global warming such as heavy rainfall, drought and heat, which defines the management of the urban water cycle as one of the most important future challenges for urban planners (Larsen *et al.* 2016). We can therefore say that we are in the midst of a paradigm shift in the way we manage water. As a result, the relationship between urban development and water resources is becoming an important part of international and national discussions to develop integrated adaptation and mitigation strategies (UNEP-DHI 2014).

To be prepared, urban planners need to consider urban water management alongside the built environment, pollution control policies and solid waste and stormwater management (Furlong *et al.* 2017). An integrated urban water management (IUWM) approach can help to improve the way resources are managed throughout the urban water cycle. It aims to include all parts of the water cycle, recognizing it as an integrated system that takes into account water needs for residential, industrial, agricultural and ecological uses, and provides a framework for planning, designing and managing urban water systems (Belmeziti *et al.* 2015; Larsen *et al.* 2016). IUWM aligns with the UN Sustainable Development Goal on water (SDG 6), which is key to creating sustainable communities (SDG 11 on cities), and directs UN member states to implement integrated water resource management at all levels by 2030 (United Nations 2015). IUWM also brings together water supply, sanitation, stormwater and wastewater management and integrates them with land use planning (Brudler *et al.* 2016; Fang *et al.* 2016; Sørup *et al.* 2020). Successful implementation requires cooperation between multiple jurisdictions over which the urban area is spread, and can help cities and water utilities develop more robust water systems to meet their needs now and in the ever-expanding urban future (Furlong *et al.* 2017). In essence, IUWM reimagines a city's relationship with water, and rethinks how water resources and associated infrastructure can be designed and managed.

Within the IUWM, stormwater management has great potential for improvement. To date, the main objective of management has been to control flooding, i.e., to collect rainwater and discharge it into the sewerage system so that it is no longer available in the city. However, changes in the distribution of rainfall, the length of dry periods and the increased frequency of heat periods are leading cities to consider countermeasures such as the integration and implementation of urban blue-green infrastructure (BGI).

In this study, we use the term BGI to refer to managed and engineered infrastructures that use vegetation for decentralized urban water management (e.g., extensive green roof, retention green roof, infiltration trench and storage infrastructure), which can be considered as multifunctional and can provide adaptation to climate change (Almeida *et al.* 2021). There is a particular focus on the development of urban green spaces and the construction of BGI (Kabisch *et al.* 2023). There is no doubt about the multifunctionality of BGI – they can address different ecosystem services such as stormwater management (Dawson *et al.* 2020), air quality (Tomson *et al.* 2021), human health (Williams *et al.* 2019), human well-being (Andersson *et al.* 2019), noise protection (Yildirim *et al.* 2022), recreational activities (Baek *et al.* 2020), microclimate (Cao *et al.* 2022), food–water–energy nexus (Bellezoni *et al.* 2021) and/or biodiversity (Pille & Säumel 2021; Donati *et al.* 2022) (Figure 1). It should be noted, however, that all of these ecosystem services mentioned will only have the desired effect if there is an adequate supply of water.

In general, however, the main focus of engineered BGI is on rainwater retention, stormwater management, infiltration or climate regulation in urban green spaces (Oberndorfer *et al.* 2007; De Vleeschauwer *et al.* 2014; Voskamp & Van de Ven 2015; O'Donnell *et al.* 2020). Increased urban densification and expansion, combined with extreme rainfall events, has led to an increase in stormwater runoff, putting tremendous pressure on existing infrastructure such as networks and centralized wastewater treatment plants (Hoffmann *et al.* 2015; Khurelbaatar *et al.* 2021). Concepts have been developed to manage and control stormwater in a decentralized and integrated manner, including low impact development (Pati & Sahoo 2022; Szeląg *et al.* 2022), water sensitive urban design (Kuller *et al.* 2017; Nguyen *et al.* 2021), sponge city concepts (Li *et al.* 2017; Chen *et al.* 2022; Siehr *et al.* 2022) and BGI (Jayasooriya & Ng 2014; Busker *et al.* 2022; Kvamsås 2022; Knappe *et al.* 2023).

The BGI concept is currently being integrated into a new development project called Leipzig416 (www.leipzig416.de) in Germany (see also www.ufz.de/leipzigerblaugruen). A major challenge in the integration of BGI in the context of urban water management is the competition for space between underground (underground car park, infiltration trench and storage infrastructure) and above-ground structures (roads, pavements, playgrounds, cycle paths and car parks), as well as the need for natural land use (e.g., tree planting and green spaces). However, urban districts can be designed in a way to combine both, with engineered BGI for ecosystem service benefits and a more compact city (McDonald *et al.* 2023). The overall objective of the project is to prevent flooding, increase the local water availability, to reduce the load on the sewerage system, improve the microclimate at the urban block level and to achieve a climate resilient urban water management through the use and integration of sustainable and resilient urban BGI.

Many studies have examined irrigation demand and water use as an important response to climate change, mainly focusing on the needs of large-scale agricultural systems (Paschold & Beltz 2010; Lupia *et al.* 2017; Schwarz-v.Raumer *et al.* 2023). For example, for outdoor vegetable crops, there is an irrigation control

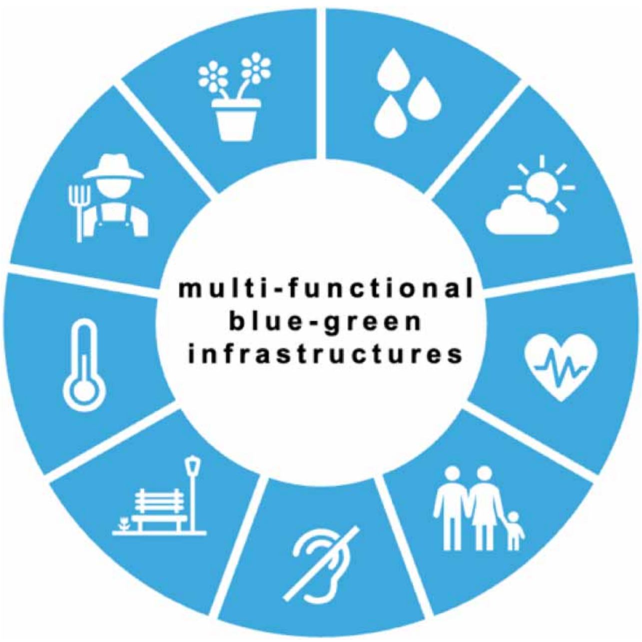

Figure 1 | Multifunctionality of blue-green infrastructure in an urban context. The individual icons, starting clockwise from the water drops, represent: stormwater management, air quality, human health, human well-being, noise protection, recreational activities, microclimate food–water–energy nexus and biodiversity.

method, the 'Geisenheim method', which considers a crop coefficient kc for many vegetable crops at different stages of development (Hochschule Geisenheim 2021). Schwarz-v.Raumer *et al.* (2023) presented a web-based tool designed to harmonize rainwater and greywater drainage while meeting the water needs of vegetation in urban green spaces. This tool integrates geographical information service (GIS) data to assess the rainwater and greywater harvesting potential within a catchment. It also calculates daily water requirements for different vegetation types, taking into account local weather patterns, shading, soil moisture and short-term soil conditions. However, the existing literature does not comprehensively address this issue in an urban context to investigate how BGI can reduce runoff and how much of this runoff is available to support BGI with irrigation.

The main objective of the City of Leipzig and the investor, in terms of stormwater management, is to ensure a zero-runoff urban district. It is, therefore, necessary to investigate the extent to which the integration of multifunctional BGIs can reduce the volume of rainwater runoff discharged into the main sewer networks, and the extent to which water is available for an optimal irrigation of green roofs, courtyards and parks, even in dry years, with rainwater collected in storage infrastructures and used for irrigation. The final results/findings will then be incorporated into the ongoing design/planning process.

The issue of incorporating or linking BGI practices for the dual purpose of stormwater management and meeting irrigation water needs in urban areas has not received sufficient attention. Therefore, in this study, we have developed and applied an irrigation model called blue-green infrastructure irrigation (B-GRIIN), which includes coupled BGIs and the possibility of including and using the collected water for irrigation.

The specific objectives of this study were (i) to perform simulations using historical rainfall data to achieve a balanced urban water system by integrating BGIs with the B-GRIIN model to eliminate network discharge; (ii) to identify the water/irrigation demand of BGIs and (iii) to determine the influence of the coefficient kc in the overall water balance of the urban district.

2. RESEARCH MATERIAL AND METHODOLOGY

2.1. Urban district: Leipzig416

On the site of the former '*Eutritzscher Freiladebahnhof*' in Leipzig, a new urban district of about 25 ha is being developed with the aim of creating an attractive and lively urban district characterized by a high proportion of green spaces. The new district will provide up to 2,400 new apartments for approximately 3,700 people, with a mix of residential and commercial buildings (Figure 2). The aim is also to make the area an environmental showcase. An overall ecological concept is being developed as part of the planning process. More than 800 individual trees will be planted, green spaces, landscaping and woody plants will be integrated into open spaces, and

Figure 2 | Overview of the Leipzig416 development, Germany. Private residential blocks and public spaces (red), which are not considered in the scope of the study. The graphic was provided by www.leipzig416.de and modified accordingly.

approximately 42,000 m^2 of public green and open spaces are planned for the area. The multi-storey buildings will be constructed of timber and will form blocks with an inner courtyard that will blend in with the existing urban development of the surrounding area (Figure 2). The development of the new urban district is designed to be compact and dense in favour of the generous public open spaces. This promotes both the urban character of the neighbourhood and a central park with its various sub-areas. The above information and more are available on the developer's website at www.leipzig416.de.

2.2. Stormwater management of Leipzig416

Stormwater management is one of the biggest challenges for the development of the urban district. The surrounding combined sewers of the municipal water utilities have already reached their maximum capacity and therefore, the city of Leipzig prohibits the discharge of rainwater into the existing network. The concept that is now being pursued is the development of a zero-runoff urban district to achieve a climate resilient urban water management through the use of sustainable and resilient urban BGI. It is planned that rainwater from private spaces will be collected/retained/evapotranspirated/stored/infiltrated in a decentralized manner on the respective properties. However, rainwater from public spaces (not covered in this study) will also be collected/retained/evapotranspirated and infiltrated semi-centrally.

2.3. B-GRIIN model assumptions and parameters

The B-GRIIN model is an estimated model not calibrated and based on the time variation of the general zero-water balance equation (Equation (1)):

$$\Delta Q_{\text{in}} / \Delta t - \Delta Q_{\text{out}} / \Delta t - \Delta (S_o - S_1)/\Delta t) = 0 \tag{1}$$

where the inflow is defined as the change in water inflow volume (ΔQ_{in}) over time (Δt), outflow is defined as the change in water outflow volume (ΔQ_{out}) over time (Δt) and storage change is defined as the sum of the amount of water (m^3) stored in the substrate (S_0) of the multifunctional surfaces (S_1) over time (Δt).

The zero-water balance equation was applied to each multifunctional surface of the coupled infrastructures for a model residential block. The model block is based on one of the residential blocks, BF05 of Leipzig416 with a total size of 6,134 m^2. It is divided into a total roof area of 3,684 m^2; an underground car park roof in the courtyard of the urban block of 1,048 m^2 and a sealed area of 1,402 m^2. In this study, extensive green roofs, a green roof on top of an underground car park, a storage infrastructure, an infiltration trench and sealed areas were combined to design a multifunctional (blue-green) residential urban block. The corresponding flow diagram is shown in Figure 3.

For the coupled blue-green infrastructure and taking into account different input parameters, the change in water flows over time of multifunctional surfaces was calculated as follows (Equation (2)):

$$(\Delta Q_{\text{in}}/\Delta t)\ (a + b) - (\Delta Q_{\text{out}}/\Delta t)\ (c + d + e + f) - (\Delta\ (S_0 - S_1)/\ \Delta t)\ (g + h) = 0 \tag{2}$$

2.3.1. Inflow

The sum of the precipitation P and irrigation water IR were considered as the inflow of water to the residential urban block (extensive green roof, underground car park roof and sealed areas).

$$a = \sum \text{Precipitation}_{\text{multifunctional surfaces}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

$$b = \sum \text{Irrigation}_{\text{multifunctional surfaces}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

2.3.1.1. Precipitation. Daily precipitation P was obtained from the German Weather Service (www.dwd.de). The Deutscher Wetter Dienst (DWD) climate station 2928 in Leipzig-Holzhausen, Germany, was chosen because it is the closest (8 km) to the Leipzig416 development (Figure 4 and Figure S1) and data obtained for 2018 and the years 2011–2022. The year 2018 was chosen as an extremely dry reference year with a recorded total rainfall of 379 mm. In addition, the 12 years 2011–2022 were chosen to represent a period of climate variability, including wet, dry and average years (2011: 552 mm; 2012: 468 mm; 2013: 606 mm; 2014:

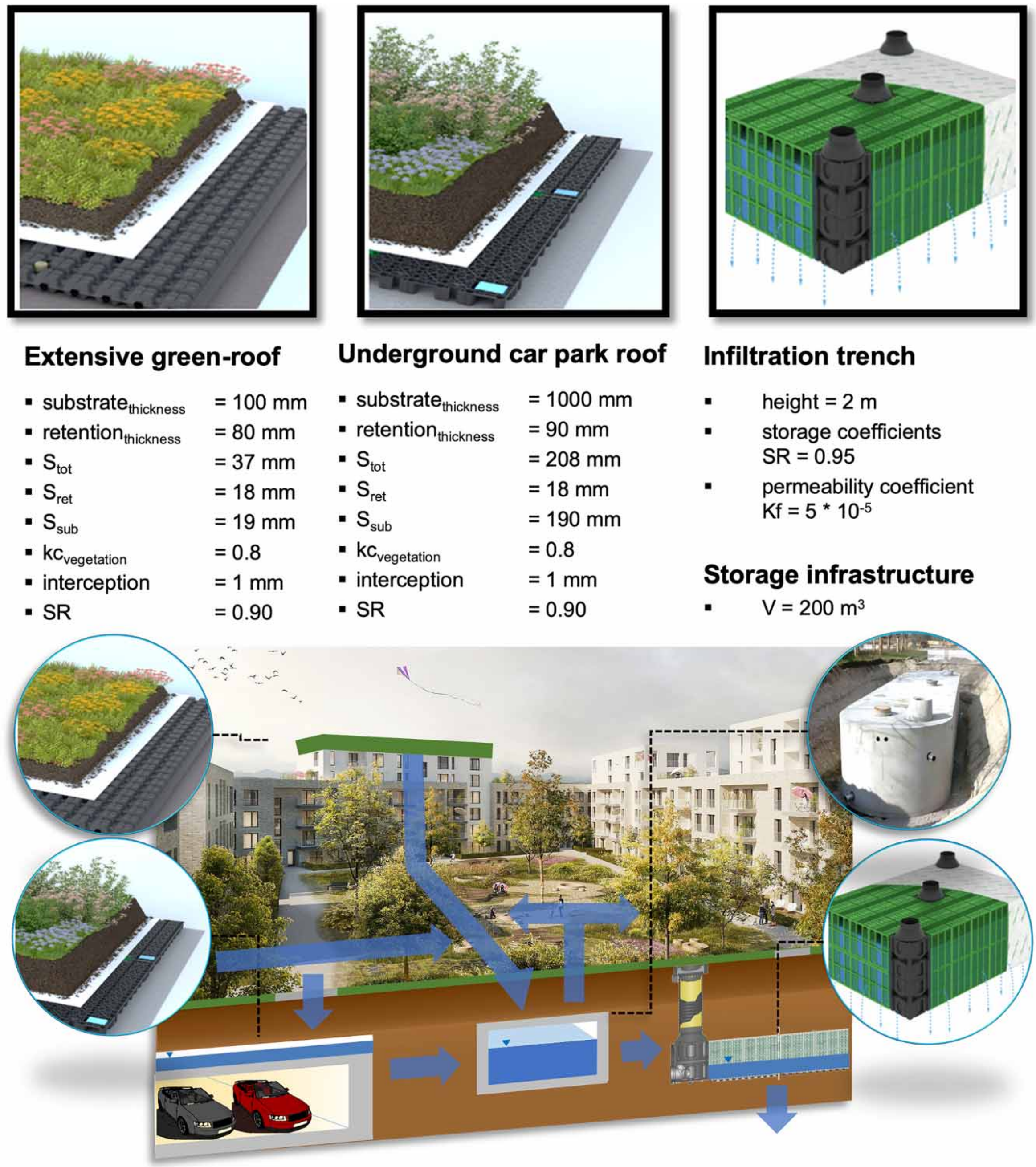

Figure 3 | Blue-green infrastructures considered: extensive green roof; green roof on top of an underground parking; infiltration trench and a storage infrastructure. The graphic shows the water flow in a model urban residential block (images of the technologies were provided by www.optigruen.de and the image of the residential block provided by 'silisight for msm Architekten' and modified accordingly by Breulmann M & Khurelbaatar G). S_{tot}: total storage; S_{ret}: retention storage; S_{sub}: substrate storage; kc$_{vegetation}$: vegetation coefficient; SR: storage coefficient of the filling material and Kf: permeability coefficient.

519 mm; 2015: 479 mm; 2016: 469 mm; 2017: 542 mm; 2018: 379 mm; 2019: 397 mm; 2020: 425 mm; 2021: 649 mm; 2022: 382 mm). B-GRIIN does not take into account conditions where part of the water in the system is immobile, e.g., freezing conditions or snow cover.

2.3.1.2. Irrigation. In order to assess irrigation needs in space and time throughout the year, it is essential to consider meteorological patterns (Schwarz-v.Raumer *et al.* 2023). Daily variations in precipitation and evapotranspiration over the course of the year play a key role in influencing the availability of soil water to plants, thereby determining the need and amount of irrigation required. The irrigation module used was modified from Paschold & Beltz (2010). The aim of urban irrigation is to maintain the water content in the

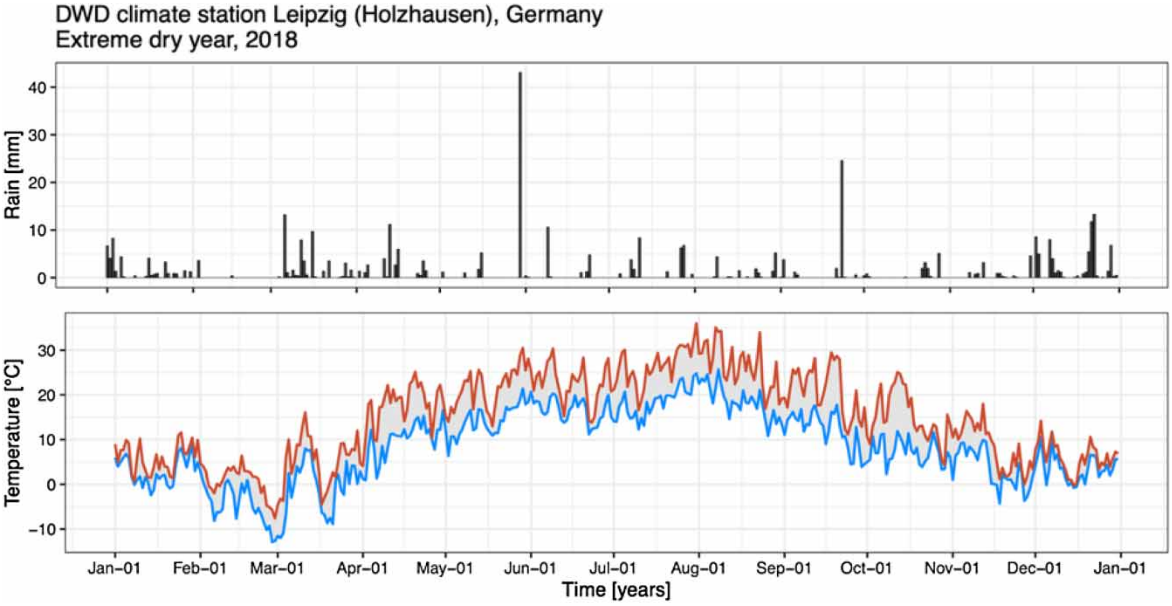

Figure 4 | Daily mean precipitation [mm] and minimum (blue) and maximum (red) temperature of the year 2018 in Leipzig (Holzhausen), Germany.

root zone at a level that allows plant growth and ensures the ecosystem services of the BGI throughout the year. The total substrate thickness of the extensive green roof and the underground car park ($S_{\text{tot-green}}$ and $S_{\text{tot-car}}$) was defined as the root zone. In this study, we further defined that the available substrate field capacity (aFC) should not fall below 30% and should not exceed 80% according to Eppel *et al.* (2012) and Hochschule Geisenheim (2021). Irrigation pulses were set to 20 mm.

A plant substrate with plant-available field capacity (FC) of 19% by volume was assumed. This refers to commercially available green roof substrates with a maximum FC in the range of 20–50% (www.zinco.de/substrate, www.optigruen.de/produkte/substrate) and a corresponding plant-available FC in the range of 10–24%. The ability of green roof substrates to store water has commonly been expressed by the maximum water holding capacity (MWHC), as defined in the German Green Roof Guideline (Lösken *et al.* 2021), but studies have confirmed that the MWHC overestimates the substrates' water holding capacity and better represents the maximum structural load. Fassman & Simcock (2012) found that agronomic measurements, corresponding to water stored between FC and wilting point, better represent the water holding capacity of green roof substrates. Thus, B-GRIIN simply expresses the water content available to the plant in the system at any given time.

The total available water storage of the extensive green roof and the underground car park $S_{\text{tot-green}}$ and $S_{\text{tot-car}}$ in the system is given by the sum of the available water stored in each substrate layer and in the retention layer. Water exchange between the layers is assumed to be instantaneous and local equilibria are reached within <1 day. However, for simplicity and modelling purposes, only the total amount of water available in the system is considered, without distinguishing between substrate and retention layer (Figure 5).

2.3.2. Outflow

For each of the multifunctional surfaces, outflow is defined as the sum of actual evapotranspiration (ET_a), interception I, groundwater infiltration (GIF) and runoff from the multifunctional surfaces.

$$c = \sum \text{Actual evapotranspiration}_{\text{multifunctional surfaces}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

$$d = \sum \text{Interception}_{\text{multifunctional surfaces}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

$$e = \sum \text{Groundwater infiltration}_{\text{infiltration trench}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

$$f = \sum \text{Outflow}_{\text{multifunctional surfaces}}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

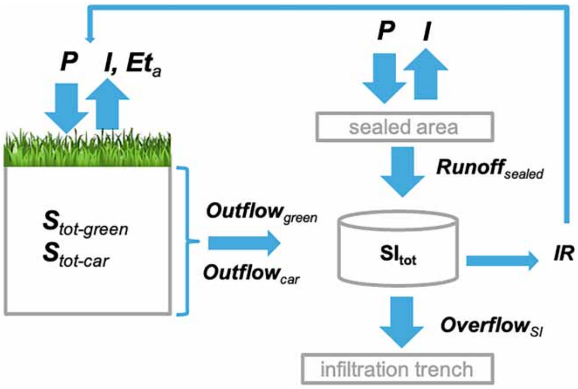

Figure 5 | Simplified overview of the zero-water balance model B-GRIIN. *P*: precipitation, Et_a: actual evapotranspiration; *I*: interception; IR: irrigation; $S_{tot\text{-}car}$: total storage of the underground car park; $S_{tot\text{-}green}$: total storage of the extensive green roof; $Outflow_{green}$: outflow of the extensive green roof; $Outflow_{car}$: outflow of the underground car park; $Runoff_{sealed}$: runoff of the sealed areas; SI_{tot}: total storage of the storage infrastructure and $Overflow_{SI}$: overflow of the storage infrastructure.

2.3.2.1. Actual evapotranspiration. Potential evapotranspiration ET_p according to Penman Monteith (see Allen *et al.* 2005) was obtained from the German Weather Service (www.dwd.de; DWD climate station 2928 in Holzhausen, Germany) for 2018 and the years 2011–2022. For the calculation of the actual evapotranspiration Et_a, an annual average crop coefficient kc (scaling factor) for grass of 0.8 was used (Sun *et al.* 2012; Pittenger 2014; Hörnschemeyer *et al.* 2021; Schwarz-v.Raumer *et al.* 2023). However, it is recognized that there may be multiple kc values for a single plant species, depending on the developmental stage of the plant and the season (Nivala *et al.* 2022). For example, during germination and establishment, most of the evapotranspiration occurs as evaporation from the soil surface. Therefore, a simplified sensitivity analysis was performed for the dry year 2018 to assess the influence of the crop coefficient kc on the irrigation requirements.

The actual evapotranspiration Et_a was calculated by multiplying the crop coefficient kc with the potential evapotranspiration ET_p from the German Weather Service (Equation (3)).

$$Et_a = kc * ET_p \tag{3}$$

2.3.2.2. Interception. The B-GRIIN model considers a constant water loss through interception *I* of 1 mm per day, which reduces the effective precipitation that infiltrates into the substrate and/or reduces the runoff from sealed spaces during each time step.

2.3.2.3. Groundwater infiltration. The overflow of the storage infrastructure is equal to the amount of water infiltrating into the groundwater from the infiltration ditch, hence $GIF = Overflow_{SI}$.

2.3.2.4. Outflow/runoff of multifunctional surfaces. The sealed area runoff $Runoff_{sealed}$ is given by the total precipitation *P* minus the interception *I* (Equation (4)) and flows into a storage facility SI:

$$Runoff_{sealed} = P - I \tag{4}$$

when the maximum water storage capacity of the substrate in the extensive green roof ($S_{tot\text{-}green}$) and the underground car park roof system $S_{tot\text{-}car}$ is exceeded, the excess water, $Outflow_{green}$ and $Outflow_{car}$, flows into a storage facility SI (Figure 5).

In the model, SI_{tot} is set to 200 m^3 as the total volume of the storage infrastructure. Excess water from SI flows into the infiltration trench ($Overflow_{SI}$). $Overflow_{SI}$ is equal to the amount of water that infiltrates from the infiltration ditch to the groundwater, therefore, $Overflow_{SI} = GIF$.

2.3.3. Change in storage

Is defined as the sum of the amount of water stored in the substrate of multifunctional surfaces over time as well as of the storage infrastructure.

$$g = \sum \text{Substrate storage}_{\text{multifunctional surfaces}}\ t_0 - \text{Substrate storage}_{\text{multifunctional surfaces}}\ t_{n+1}\ (\text{mm m}^{-2}\ \text{d}^{-1})$$

$$h = \text{SI}_{\text{tot}}\ t_0 - \text{SI}_{\text{vol}}\ t_1\ (\text{mm d}^{-1})$$

2.3.3.1. Substrate storage. For modelling purposes, we assume that the substrate and retention layers of the extensive green roof as well as from the underground car park roof are saturated on day t_0. Therefore, the total available substrate storage in the extensive green roof ($S_{\text{tot-green}}$) is 37 mm (19 mm available water stored in the substrate layer and 18 mm in the retention layer) and 208 mm (190 mm stored in the substrate layer and 18 mm in the retention layer) in the underground car park roof system ($S_{\text{tot-car}}$; Figure 3). Expressed as a sequential model, $S_{\text{tot-green}}$ and $S_{\text{tot-car}}$ depend on the previous day's storage.

2.3.3.2. Volume change of SI. As described above, the initial volume of SI_{tot} is set to 200 m^3 as the total volume of the storage infrastructure, assuming that SI was full at the start of the simulation. The change in water volume at t_1 is defined by the inflow to SI as the sum of $\text{Outflow}_{\text{green}}$, $\text{Outflow}_{\text{car}}$ and $\text{Runoff}_{\text{sealed}}$ minus the water that is used for irrigation ($\text{Extraction}_{\text{SI}} = \text{IR}$) and the $\text{Overflow}_{\text{SI}}$.

2.4. Scenarios definition

In order to develop comparable stormwater management scenarios for private areas, a 'model block' was used for the calculation (see Section 2.3).

In order to simulate the water balance of the private spaces, the following scenarios were considered for the private and public areas:

Scenario 0 (S0): Baseline scenario. No consideration of the extensive green roof (GR_{roof}) and the underground car park roof system (GR_{car}).

Scenario 1 (S1): Consideration of both types of green roof (GR_{roof} and GR_{car}) but no irrigation.

Scenario 2 (S2): Consideration of both types of green roof (GR_{roof} and GR_{car}) and irrigation of the underground car park roof only (GR_{car}).

Scenario 3 (S3): Consideration of both types of green roof and irrigation of both (GR_{roof} and GR_{car}).

3. RESULTS AND DISCUSSION

Based on the objectives of the City of Leipzig and the investor for the development of a zero-runoff urban district, the irrigation model B-GRIIN was developed to model the total water budget of residential, private areas. The basic principle for determining individual irrigation inputs is based on the usable FC in the root zone of the vegetation and its evapotranspiration. By integrating and coupling irrigated and non-irrigated green areas with sealed areas, infiltration and storage structures, the water balance with and without irrigation of sub-areas can be estimated for the model block.

In the baseline Scenario 0, without any BGI, the majority of the rainwater, approximately 68%, is discharged into the network over the 12-year period considered (2010–2022; Figure 6). In order to achieve the main objective of the City of Leipzig and the investor, the development of a zero-runoff urban district, this is the amount of water that needs to be collected/retained/evapotranspirated/stored/infiltrated in a decentralized manner at block level. With the integration of the BGI (Scenario 1), such as the extensive green roof and the roof of the underground car park, a large amount of water (42%) is lost through evapotranspiration and approximately 33% can be stored/infiltrated (Figure 6). Adding the irrigation component for the courtyard (Scenario 2), a sufficient amount of water (33%) can potentially be stored/used for an optimal irrigation, where the irrigation demand is 3% of the total available water. In addition, depending on the ecosystem services to be addressed by the extensive green roof (Figure 1), sufficient water is also available to irrigate both the courtyard and the extensive green roof, with a significantly higher irrigation demand of 28% (Scenario 3; Figure 6). Selecting appropriate thresholds for irrigation could optimize the benefits of extensive green roofs, guaranteeing significant water savings and proper plant establishment (Tomasella *et al.* 2022), and could lead to better cooling efficiency in cities, for

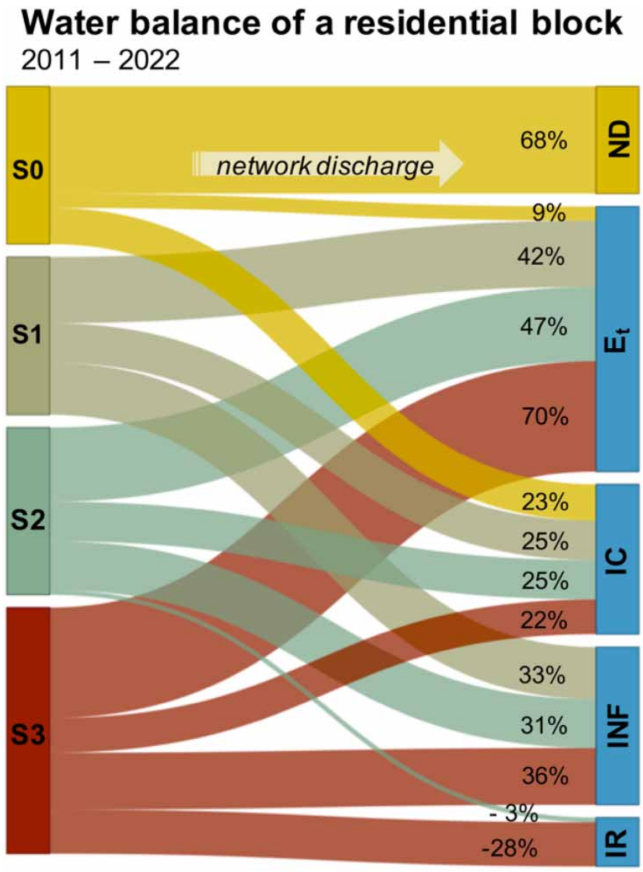

Figure 6 | Water balance of the calculated scenarios S0, S1, S2 and S3 for a model residential block in the urban district for the years 2011–2022. ND: network discharge; E_t: evapotranspiration; IC: interception; INF: infiltration and IR: irrigation need. Calculated on a daily basis from 2011 to 2012, but representing the average condition over the whole period.

example (Cirkel *et al.* 2018). By modelling the blue-green scenarios over 12 years, it has been shown that it is possible to achieve a zero-runoff water balance with the blue-green infrastructure, in addition to providing irrigation water from the cistern for the courtyard and potentially for the extensive green roof (Figure 6).

To date, the literature on this topic is still scarce. However, Schwarz-v.Raumer *et al.* (2023) follow the same basic idea to better understand the relationship between urban water collection and irrigation needs, and address three key questions: (i) how much water can an area supply, (ii) what is the amount of water needed to sustain vegetation in that area? and (iii) what storage capacity is needed to bridge the gap between rainfall and irrigation periods?

As shown for the dry year of 2018, 28% of the available water is needed to irrigate the entire urban block. This requires a sufficiently large storage infrastructure (e.g., a cistern) and is associated with high investment costs. To estimate a suitable cistern volume for the block, the volume of water in the storage infrastructure was simulated over time for S3 of the 12-year simulation. Required storage volume fluctuates greatly, especially in dry years such as 2018 (Figure 7). In order to ensure a sufficient water supply even in dry years and to avoid high investment costs, the use of groundwater as a storage space is a promising alternative.

Looking at the overall water balance over the course of the extremely dry year 2018, the simulations showed that a zero-runoff water balance can also be achieved. A 'self-sufficient' blue-green rainwater management system is possible as a zero-runoff residential block with an irrigated courtyard (Figure 8). The integration of BGI (Scenario 1) results in large amounts of water (45%) being lost through evapotranspiration (Figure 8). For the irrigation of the courtyard (Scenario 2), a sufficient amount of water (20%) can also potentially be stored/used for an optimal irrigation, as the irrigation demand is also 20% of the total available water in the dry year 2018 (Figure 8). However, if the extensive green roof is irrigated in addition to the courtyard, the water availability in dry years like 2018 limits the full irrigation of all green areas at residential block level. Van Mechelen *et al.* (2015) and Shahmohammad *et al.* (2022) also showed that by controlling and monitoring irrigation regimes, water can be

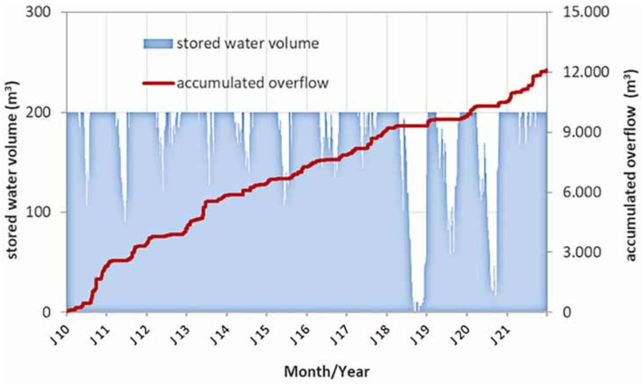

Figure 7 | Water volume in the storage infrastructure of 200 m^3 size of the years 2010–2021 in Leipzig (Holzhausen), Germany.

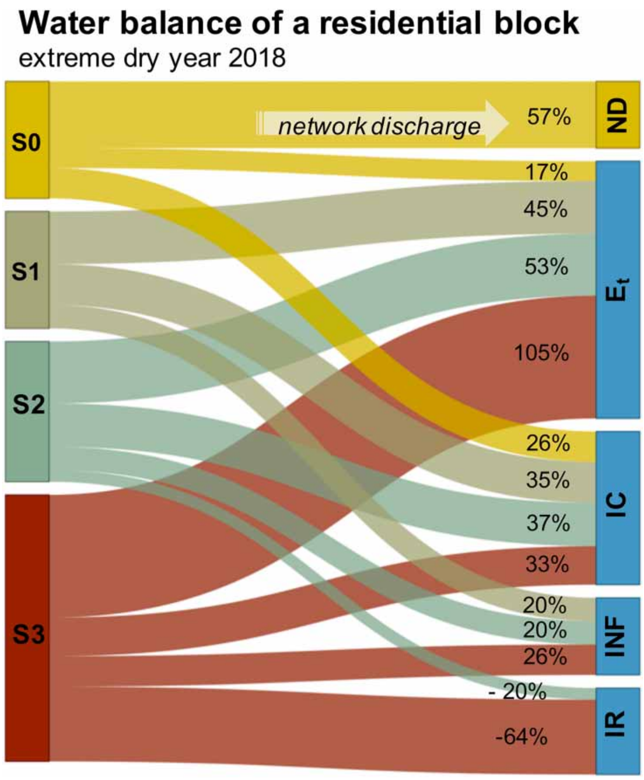

Figure 8 | Water balance of the calculated scenarios S0, S1, S2 and S3 for a model residential block in the urban district for the extremely dry year 2018. ND: network discharge; E_t: evapotranspiration; IC: interception; INF: infiltration and IR: irrigation need.

saved for irrigation needs. Irrigation is essential for all types of green roofs during establishment and the first growing season, and thereafter for green roofs in (semi-)arid climates, and in small amounts in other climates.

A simplified sensitivity analysis was performed for the dry year 2018 to assess the influence of the crop coefficient value kc on the irrigation requirements. It was shown that the scaling factor (kc) used to estimate the actual evapotranspiration has a large influence on the predicted irrigation volume and thus on the overall water balance (Figure 9). This result underlines the central importance of the scaling factor for the process design and the need to specify the factor as a function of climate, vegetation, technology and location and to calibrate it to real infrastructure. Similar results were reported by Nivala *et al.* (2022), where evapotranspiration dynamics in saturated treatment wetlands were highly seasonal and evapotranspiration loss in small wetlands was not adequately described by a single value scaling factor (kc).

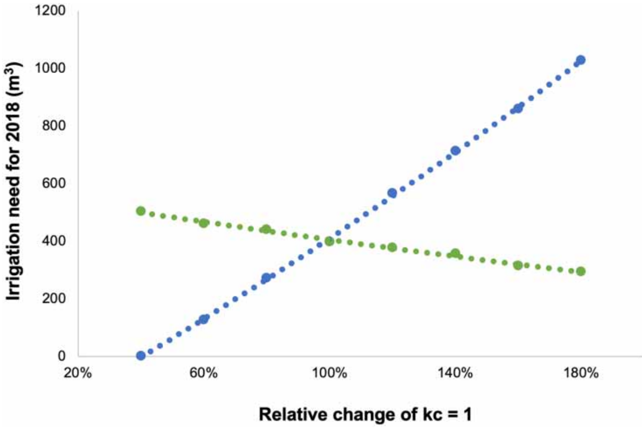

Figure 9 | Change in value of the crop coefficient kc (green line) and its influence on optimal irrigation needs (blue line) in the extremely dry year 2018.

4. CONCLUSIONS

The implementation of BGI in an urban context has become increasingly interesting and can contribute to climate change adaptation and mitigation. In this study, we developed and applied an irrigation model called B-GRIIN and identified the water/ irrigation demand of BGI using the collected/available water for irrigation. In order to achieve a positive and zero-water balance without network discharge, BGI was coupled and integrated into the B-GRIIN model. The modelling results over a 12-year period show that it is possible to achieve a zero-water balance by implementing BGI at the block level, and to provide additional water for the irrigation of the courtyard (underground car park roof) and possibly the extensive green roof. Irrigation is particularly important to establish stable urban vegetation throughout the year, in order to fully utilize the engineered water management and ecosystem services of the BGI. The B-GRIIN model uses a general crop coefficient factor (scaling factor) kc of 0.8 for grass, but we have also shown that this has a large influence on the predicted irrigation volume and thus on the overall water balance. This result highlights the importance of the scaling factor in process design and the need to specify the factor as a function of climate, vegetation, technology and site. Further research is needed to calibrate the model to real infrastructure at city scale. There is no doubt that B-GRIIN is a simplified model based on an idealized system, but it can serve as a benchmark to further investigate the influence of BGI on the overall urban water balance and to support the integrated planning process for climate resilient cities.

A practical implementation of the integrated concepts of a 'Water Sensitive City' requires (a) the coupling of heavy rainfall management and irrigation of BGI + urban green; (b) placing the availability of land and water as essential design variables at the centre of blue-green planning; (c) a precise (quantitative) definition of the targeted water management functions (flood control, irrigation and cooling) while maintaining the natural local water balance and (d) the interdisciplinary engineering design of coupled BGI.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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