Balancing water demand reduction and rainfall runoff minimisation: modelling green roofs, rainwater harvesting and greywater reuse systems

Domniki Stratigea and Christos Makropoulos

ABSTRACT

Recent years have seen a growing interest in more distributed approaches towards stormwater management, often integrated with other forms of distributed management of urban water such as water demand management technologies. This paper focuses on the role of green roofs (GR), rainwater harvesting (RWH) and greywater reuse and their integration at the building level. A number of models were developed to simulate these systems, and provide design curves able to simultaneously minimise both total runoff volumes and the amount of potable water used in the building (for irrigation and toilet flushing). The models developed were applied to the design of stormwater infrastructure for the building of the National Gallery, in Athens, Greece. A sensitivity analysis of various model parameters was conducted, with results suggesting, *inter alia*: (i) a significant decrease of total runoff volumes for rainfalls of medium-to-small return periods; (ii) a significant influence of the plant factor on water requirements (with implications for selecting vegetation for GR in a Mediterranean climate); and (iii) a significant impact of latent heat peaking during the months of June and July. The trade-off, on runoff volumes, between percentage of green roof area and the dimensions of the water storage tank was also investigated. The results suggest that the most preferable solution for conserving potable water was RWH combined with greywater recycling, while for runoff minimisation the best option was the combination of green roof and greywater recycling.

Key words | green roofs, greywater reuse, rainwater harvesting, stormwater management

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INTRODUCTION

Traditional stormwater management practices are designed to quickly convey the stormwater from urban land towards the nearby natural water bodies. During the 1990s, a new approach in stormwater management emerged, commonly known as Water Sensitive Urban Design in Australia (CSIRO 1999; Donofrio *et al.* 2009), Sustainable Drainage Systems (SuDS) in the UK (CIRIA 2007) and Low Impact Development in the USA (Coffman 2000; EPA 2007). All of these related concepts are essentially about controlling stormwater at the source by the use of micro-scale, distributed controls (Sansalone *et al.* 2008). These micro-controls aim to mimic a site's predevelopment hydrology by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source (Makropoulos *et al.* 1999; Coffman 2000; EPA 2007).

In this context and considering the lack of available urban land space to place such distributed controls, green roofs (GR) may be one of the most well-known and ubiquitously applicable technologies of this kind (CIRIA 2007; Ward *et al.* 2013). Benefits of GR are numerous, including, but not restricted to, providing part of the water demand (Goonrey *et al.* 2009), improving air quality (Banting *et al.* 2005; Currie & Bass 2008), providing thermal performance and roof insulation (Takakura *et al.* 2000; Carter & Butler

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2008), reducing urban heat island effects (Alexandri & Jones 2008; Rozos *et al.* 2013) and noise disturbance (Van Renterghem & Booteldooren 2009), increasing biodiversity (Gedge & Kadas 2005) and ameliorating stormwater (Mentens *et al.* 2005; van Woert *et al.* 2005; Carter & Rasmussen 2006). Depending on which of the above benefits is targeted, either an extensive (lightweight) green roof or an intensive (heavier) green roof can be installed (FLL 2002).

Unfortunately, this distributed (source) control of runoff comes at the price of increased water needs for irrigation, especially in arid and semi-arid climates (such as, for example, the Mediterranean). It has been suggested, however, that this obstacle can be overtaken with the combined use of rainwater harvesting (RWH) and greywater reuse technologies (Makropoulos & Butler 2010; Rozos & Makropoulos 2012).

- *Rainwater harvesting* is a term that describes the collection, conveyance and storage of the rainwater for later use. The factors that are taken into account in calculating the quantity of stored rainwater include the temporal distribution of the rain, the collection area and collection losses, while the quality of rainwater is affected by air quality, the collection area (land-based or roof-based) and the residence time of water within the rainwater tank (Liu *et al.* 2010). Even taking these quality issues into account, roof surfaces provide a relatively clean source of water which needs little treatment for reuse (Gould & Nissen-Petersen 1999). In addition, RWH is a simple technology with little maintenance and low running costs (Environment Agency 2008).
- *Greywater* is the water coming from showers, baths, washbasins, washing machines and (sometimes) kitchen sinks. Its production and quality depend on household activities, habits and the products used in everyday life in the household (Jefferson *et al.* 1999). The treatment method used is highly dependent on the greywater source. The treatment technologies that are being used for this purpose include physical, chemical, biological and extensive treatment technologies. Minimum standards for greywater reuse vary from country to country (e.g. Pidou *et al.* 2007). In general, greywater from bathtubs, showers and washbasins is the least polluted and hence these are the most common sources for reuse (FBR 2005).

In this paper we develop models describing the possible interaction between GR, RWH and greywater reuse (GWRU) at the building level, in order to produce design curves for such systems and simultaneously minimise total runoff volumes and the amount of potable water used indoors (for irrigation and toilet flushing). We present the methodology and modelling approach, followed by a description of the case study (the National Gallery in Athens). Results are presented in the form of both timeseries and design curves and also include an attempt to capture heat island effects. The paper concludes with recommendations for practitioners and policy makers.

METHODOLOGY

Models

Three model variants were introduced to describe the different water cycles that are generated within the household when using decentralised technologies such as GR, RWH and GWRU (Figure 1).

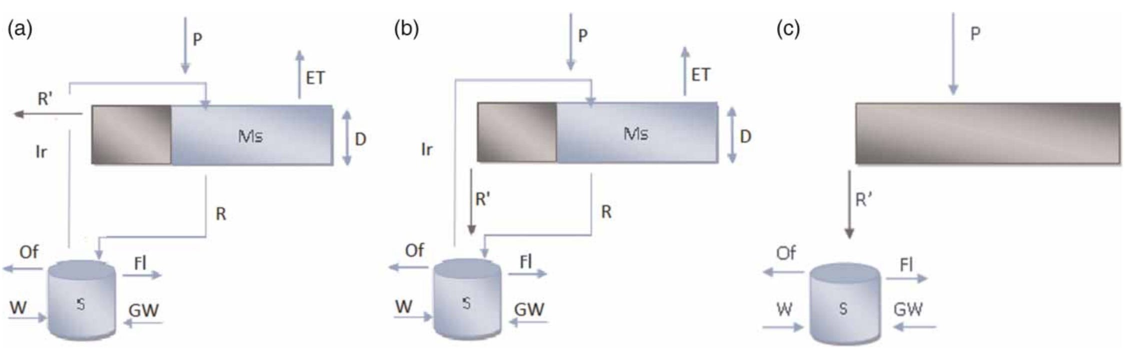

Figure 1 | Structure of the GR-RWH-GWRU model (a), the GR-GWRU model (b) and the RWH-GWRU model (c).

- The first model (GR-RWH-GWRU) combines all the aforementioned technologies.
- The second model (GR-GWRU) includes only a green roof and a greywater system.
- The third model (RWH-GWRU) consists of a RWH and a greywater system, without a green roof.

A simple water mass balance approach was implemented in the models with the following expressions developed to describe the processes within each model:

GR-RWH-GWRU model

Mass balance equation for green roof

$$P + Ir - ET - R = Ms \quad (1)$$

Mass balance equation for the water storage tank

$$R + GW + W - Fl - Of - Ir + R' = S \quad (2)$$

GR-GWRU model

Mass balance equation for green roof

$$P + Ir - ET - R = Ms \quad (3)$$

Mass balance equation for the water storage tank

$$R + GW + W - Fl - Of - Ir = S \quad (4)$$

RWH-GWRU model

Mass balance equation for the water storage tank

$$GW + W - Fl - Of + R' = S \quad (5)$$

where:

P = Precipitation during the time interval, t (m^3).
Ir = Irrigation during the time interval, t (m^3).
ET = Evapotranspiration during the time interval, t (m^3).
R = Runoff from green roof during the time interval, t (m^3).
Ms = Growing media storage – soil moisture at the end of time interval, t (m^3).
GW = Greywater during the time interval, t (m^3).
W = Additional water during the time interval, t (m^3).
Fl = Flushing during the time interval, t (m^3).
Of = Overflow during the time interval, t (m^3).
R' = Runoff from RWH during the time interval, t (m^3).
S = Water tank storage at the end of the time interval, t (m^3).

Mass balance for the green roof

The FAO Penman–Monteith method was selected to determine the reference crop evapotranspiration (PET) (Allen *et al.* 1998). When solar radiation data, relative humidity data and/or wind speed data are missing, the reference crop evapotranspiration is estimated using the Hargreaves PET equation (Hargreaves 1983). Crop water use is computed using the reference crop evapotranspiration and a crop coefficient. The soil moisture is calculated with a modified Thornthwaite model (Thornthwaite 1948) as follows:

$$Pt + Ir_t > ET_t \quad Pt + Ir_t < ET_t \quad (6)$$

where:

$Ms_{t+\Delta t} = Ms'_t + Ir_t + P_t - ET_t$.
$Ms'_t = \min\,(Ms_t,\ Ms_{max})$.
$R_t\ Ms_t - Ms'_t$.
$Ms_{t+\Delta t} = Ms_t \times e^{[I_t + P_t - ET_t)/Ms_{max}]}$.
$Ms'_t = \min\,(Ms_t,\ Ms_{max})$.
$R_t = Ms_t - Ms'_t$.

It should be mentioned that the maximum amount of water that a growing medium can hold within its structure against the pull of gravity is termed *field capacity* of the growing medium (Ms_{max}) (Lindeburg 2003; Chorley 1984) and it can be quantified with laboratory tests (FLL 2002). On the contrary, the parameter Ms_{min} is defined as the *permanently retained moisture* and is not easily measured (Kasmin *et al.* 2010; Stovin *et al.* 2012). Regarding irrigation, two different irrigation rates (discussed in the next section) were assumed whenever the ratio of the soil moisture Ms_t/Ms_{min} reached specific values.

Mass balance for the water storage tank

Both the initial volume and the capacity of the storage tank in the model are determined by the user. At each step, when the volume of the water in the storage tank is less than the required amount for irrigation, water is added to the system (W) through external water supply. The quantity of additional water was assumed to be equal to the difference of the total demand and the current storage tank volume. Conversely, if the difference of tank inflows and current volume of storage tank minus the tank outflows is greater than the capacity of the storage tank, the excess water volume is allowed to overflow.

Energy demand during evapotranspiration (En)

Water consumes energy to evaporate, which leads to cooling of the surrounding air. This amount of energy is calculated by the following expression (Rozos *et al.* 2013):

$$En = 0.000278 \times d \times A \times ET \times \rho_w \times \lambda (\text{kWh/day}) \quad (7)$$

where:

d = Calendar days of each month.
A = Green area (m^2).
ET = Evapotranspiration (m^3/month).
ρ_w = Density of water (kg/m^3).
λ = Latent heat of vaporisation (or latent heat flux) (kJ/kg).

The models operate on a daily time step and as such do not take into account diurnal variations (e.g. for indoor uses). The user-determined parameters are as follows, for each part of the model.

- *For the green roof*: The percentage of green roof; the normal and high values of irrigation and the corresponding safety coefficients; the crop coefficient Kc; the depth of growing media D; the field capacity Ms_{max}; the permanently retained moisture Ms_{min}; the initial amount of water in the media storage $Ms_{t=0}$.
- *For the RWH technology*: The coefficient of effectiveness: a coefficient which includes the collection losses and the filter efficiency.
- *For the water storage tank*: The capacity S and the initial amount of water in the tank $S_{t=0}$.
- *For flushing*: The toilet-flushing capacity and the average number of users.
- *For greywater*: The average flow rate of washbasins and showers; the average water volume used for a bath; the average number of users.

Case study

All models were applied for the preliminary design of a combined system of RWH, green roof and greywater recycling for the building of the National Gallery in Athens, Greece. The average daily visitors of the National Gallery were estimated as 1,095. The roof area is 1,963 m^2. All hydrological variables (rainfall, temperature and relative humidity) were collected from the meteorological station of Zografou (http://www.hoa.ntua.gr/), which is located reasonably close to the Gallery. The time step of the hydrological variables was 10 minutes and, in order to be compatible with the daily time step of the model, the values were converted to daily values. The historical daily timeseries for the sunshine duration were obtained from the Hellinikon meteorological station (http://freemeteo.com). The analyses were performed for a period of 7 years (2005–2012).

For the GR-RWH-GWRU model it was assumed that 60% of the roof area would be covered by an extensive green roof. Turf grass and sedums were selected for vegetation. The depth of growing media was fixed at 0.06 m, while the minimum and the maximum media storage were 21 m^3 and 46 m^3 respectively. The initial amount of water in the media storage was equal to Ms_{max} to avoid early irrigation needs.

In the remaining 40% of the roof area, it was assumed that a RWH system would be installed. The coefficient of effectiveness was considered to be 0.9. The capacity of the water storage tank was 200 m^3. The greywater was collected from the Gallery's washbasins after appropriate treatment. The daily quantity of the treated greywater was calculated as 2.45 m^3. Whenever the ratio of the soil moisture Ms_t to the Ms_{min} reached specific values (in this example 1.3 and 1.4), two different irrigation rates were available: a 'regular' and a 'high' volume added to the system, corresponding to 5 mm × (area of green roof) and 8 mm × (area of green roof) respectively. Finally, the volume of water from toilet flushing was set to 6 L/flush.

For the GR-GWRU model all parameters were set exactly the same, with the exception of the absence of a RWH scheme which results in a different storage tank (70 m^3). This is smaller than the storage tank of the GR-RWH-GWRU system (200 m^3), given that in this case the remaining 40% of the roof, which is not green, can be considered a traditional 'black' roof (TBR), with rainwater running off immediately. Lastly, for the RWH-GWRU model, all parameters were set exactly the same, with the exception that in this case, rainwater is harvested from the entire roof. Subsequently, the total runoff from GR-RWH-GWRU was compared with runoff from the TBR of the National Gallery. A sensitivity analysis of various parameters was conducted and the model was optimised for (a) reduction of runoff and (b) reduction of required additional water from external supply. Moreover, the latent heat and the energy demand during evapotranspiration were estimated. Results and comparisons of the three models are discussed next.

RESULTS AND DISCUSSION

The results from the GR-RWH-GWRU model for the hydrological year 2007–2008 can be seen in Figure 2 (left). In particular, the daily distribution of inflows and overflows of the water storage tank are displayed. Additional water was needed for irrigation from mid-May to late September, when stored water was practically zero.

In Figure 2 (right) the response of the TBR and the GR-RWH-GWRU roof for the hydrological year 2005–2006 is demonstrated. The results for the GR-RWH-GWRU model showed that total runoff decreased significantly in casual rainfall, but the system behaved similarly to the TBR during heavy storms because the media storage became fully saturated.

Furthermore, the GR-RWH-GWRU model was optimised for (a) reduction of runoff and (b) reduction of required additional water from external supply. The results are displayed in Figures 3 and 4 in the form of design nomograms. The objective of reducing the total runoff volume can be achieved by increasing the percentage of green roof and/or increasing the dimensions of the water storage tank (Figure 3(a)). Accordingly, the objective of minimising the need for additional water can be achieved either by lowering the percentage of green roof or by augmenting the volume of the tank (Figure 3(b)). In the extreme case where the goal is solely the minimisation of the total runoff volume, one can observe that the percentage of green roof needs to reach 100%. On the other hand, when the goal is the minimisation of the additional water need, selecting no green roof was the obvious result (Figure 4). Clearly, when the percentage of green roof increases the percentage of RWH system decreases, and vice versa.

A (univariate) sensitivity analysis of the parameters examined (crop coefficient, depth of media storage and Ms_{min}) to water demand and runoff volumes revealed that only the crop coefficient had a direct influence on water requirements. Increase of the value of crop coefficient (K_{c}) led to an increase of water demand and a reduction of total runoff volume (Figure 5).

The modelling also captured changes in evapotranspiration with a peak in the months of June and July and

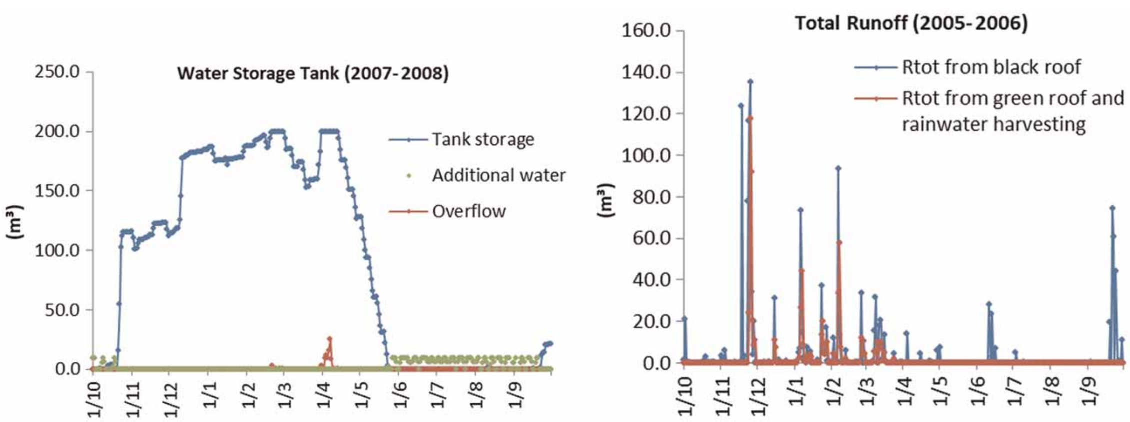

Figure 2 | (left) Daily fluctuations of the water tank storage, overflow and additional water required for irrigation; (right) comparison between total runoff volumes from GR-RWH-GWRU and TBR.

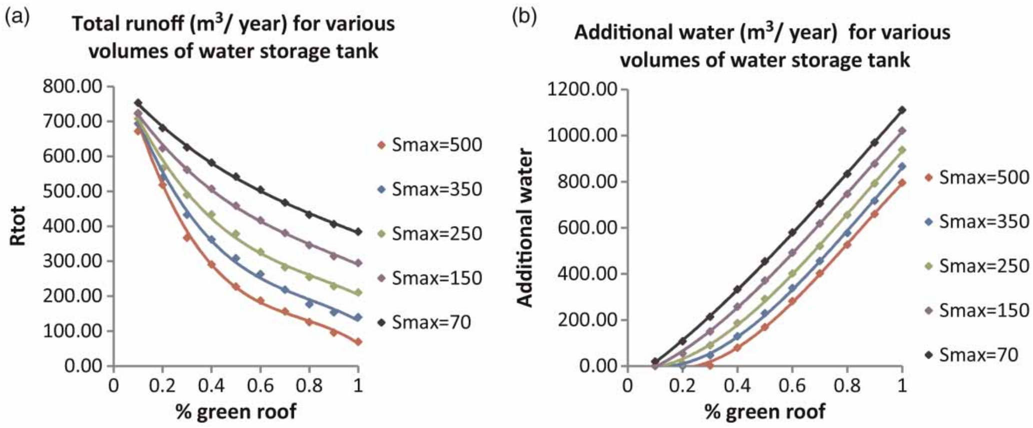

Figure 3 | Relationship between percentage of green roof and (a) total runoff; (b) additional water for various volumes of water storage tank.

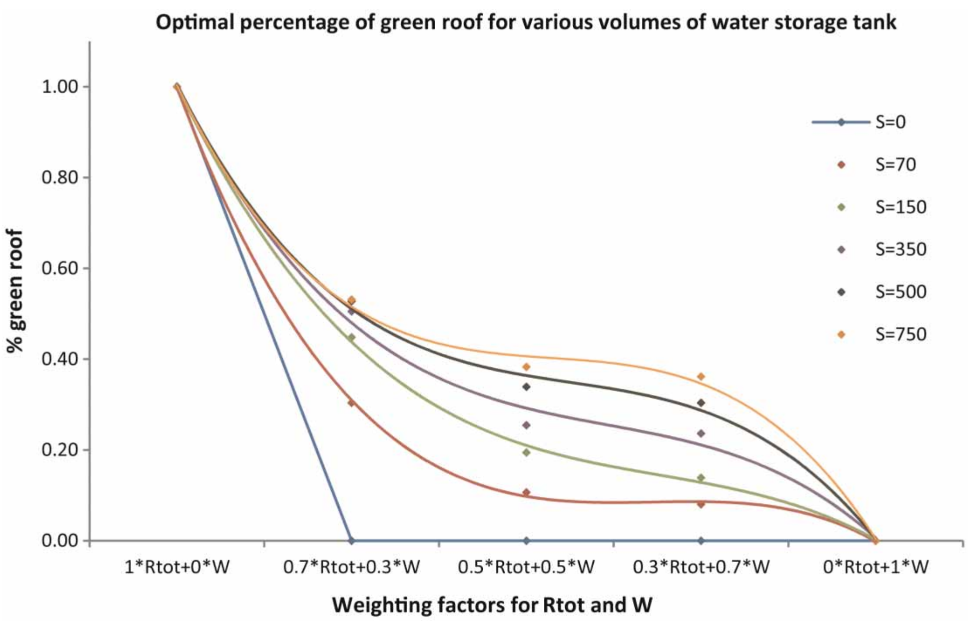

Figure 4 | Relationship between percentage of green roof and degree of focus on minimisation of total runoff and additional water for various volumes of water storage tank.

translated it to energy demand (Figure 6). This energy can be considered as a direct (and quantifiable) benefit of such an irrigated green roof towards mitigation of the heat island phenomenon, which is quite significant in urban areas in the Mediterranean during summer (see also Rozos *et al.* 2013).

Finally, a comparison of the three models shows that the annual average quantity of additional water requirement was 444.2, 635.46 and 0 m^3 for the GR-RWH-GWRU model, the GR-GWRU model and the RWH-GWRU system, respectively, while average annual quantities of runoff are 369.22 m^3, 599.77 m^3 and 874 m^3, respectively. Hence the most preferable solution from a potable water conservation perspective is the RWH-GWRU system, while the opposite holds true for a flood management perspective, with the GR-RWH-GWRU system being the most desirable.

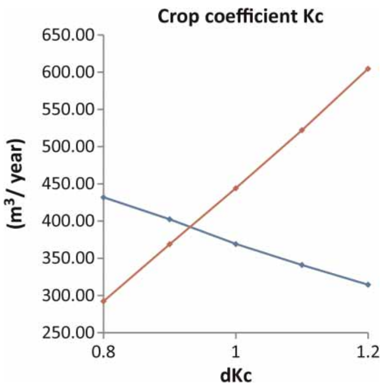

Figure 5 | Sensitivity analysis for the crop coefficient Kc (red line: water demand; blue line: total runoff volume). The full colour version of this figure is available online at http://www.iwaponline.com/ws/toc.htm.

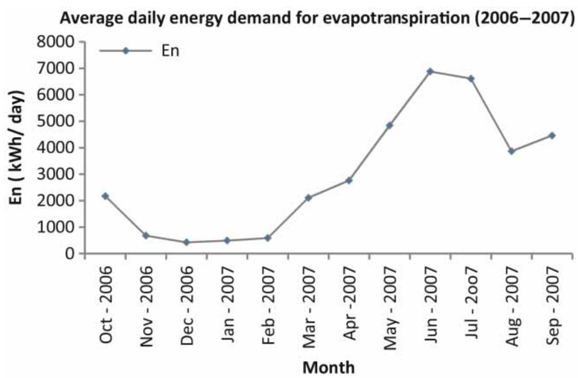

Figure 6 | Distribution of energy demand associated with evapotranspiration within a year.

CONCLUSIONS

In this study three mass-balance models were developed to describe an urban water system consisting of some or all of the following subsystems: a green roof, a water storage tank, a RWH and a GWRU subsystem. The purpose of the overall system was to minimise total runoff volume and use of potable water for activities such as irrigation and toilet flushing. The models were tested in the case of the building of the National Gallery in Athens, Greece. The analysis indicated that the total runoff was reduced substantially compared with a 'standard' black roof. As was to be expected, water demand was increased during summer (particularly due to the hydrometeorologic conditions of Athens) as a result of the green roof's irrigation. However, it was shown that the necessary additional water could be controlled, if a smaller green roof or a bigger reservoir was installed. It was further shown that the use of treated greywater from the washbasins of the National Gallery, although used mainly to cover the Gallery's demand for toilet flushing in our case, did contribute to the reduction of irrigation needs – and this could be pronounced if no indoor reuse took place. It was also suggested that, due to the increase of evaporation during the summer months, a decrease of local urban heat island effect could also be achieved. The models developed allow the design of such systems by practitioners, where each solution is customised to the designer's preference towards either water conservation or flood control (and any balanced approach in between), so that an optimal percentage of green roof–RWH can be identified, for the specific hydrometeorological and case (demand/runoff) conditions and constraints. It is finally argued that such interventions should be considered within the wider context of interactions between blue and green city infrastructure (Rozos *et al.* 2013), which could provide a way forward towards more resilient and robust cities of the future.

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