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Evapotranspiration from Green Infrastructure: Benefit, Measurement, and Simulation

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Abstract

Green infrastructure (GI) is a common solution for stormwater management in an urban environment, with attached environmental benefits like flood control, urban heat island relief, adaptations to climate change, biodiversity protection, air pollution reduction, and food production. Evapotranspiration (ET) controls the GI's hydrologic performance and affects all related benefits. Essentially, ET constrains the turnover of moisture storage and determines the demand for supplemental irrigation and then the cost-effectiveness of a GI project. Considering the spatial heterogeneousness of an urban space and the GI's multi-layer designs, the classic ET equations have challenges in representing the ET variations from GI units. The underperformance of the existing ET models is partly due to the lack of corresponding high-quality field observations for each GI type in various urban settings. This chapter, therefore, summarizes the current research progress and existing challenges regarding the benefit, measurement, and simulation of ET process from GI.

Keywords: green infrastructure, evapotranspiration, stormwater, drainage, urban heat island, ecosystem service, bioretention, green roof, permeable pavement

1. Introduction

During the past decade, green infrastructure (GI) gradually becomes a favorable concept to be associated with sustainable solutions to manage firstly water then later energy and food nexus in the urban environment. Traditional drainage infrastructure (often referred to as gray infrastructure) makes use of pipelines to rapidly export stormwater out of urban domain and then mitigate the rising flood risk induced by the expansion of impervious surface through urbanization. This water deficit then has to be resolved by importing high-quality potable water back into cities for irrigation and other uses [1]. In contrast to gray infrastructures with dull appearance and often hidden under covers, the visible components and lively forms make GI a more persuasive concept that is easily accepted and appreciated by the public. As a bridge connecting the water and energy cycles, evapotranspiration (ET) affects the overall performance of GI and will only receive more attention in the near future when more sub-disciplines can be taken into consideration.

The term green infrastructure emerged in the United States in the 1990s representing a network of green space stitching together the fragmented urban

areas [2]. Its function in the field of stormwater management was widely realized only until the last decade, but the scope of GI quickly expands to involve other urban drainage terms such as Low Impact Development (LID), Best Management Practice (BMP), Stormwater Control Measure (SCM), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDS), and Alternative Technique (AT) or Technique Alternative (TA) [3]. Besides the vegetated formats like green roof, bioretention, and vertical greenery systems [4, 5], GI also evolves to include other nonvegetation-based devices such as permeable/porous pavement and rainwater harvesting system designed for places, where vegetated GI is impractical to use due to heavily polluted runoff or the competing drinkable water demand [1]. More broadly, conventional urban green space, e.g. urban lawns, forests, farmlands, parks, and public gardens, has been used as a type of GI [6–9], owing to their capacity to promote retention and ET, as so-called natural water retention measures [10]. Recently, lakes and surface waters (so-called blue space) have futher been regarded as GI for improve local groundwater recharge, cooling, water purification, dust control, and a esthetics in an urban environment [11–13].

Evaporation happens directly from the water surface and porous media like soil, gravel, or permeable pavement. Transpiration occurs through the stomata on leaves as a subprocess of plant respiration. As two quantities are difficult to separate during measurement and modeling, they are often counted and treated as a total as referred to ET. As a stormwater management strategy, GI harvests and retains stormwater in the urban landscape [14], and then reuses and drains the captured water partly by ET. Evapotranspiration process also draws heat from surface when converting liquid moisture into vapor. It, therefore, provides a mechanism to mitigate the urban heat island effect [1]. The proportion of ET within urban water and energy budgets usually rises with vegetation coverage [8]. But only taking a small fraction of the urban surface, GI can provide an order of magnitude larger ET compared to the evaporation contribution from impervious surface [15]. Being spatially distributed within the street canyons, GI imports evapotranspiring "cool spots" into the urban ecosystem.

Previous research has given extensive reviews of the overall benefits of GI and listed ET as a process that requires more studies [16–18]. A critical review centering on ET process in GI, however, is lacking for GI community up to date. Therefore, this work endeavors to summarize the current research progress of ET with regards to GI and the knowledge gaps that restrict the development of the disciplines. Based on a survey of 100+ relevant peer-reviewed journal articles and book chapters in the previous decade, three current research areas are identified, which include the ecosystem service, measurement, and simulation of ET process from GI.

2. Ecosystem benefits of evapotranspiration from green infrastructure

Green infrastructure provides a wide spectrum of ecosystem services far beyond stormwater management as it is being accepted by more disciplines. Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life [8]. The ecosystem services of GI can be classified into four types: provisioning, regulating, cultural, and habitat [19]. Most current studies focused on its regulating service, since GI can regulate temperature [20] and air quality [21] as well as remedy stream-related water quantity and quality issues (so-called urban stream syndrome) such as

alternations in flow regimes, morphology, water and sediment quality, and associated biological composition [22–24]. From the cultural perspective, GI creates more green space accessible by the public and adds amenity values to municipal infrastructures [25, 26]. Green infrastructure also can be used as arable space to promote urban agriculture and to supplement the local food chain [27–31]. A study in Bologna, Italy, found that 82 ha green roofs could provide more than 12,000 tons year^{-1} vegetables that satisfy 77% of the city's yearly demand [28]. Lastly, vegetated GI provides habitats to protect biogeographic representativity, ecological coherence, and landscape connectivity [28, 32–34].

Evapotranspiration is relevant to most of those ecosystem services such as improving urban air quality, carbon sinks, and biodiversity and enhancing the local rain-driven water cycle [35]. But most of the current publications mainly associate ET with three ecosystem services of GI including urban heat island relief, baseflow regulation, and water budget reestablishment. These three perspectives are discussed in detail.

2.1 Urban heat island relief

Since dark paint and material of impervious surfaces tend to trap heat, urban environments usually have higher air temperature compared to surrounding suburban areas. This is referred to as the urban heat island (UHI) effect. In urban areas, material heating and anthropogenic heat release warm the near-ground air, maintaining the UHI effect and increasing building's energy consumption [36]. During drought periods, cities may have to restrict irrigation use, which further facilitates the development of uncomfortable urban climates with intensified heating and drying [1]. Introducing green and blue space in cities is often seen as a cost-effective strategy for mitigating UHI effect, since ET process is able to convert a large portion of incoming solar radiation into latent heat leaving from the urban surface [37–39]. Such active cooling can be realized by common GI which contains a vegetation layer and a moisture storage. Active cooling can also come from nonvegetated GI such as pervious pavement and water bodies where soil or open water evaporates [11–13]. Though the cooling effect of water bodies is not widely agreed [40]. Furthermore, GI takes advantage of the space (e.g. rooftop, external wall, and subsurface) that is rarely used otherwise. Therefore, although a single GI only takes a limited space, the network of GI can overall increase the ET strength of a city and contribute to mitigating the UHI effect.

A green roof is a GI type that is commonly adopted and studied to mitigate UHI effect and reduce building energy cost, because it does not take ground area in a dense city. The rooftop usually represents the top elevation of an urban valley and receives the intensive sunshine without much shade, so planting rooftops tends to provide effective cooling benefit. A study based on EnergyPlus simulations found that green roofs could reduce the annual building energy consumption by 3.7% [41]. The cooling effect depends on the green roof coverage and climate zones. An observation has shown that green roof reduced the temperature of the urban boundary layer (from the rooftop level up to a few kilometers in elevation) by 0.3 and 0.2°C per 10% increase of green roof coverage at daytime and nighttime, respectively [42]. The same study also shows that the cooling effect of green roof can be even stronger than the reflective (cool) roof with the same roof coverage. The reduction in highest electricity peak because of green roof implementation ranges from 5.2% in hot-dry climate to 0.3% in temperate climate [43].

The cooling effect of the green roof highly depends on its roof coverage and the substrate moisture content. Irrigation can improve the cooling performance of

green roofs by enhancing ET [39]. Under well-watered conditions, the nighttime air above green roof can be even colder than the cool roof, though the reverse may be found during the daytime [42, 44]. With unrestricted irrigation, green roof has a comparable cooling potential as the white roof, but green roof becomes less effective when only sustainable irrigation (harvested roof runoff) or no irrigation is available [45]. During dry summer, mean daytime Bowen ratio (sensible heat flux/latent heat flux) above a green roof could reach 3, as a typical value for the urban environment; while during wet periods, mean daytime Bowen ratio can be as low as 0.3 [46]. The substrate volumetric water content is recommended to be at least 0.11 $m^3 m^{-3}$ to maintain a favorable green roof energy partitioning (Bowen ratio < 1) [46]. In a study in Australia, the daytime Bowen ratio on top of a green roof reduced from above four during dry conditions to less than one after irrigation; however, the sensible heat flux on the green roof was still larger than that on the cool roof [47]. A downside of applying irrigation is that the increased moisture content may build a notable heat sink, which partly offsets the cooling effect; therefore, finer soil mix with fewer mesopores and minimized moisture storage was recommended to reduce the heat-sink effect [36]. Apart from supporting active cooling, irrigation is necessary for establishment, survival, and success of green roof plants in semi-arid and arid climates [48]. Deficit watering strategy (adapting to the vegetation requirement) and alternative sources (gray water, harvested rainwater, or condensed water from air conditioning) can be tested for controlling irrigation demand [48, 49]. So far, the role of irrigated GI for cooling urban areas is still not fully examined yet, while less is known regarding how the optimum type, amount, and arrangement of GI units influence the overall cooling effect [50].

The choice of plant species also affects the cooling effect of a green roof. Sedum, though proposed as the default green roof species, often comes with incomplete plant cover, sluggish transpiration, and limited substrate moisture storage, which altogether result in a weak ET cooling effect or even a downward heat transmission toward indoor space that raises the cooling load [36]. Sedum provided no significant cooling potential over a soil substrate roof alone, so adding a thin cover of white gravel or stones on top of the green roof is recommended to increase the albedo [47]. Furthermore, sedum is also difficult to maintain and subject to the widespread decline caused by high temperature and humidity [36, 49]. Plants with higher transpiration rates and denser foliage have better cooling effect and create a blanket on top of substrate and roof to block heat transmission [36]. A promising option is woodland vegetation, which, with a 1-m substrate, can filter 90% of incoming short-wave radiation during daytime [51]. Although a deeper substrate (>10 cm) was often preferred because of the larger moisture storage [48], shallow-rooted plants like sedum may not able to take this advantage [49].

Urban greening in the street canyon level includes mesic lawns and shade trees. Their cooling effect, limited by the vegetation abundance and moisture content as well, tends to be more effective over desert/xeric than over mesic/oasis landscapes [42]. At a city scale, increasing the ground vegetation has a stronger impact than implementing green roofs on reducing street temperature; whereas green roofs are more cost-effective to reduce a building's energy consumption [52]. Turfgrass was observed to represent the largest contribution to annual ET in recreational and residential land types (87 and 64%, respectively), followed by trees (10 and 31%, respectively) [53]. Urban ET amount overall relates to the urban forest coverage. Following the increasing ET gradient (464.43–1000.47 mm) through the conterminous United States, urban forest cover and forest volume correspondingly had a doubled and a threefold increase, respectively [7]. Under the shade of tree canopies, the cooling effect of the added lawn will be significantly restrained [42]. Of all

types of green and blue space, tree-dominated greenspace offers the greatest heat stress relief [54]. Therefore, xeriscaping trees with drip irrigation system, present a promising UHI mitigation strategy compared to traditional water-demanding urban lawns especially in an arid or semi-arid environment [42]. Stormwater captured from cool roofs can be additional irrigation sources for ground-level GI to promote evaporative cooling [15, 47].

2.2 Baseflow regulation

Another major ecosystem service provided by evapotranspiration from green infrastructure is to regulate the regime of urban baseflow in terms of its peak discharge, lag time, recession coefficient, and water yield [46, 55]. Runoff and infiltration determine the upper limit in the volume of surface and subsurface return flows to streams, respectively; while ET, as a sink/loss term in the water balance, determines the lower limit in the volume of the return flow.

The goal of regulating baseflow is ambiguous to define and dependent on each case. Urbanization tends to elevate imperviousness percentage and leads to excessive surface runoff in the postdevelopment condition, which raises flooding risk and causes the urban stream syndrome at the downstream [22]. Reducing the volume of surface runoff is often set as a common goal of all GI applications [6, 10], since GI creates the extra sink near the source of rainfall and effectively reduces the volume of surface runoff traveling downstream [6, 56, 57]. In this case, the ET-focused GI (green roof, lined bioretention) would be recommended, which would transform portions of recharge and baseflow into ET [35, 58–60].

On the other hand, regulating baseflow can also mean to strengthen the percolation, when the aquifer is heavily tapped by the urban basin [61, 62]. In such case, the percolation-focused GI would be recommended such as drywell, unlined bioretention (sometimes referred as bioinfiltration), retention pond, and permeable pavement, which would transform portions of ET into recharge and eventually baseflow [63]. However, the influence of percolated water on ET is not clearly understood. Conventionally, percolation is assumed to recharge groundwater and contribute to baseflow through subsurface hidden paths [60]. Yet, lateral seepage from the bioretention is not negligible, and it can be comparable to ET amount [64] or even a much more dominant term than both ET and vertical percolation [65]. The fate of the lateral seepage has not been extensively studied yet, which could end up being intercepted by downstream rooting systems and eventually released into the air by ET again, instead of reaching the channels as baseflow. Further, water from shallow water table (<2.5 m deep) can move upwards to the root zone as capillary flow; for example, 1-m capillary upward groundwater can supply 41% of ET [66]. The knowledge gaps regarding the fate of percolation water as well as occasional capillary flow prevents the accurate appraisal of the GI influence on the local or broader scale water balance. The contributing areas to the baseflow of an urban watershed should be identified, and building GI at such locations would be cost-effective.

Connection to storm drainage network is another factor affecting the ratio of rainfall redistribution. Employment of an underdrain underneath bioretention can bypass most infiltration through the drainage network and lead to minimal ET and percolation [67, 68]. From the volume reduction perspective, underdrains make GI more resemble a conventional storm pipeline. Without connecting to a drainage network, GI can manage infiltrated water more through ET or percolation.

Choosing the percolation-focused GI in the urban areas with limited aquifer extraction and ecosystem water demand (humid climates) may overcompensate the groundwater and increase the volume of return flow to the downstream channels due to the increased baseflow. Further, the percolation-focused GI, only designed

for managing impervious surfaces, may also drain extra stormwater from pervious surfaces and then unintendedly result in a larger baseflow than the predevelopment condition [60]. Overcompensating groundwater recharge can lead to deleterious effects on downstream waters and ecosystem like in arid regions with intermittent and ephemeral streams [24]. Moreover, excessive recharge from GI may cause groundwater mounds, which, taking a long time to dissipate [69], endanger the foundations of other infrastructures and compromise drought resilience by promoting shallow-rooted plant systems that do not extract water from deep soil [70]. Therefore, determining the appropriate ET amount for an urban watershed is complicated and requires an overview of the complete water budget. This discussion goes beyond the viewpoint of baseflow restoration and gives rise to the emerging trend of using GI to reestablish the urban water budget.

2.3 Water budget reestablishment

Type and configuration of GI can not only regulate the baseflow but also affect the rest of the water budget for a single site [71, 72]. Designing a GI unit, therefore, needs to be reviewed in a broader sense. The configuration of each GI unit, though possibly having already accomplished the local-scale objectives, can be further tweaked to target the optimum goal of a greater scale such as of an urban watershed or an urban ecosystem. Then, the baseflow regulation by GI implementations eventually turns into the redesign of the water budget, such as the proposals for restoring the near-natural water budget [24, 35, 73].

Targeting water budget, however, may not be so straightforward to develop due to considerations for the integrated ecosystem management for each specific climate. From the ecological perspective, aquifer recharge might be beneficial ecologically only when the recharge amount matches the predevelopment condition [60]. So, the excessive rainwater should be harvested near the rain source [24]. However, in dry environments, ET can be dominant component of the predevelopment water budget before urbanization occurred [35]. Recovering the predevelopment ET ratio will be prohibitive in such urban settings [24]. Therefore, reestablishing a new water budget somewhere between the predevelopment and postdevelopment conditions is most feasible and beneficial for human and ecosystem water demands together. Regional water budget should be determined by the weights assigned between human water demand and ecosystem water demand.

The new equilibrium will need to integrate multiobjectives from different perspectives. For example, for the interests in urban heat island relief, GI is designed to enhance ET process, which requires the ET-focused GI with adequate storage capacity [1, 74]. For the interests in stormwater management in wet and cold regions with excessive return flows, the ET-focused GI is recommended to maximize the runoff reduction. In semi-arid environments with intermittent but intense rain events, high ET rates also guarantee the rapid update of storage capacity between storms, though irrigation supplement may be needed [75]. For regions with low recharge rate and high groundwater exploitation rate, the percolation-focused GI with highly permeable mediums might be a better option [76, 77]. In any case when increasing irrigation demand is most concerned, GI with low ET potential or drought-resistant plant species would be preferred [78].

3. Measurement of evapotranspiration from green infrastructure

Depending on the configuration, inflow and irrigation, climate, and the microscale hydraulic, thermal, and aerodynamic contexts, observed evapotranspiration from the

same type of green infrastructure can vary case by case. Based on the existing observations (excluding modeling results), ET of a bioretention unit generally varies within the range of 2–9 mm day^{-1} [79, 80], ET of a green roof unit generally falls within the range of 0.003–11.38 mm day^{-1} [49, 81–84], and the evaporation of a permeable pavement unit after rainfall is generally 0.5–1.5 mm day^{-1} [85–87]. From the water budget perspective, ET was observed to be able to remove 0.4–70% of inflows from a bioretention unit [67, 68, 80, 88], 58–72% of inflows from a green roof unit [82, 84, 89], and 2.4–30% from a permeable pavement unit [85, 86].

Similar to observation tasks for other landscapes, the ET measurement methods for GI can be divided into mass-balance tracking, meteorological observation, and biological diagnostic. Among them, mass-balance tracking is most often adopted due to its simplicity and cost-effectiveness. Mass balance can be tracked indirectly by interpreting the variations in moisture content or ponding water such as in permeable pavement [85], green roof [90], and bioretention cases [65] or, more often, directly monitored by the weight change via a lysimeter. These methods generally focus on a small piece of GI and by various degrees block moisture, momentum, and energy exchanges between the monitored piece and the unmonitored environment.

Weighing lysimeter has been widely used to measure ET for major GI types, e.g. bioretentions [80, 83], green roofs [75, 78, 83, 84], and permeable pavement [86, 87]. It uses a load cell to monitor the total mass change of the container holding the GI sample. Because only the mass readings are recorded, this technique requires extra observations to distinguish the weight changes caused by ET from the changes caused by the wetting events (rainfall, irrigation) or other possible loss terms (drainage, percolation). Drainage and percolation are often difficult to measure with the matching accuracy and temporal resolution as the load cell readings. Traditional tipping bucket is designed for rainfall measurement. Its funnel collector and tipping container can be easily overwhelmed by the massive flows from the lysimeter's underdrain. So although a tipping bucket can record the occurrence and possibly the timing of the outflow events, its volumetric readings are usually unreliable. A pressure transducer can be useful for measuring still water with enough depth and open water surface but is not helpful for detecting the shallow drainage water usually collected in a container that needs to be released after each event. For each container with a different shape, the water depth sensor would need a re-calibration. Considering the difficulty of tracking drainage and percolation, the common workaround is only analyzing the lysimeter time series during the dry spells when the water balance only has ET and the change term remaining (without other inflow and loss terms).

Besides the state change, vapor fluxes through a part of a plant, a closed chamber, a building's footprint, and a neighborhood can be directly monitored and used to estimate ET from GI by the means of sap/leaf flux sensor [17], gas-exchange chamber [47, 78, 81, 89], eddy covariance technique [82], and airborne remote sensing [91], respectively. Both sap/leaf flux sensors and closed chambers provide a decisive way to examine the fundamental theories behind ET models. But they can only examine the flux exchange within a very limited space; the former can only measure a piece of a plant, while the latter can hold a volume up to 0.12 m^3 [47, 78, 81, 89]. The observed ET rates by these two methods are also (if not more) hardly to upscale compared to the mass balance methods due to the variations in environmental factors.

Eddy covariance technique quantifies the surface-atmosphere flux exchanges from a certain surface area at the upwind side of the measurement sensor (flux footprint), which should not include a large fraction of unwanted land covers. This requirement poses practical challenges for using it to monitor ET from a single

GI unit, which usually only takes a small fraction of a flux footprint and is mixed with other urban land covers with distinct thermal and hydraulic properties. The eddy covariance method can be feasible for a large GI unit that covers the majority of a flux footprint, irrespective of the unsolved energy balance closure issue. A case study using eddy covariance on an 8600 m^2 green roof found that an average 70% daytime flux footprint matched the green roof surface [82]. A flux tower may become more useful to measure the total change in ET for a neighborhood scale before and after implementing GI, which will provide a critical dataset that is often lacked for calibrating stormwater and urban atmospheric models.

The challenges of measuring ET from GI were partly caused by the limitations in the current sensing technology. To help build a database useful for future research and a wider community, field experimenters should start to record a more complete background information for a GI site, such as detailed species information [78], the surrounding impervious and pervious landscapes, and a broader field of temperature, wind, and humidity conditions that can account for advection and roughness. Meanwhile, the uncertainty information including the accuracy of measurement sensors and the selective ranges of parameters is recommended to be provided [49, 92], especially when the purpose of the observation is to improve the simulation of ET from a GI.

4. Simulation of evapotranspiration from green infrastructure

Simulation of evapotranspiration from green infrastructure is usually a necessary subtask of modeling a larger system such as the building's energy and water budgets, a catchment's drainage network, or a city's land-surface process. Most current efforts regarding ET simulation for GI centered on establishing a well-calibrated ET model for a single GI unit/type at one site. Such microscale-calibrated models, however, are very difficult to be reused at a different site due to the differences in the configuration of GI, micrometeorological conditions, and data availability. Therefore, most hydrologic and atmospheric models seldom use such locally-calibrated ET modules but directly use more generic equations.

Evapotranspiration simulation usually can be divided into two steps. Potential evapotranspiration (PET) is calculated firstly, which represents the maximum ET amount allowed by the instantaneous meteorological conditions forced by air temperature, solar radiation, wind, air pressure, and humidity [93–95]. Actual evapotranspiration (ET_a) is then achieved by adjusting PET by further limiting factors such as moisture availability and properties of evapotranspiring media (e.g. physiological characteristics of plant species and hydraulic features of a soil type). Since PET and ET_a are usually quantified separately, these two terms are discussed separately.

4.1 Potential evapotranspiration models

Penman-Monteith (P-M) equation, taking a full account of energy balance, convection, and canopy resistance while well documented by previous agricultural studies, is widely applied to estimate ET from almost all types of GI such as green roof [6, 57, 74, 83, 93, 96–99], bioretention [64, 80, 100], and permeable pavement [101]. Simpler models, such as Priest-Taylor equation without considering convection [102], or solely temperature-based Thornthwaite Equation [59, 85, 103] and Hargreaves Equation [96, 104], have also applied for GI when fewer inputs and less calibration effort required. Although a simpler method may achieve a better estimate for a unique site, the P-M equation has been framed into the classical protocol [105] to compute reference evapotranspiration (ET_o), which represents ET from a standard

land cover with fixed vegetation characteristics (resistance, height, etc.). The concept of ET_o has been widely accepted and integrated with the adjustments by lists of crop coefficient (K_c) and water stress coefficient (K_s) [105]. Potential evapotranspiration of a plant can be achieved by multiplying ET_o by K_c.

Although the P-M equation is physically sound, it is problematic to apply it in the urban environment. Originally, the P-M equation was developed to estimate ET from a uniform surface with a homogenous footprint (like open water or well-watered farmland). Urban environment, however, is composed of heterogeneous surfaces with distinct regimes of reflecting, absorbing, and releasing the incoming radiation, which result in intensive turbulence exchanges within a short period of time. Directly applying the P-M equation in the urban environment essentially breaks its underlying assumption of a homogeneous surface. The P-M equation would need adjustments for such cases after capturing the 3D field of weather variables, especially temperature, wind, and humidity fields. For example, the current practices of implementing the P-M equation only calculate aerodynamic resistance for the neutral stability condition by assuming a logarithmic profile of wind, temperature, and humidity [105, 106]. This assumption is only valid for inertial sublayer well above the building tops but will not hold in the roughness sublayer and urban canopy layer where GI exists [107]. This violation, mostly due to a high degree of vertical mixing (convection) and horizontal transport of air mass (advection), is seldom and hardly addressed during ET estimation for GI. Fundamentally, the P-M equation assumes an equivalent aerodynamic resistance for both sensible heat and momentum transfer under the neutral stability condition and ignores the contribution of advection to the energy supply commonly occurred in an urban environment. Stability correction [108] is cumbersome and may not be influential close to the canopy [109]. The advection tends to be negligible where relatively small differences in surface temperatures exist (like cropland), which is seldom the case in the urban domain [109].

A pioneering study proposed two crop coefficients to separately calibrate radiation and convection terms to improve ET estimation for green roofs [84]. This method implicitly assumes that the nightly convection would have the same magnitude as the daytime convection and also removes the moisture restriction on the convection term because of the weak correlation between convection and substrate moisture at nighttime. The two-round correction was able to improve RMSE by 37% for water-limited conditions when ET is generally low but still suffered by underestimating large ET values during wet conditions [84]. This method still does not resolve the inherited problem of the neglect of horizontal advection in P-M equation, which seems to explain why the ratio of observed ET versus ET_o was much higher during nighttime when no solar radiation exists.

Another implicit barrier in using the P-M equation for GI application lies in the complexity of the concept of surface resistance. Stomatal conductance, as the backbone of surface resistance, is highly variable and can be a function of instantaneous levels of temperature, vapor pressure deficit, leaf water potential, and ambient carbon dioxide concentration [110]. Stomatal resistance (the reciprocal of conductance) of green roof species could vary from 13 to 2500 s m^{-1} [49, 78]. However, in practice, the surface resistance is usually fixed at a constant value in [105, 106]. Therefore, the P-M equation and other common methods tend to struggle to capture both the high and low ET extremes for GI; e.g. for green roofs, the P-M methods often underestimate ET peaks, when moisture supply is adequate to support large ET values (close to PET level) [49, 81, 84, 89, 90]. The average surface resistance adopted by most studies keeps the simulated results approaching the average ET level but missing the higher and lower extremes. Adding a constant crop coefficient will still not improve this situation.

The dilemma is that neither proposing a new framework nor improving the existing one is conceivably easy. Proposing a new PET equation with better representation of convection, advection, and surface resistance will change the ET_o standard, and then the existing references of crop coefficient and water stress coefficient will need to be recalibrated. On the other hand, existing references of the current practices of using the P-M equation to estimate PET will require additional correction procedures to take account of those misrepresented terms and perhaps other unrepresented background terms.

Advection-Aridity model [111] can be a different method to estimate ET_o for GI ignoring the restrictions in substrate moisture content and plant responses such as stomatal conductance [102]. Essentially, it merges the Penman equation that captures energy balance and vertical convection with the 'advection-free' Priest-Taylor equation; however, neither of them takes account of horizontal advection, which can be prevalent due to oasis effect in urban canyons. Artificial neural network provides an alternative workaround that establishes a best ET model for a specific GI unit at the microscale [112]. In the new era of big data, it can be envisioned that machine learning can also have a bright future given regional or global training datasets to be established and shared.

4.2 Actual evapotranspiration models

Potential evapotranspiration represents the ET rate limited only by energy supply instead of water supply. In current practices such as stormwater management, it is common to use PET or pan evaporation to represent ET_a [100, 104, 113–116] and calculate other unknowns in the water balance [62]. However, without the adjustment for the substrate moisture content, ET_a will be overestimated for unsaturated conditions [89, 117]. Therefore, the water stress coefficient [105] is used to take account of moisture dynamics, and has been used as the benchmark for assessing other predictive ET_a models in lieu of physically monitored data [90, 97]. Actual evapotranspiration can be achieved by multiplying ET_o by K_s. Simpler equations have been applied to green roof, such as the Thornthwaite-Mather version neglecting the rooting depth and moisture stress [83], or the soil moisture extraction function (SMEF) that further removes the restriction of wilting point [59, 74, 93, 97]. All these methods tend to exaggerate the magnitude of ET reduction during dry periods, since they do not account for processes that could increase the moisture availability such as depression storage, interception, vegetation storage, and ponding water, or factors that alter ET fluxes like the subsurface moisture movement and non-ideal environmental conditions [81]. A fundamental assumption behind these water stress models is that ET from plant and medium should follow a linear response curve with the moisture content. The linear assumption, however, may not well reflect the plant's real response, since plant's stomatal activity also depends on other factors as discussed above. This linear trend and becomes much more problematic when representing special species such as succulent plants with distinct metabolism mechanism [49, 78].

5. Summary

A critical review was made to summarize the current research progress with regard to evapotranspiration from green infrastructure in term of the ecosystem services, measurement, and simulation. The related research gaps have been recognized as follows. The optimum combinations of GI units in terms of types, amounts, and configurations for urban cooling are not identified at various scales. The fate

of percolation water is unknown, and this knowledge gap prevents the accurate appraisal of the influence of GI on the local or broader scale water balance. The contributing areas to the baseflow of an urban watershed should be recognized, so building GI at such locations would be most cost-effective. Baseflow should not be determined only by the local water budget but should be in line with the goals of regional or watershed strategic planning. Reestablishing a new water budget somewhere between the predevelopment and postdevelopment conditions is most feasible and beneficial for both human and ecosystem water demands in the future. Regional water budget planning should be made according to the weights assigned between human water demand and ecosystem water demand. To help build a ET database that can also be useful for future research and a wider community, field experimenters should start to record a more complete background information for a GI site, such as detailed species information, the surrounding impervious and permeable landscapes, and broader fields of temperature, wind, and humidity. Meanwhile, the uncertainty information regarding sensors and parameters is recommended to be provided, especially when the purpose of the observation is to improve the simulation of ET from a GI. The P-M equation assumes an equivalent aerodynamic resistance for sensible heat and momentum transfer under the neutral stability condition and ignores the contribution of advection to the energy supply in urban environment. A fundamental assumption behind the water stress models is that ET from plant and medium should follow a linear response curve with the medium moisture content. The linear trend, however, is hardly to follow in practice.

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References

[1] Coutts AM, Tapper NJ, Beringer J, Loughnan M, Demuzere M. Watering our cities: The capacity for water sensitive urban design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography. 2013;**37**(1):2-28

[2] Walmsley A. Greenways and the making of urban form. Landscape and Urban Planning. 1995;**33**(1-3):81-127

[3] Fletcher TD, Shuster W, Hunt WF, Ashley R, Butler D, Arthur S, et al. SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. Urban Water Journal. 2014;**12**(7):525-542

[4] Wang C, Wood LC, Teo LT. Tropical vertical greenery systems: Irrigation systems, biophysical characteristics, and influential criteria. Journal of Green Building. 2016;**11**(4):57-90

[5] Jim CY. Cold-season solar input and ambivalent thermal behavior brought by climber greenwalls. Energy. 2015;**90**:926-938

[6] Zölch T, Henze L, Keilholz P, Pauleit S. Regulating urban surface runoff through nature-based solutions–An assessment at the micro-scale. Environmental Research. 2017;**157**:135-144

[7] Ossola A, Hopton ME. Climate differentiates forest structure across a residential macrosystem. Science of the Total Environment. 2018;**639**:1164-1174

[8] La Greca P, La Rosa D, Martinico F, Privitera R. Agricultural and green infrastructures: The role of non-urbanised areas for eco-sustainable planning in a metropolitan region. Environmental Pollution. 2011;**159**(8-9):2193-2202

[9] La Rosa D, Privitera R. Characterization of non-urbanized areas for land-use planning of agricultural and green infrastructure in urban contexts. Landscape and Urban Planning. Dordrecht, Netherlands: Springer. 2013;**109**(1):94-106

[10] Collentine D, Futter MN. Realising the potential of natural water retention measures in catchment flood management: Trade-offs and matching interests. Journal of Flood Risk Management. 2018;**11**(1):76-84

[11] Wong CP, Jiang B, Bohn TJ, Lee KN, Lettenmaier DP, Ma D, et al. Lake and wetland ecosystem services measuring water storage and local climate regulation. Water Resources Research. 2017;**53**(4):3197-3223

[12] Völker S, Baumeister H, Claßen T, Hornberg C, Kistemann T. Evidence for the temperature-mitigating capacity of urban blue space—A health geographic perspective. Erdkunde. 2013;**67**(04):355-371

[13] Wu D, Wang Y, Fan C, Xia B. Thermal environment effects and interactions of reservoirs and forests as urban blue-green infrastructures. Ecological Indicators. 2018;**91**:657-663

[14] Kirnbauer M, Baetz B, Kenney W. Estimating the stormwater attenuation benefits derived from planting four monoculture species of deciduous trees on vacant and underutilized urban land parcels. Urban Forestry & Urban Greening. 2013;**12**(3):401-407

[15] Demuzere M, Coutts AM, Göhler M, Broadbent AM, Wouters H, van Lipzig NPM, et al. The implementation of biofiltration systems, rainwater tanks and urban irrigation in a single-layer urban canopy model. Urban Climate. 2014;**10**:148-170

[16] Eckart K, McPhee Z, Bolisetti T. Performance and implementation of low impact development—A review. Science of the Total Environment. 2017;**607-608**:413-432

[17] Berland A, Shiflett SA, Shuster WD, Garmestani AS, Goddard HC, Herrmann DL, et al. The role of trees in urban stormwater management. Landscape and Urban Planning. 2017;**162**:167-177

[18] Jayasooriya VM, Ng AWM. Tools for modeling of stormwater management and economics of green infrastructure practices: A review. Water, Air, and Soil Pollution. 2014;**225**(8)

[19] Gómez-Baggethun E, Gren Å, Barton DN, Langemeyer J, McPhearson T, O'Farrell P, et al. Urban Ecosystem Services, in Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer, Dordrecht, Netherlands. 2013. pp. 175-251

[20] Cavan G, Lindley S, Jalayer F, Yeshitela K, Pauleit S, Renner F, et al. Urban morphological determinants of temperature regulating ecosystem services in two African cities. Ecological Indicators. 2014;**42**:43-57

[21] Francis LFM, Jensen MB. Benefits of green roofs: A systematic review of the evidence for three ecosystem services. Urban Forestry & Urban Greening. 2017;**28**:167-176

[22] Askarizadeh A, Rippy MA, Fletcher TD, Feldman DL, Peng J, Bowler P, et al. From rain tanks to catchments: Use of low-impact development to address hydrologic symptoms of the urban stream syndrome. Environmental Science and Technology. 2015;**49**(19):11264-11280

[23] Liquete C, Udias A, Conte G, Grizzetti B, Masi F. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. Ecosystem Services. 2016;**22**:392-401

[24] Walsh CJ, Booth DB, Burns MJ, Fletcher TD, Hale RL, Hoang LN, et al. Principles for urban stormwater management to protect stream ecosystems. Freshwater Science. 2016;**35**(1):398-411

[25] Andersen JS, Lerer SM, Backhaus A, Jensen MB, Danielsen Sørup HJ. Characteristic rain events: A methodology for improving the amenity value of stormwater control measures. Sustainability (Switzerland). 2017;**9**(10):1793

[26] Everett G, Lamond JE, Morzillo AT, Matsler AM, Chan FKS. Delivering green streets: An exploration of changing perceptions and behaviours over time around bioswales in Portland, Oregon. Journal of Flood Risk Management. 2018;**11**:S973-S985

[27] Martinico F, La Rosa D, Privetera R. Green oriented urban development for urban ecosystem services provision in a medium sized city in southern Italy. iForest–Biogeosciences and Forestry. 2014;7(6):385-395

[28] Orsini F, Gasperi D, Marchetti L, Piovene C, Draghetti S, Ramazzotti S, et al. Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: The potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. Food Security. 2014;**6**(6):781-792

[29] Gallo P, Casazza C, Sala M. Performances and potential of a productive urban green infrastructure. TECHNE-Journal of Technology for Architecture and Environment. 2016;**11**:104-112

[30] Lupia F, Baiocchi V, Lelo K, Pulighe G. Exploring rooftop rainwater harvesting potential for food production in urban areas. Agriculture. 2017;**7**(6)

[31] Russo A, Escobedo FJ, Cirella GT, Zerbe S. Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments. Agriculture, Ecosystems and Environment. 2017;**242**:53-66

[32] Capotorti G, Del Vico E, Anzellotti I, Celesti-Grapow L. Combining the conservation of biodiversity with the provision of ecosystem services in urban green infrastructure planning: Critical features arising from a case study in the metropolitan area of Rome. Sustainability. 2016;**9**(1):10

[33] Pelorosso R, Gobattoni F, Geri F, Leone A. PANDORA 3.0 plugin: A new biodiversity ecosystem service assessment tool for urban green infrastructure connectivity planning. Ecosystem Services. 2017;**26**:476-482

[34] Xie G, Lundholm JT, Scott MacIvor J. Phylogenetic diversity and plant trait composition predict multiple ecosystem functions in green roofs. Science of the Total Environment. 2018;**628-629**:1017-1026

[35] Feng Y, Burian S, Pomeroy C. Potential of green infrastructure to restore predevelopment water budget of a semi-arid urban catchment. Journal of Hydrology. 2016;**542**:744-755

[36] Jim CY. Assessing climate-adaptation effect of extensive tropical green roofs in cities. Landscape and Urban Planning. 2015;**138**:54-70

[37] Zhao TF, Fong KF. Characterization of different heat mitigation strategies in landscape to fight against heat island and improve thermal comfort in hot–humid climate (Part I): Measurement and modelling. Sustainable Cities and Society. 2017;**32**:523-531

[38] Zhou Y, Shepherd JM. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. Natural Hazards. 2010;**52**(3):639-668

[39] Lehmann S. Low carbon districts: Mitigating the urban heat island with green roof infrastructure. City, Culture and Society. 2014;**5**(1):1-8

[40] Steeneveld GJ, Koopmans S, Heusinkveld BG, Theeuwes NE. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landscape and Urban Planning. 2014;**121**:92-96

[41] Boafo FE, Kim J-T, Kim J-H. Evaluating the impact of green roof evapotranspiration on annual building energy performance. International Journal of Green Energy. 2017;**14**(5):479-489

[42] Song J, Wang ZH. Diurnal changes in urban boundary layer environment induced by urban greening. Environmental Research Letters. 2016;**11**(11):114018

[43] Morakinyo TE, Kalani KWD, Dahanayake C, Ng E, Chow CL. Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study. Energy and Buildings. 2017;**145**:226-237

[44] Solcerova A, van de Ven F, Wang M, Rijsdijk M, van de Giesen N. Do green roofs cool the air? Building and Environment. 2017;**111**:249-255

[45] Heusinger J, Sailor DJ, Weber S. Modeling the reduction of urban excess heat by green roofs with respect to different irrigation scenarios. Building and Environment. 2018;**131**:174-183

[46] Jefferson AJ, Bhaskar AS, Hopkins KG, Fanelli R, Avellaneda PM, McMillan SK. Stormwater management network effectiveness and implications for urban watershed function: A critical

review. Hydrological Processes. 2017;**31**(23):4056-4080

[47] Coutts AM, Daly E, Beringer J, Tapper NJ. Assessing practical measures to reduce urban heat: Green and cool roofs. Building and Environment. 2013;**70**:266-276

[48] Van Mechelen C, Dutoit T, Hermy M. Adapting green roof irrigation practices for a sustainable future: A review. Sustainable Cities and Society. 2015;**19**:74-90

[49] Feng Y, Burian S, Pardyjak E. Observation and estimation of evapotranspiration from an irrigated green roof in a rain-scarce environment. Water (Switzerland). 2018;**10**(3):262

[50] Bartesaghi Koc C, Osmond P, Peters A. Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. Solar Energy. 2018;**166**:486-508

[51] Lee LSH, Jim CY. Thermal-cooling performance of subtropical green roof with deep substrate and woodland vegetation. Ecological Engineering. 2018;**119**:8-18

[52] de Munck C, Lemonsu A, Masson V, Le Bras J, Bonhomme M. Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change. Urban Climate. 2018;**23**:260-286

[53] Peters EB, Hiller RV, McFadden JP. Seasonal contributions of vegetation types to suburban evapotranspiration. Journal of Geophysical Research – Biogeosciences. 2011;**116**(G1):G01003

[54] Gunawardena KR, Wells MJ, Kershaw T. Utilising green and bluespace to mitigate urban heat island intensity. Science of the Total Environment. 2017;**584-585**:1040-1055

[55] Lim TC, Welty C. Effects of spatial configuration of imperviousness and green infrastructure networks on hydrologic response in a residential sewershed. Water Resources Research. 2017;**53**(9):8084-8104

[56] Garcia-Cuerva L, Berglund EZ, Rivers L III. An integrated approach to place green infrastructure strategies in marginalized communities and evaluate stormwater mitigation. Journal of Hydrology. 2018;**559**:648-660

[57] Brandão C, Cameira MDR, Valente F, Cruz de Carvalho R, Paço TA. Wet season hydrological performance of green roofs using native species under Mediterranean climate. Ecological Engineering. 2017;**102**:596-611

[58] Jones D, Jha MK. Green infrastructure: Assessing the benefits of bioretention over traditional stormwater management. Environmental Science and Sustainability. 2nd World Scientific and Engineering Academic and Society (WSEAS) International Conference on Natural Hazards, Morgan State University, Baltimore, MD. 2009:134-141

[59] Stovin V, Poë S, Berretta C. A modelling study of long term green roof retention performance. Journal of Environmental Management. 2013;**131**:206-215

[60] Bhaskar AS, Hogan DM, Archfield SA. Urban base flow with low impact development. Hydrological Processes. 2016;**30**(18):3156-3171

[61] Bonneau J, Fletcher TD, Costelloe JF, Burns MJ. Stormwater infiltration and the 'urban karst'—A review. Journal of Hydrology. 2017;**552**:141-150

[62] Beganskas S, Fisher AT. Coupling distributed stormwater collection and managed aquifer recharge: Field application and implications. Journal

of Environmental Management. 2017;**200**:366-379

[63] Xiao Q, McPherson E, Simpson J, Ustin S. Hydrologic processes at the urban residential scale. Hydrological Processes. 2007;**21**(16):2174-2188

[64] Stewart Ryan D, Lee Joong G, Shuster William D, Darner Robert A. Modelling hydrological response to a fully-monitored urban bioretention cell. Hydrological Processes. 2017;**31**(26):4626-4638

[65] Winston RJ, Dorsey JD, Hunt WF. Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. Science of the Total Environment. 2016;**553**:83-95

[66] Gao X, Huo Z, Qu Z, Xu X, Huang G, Steenhuis TS. Modeling contribution of shallow groundwater to evapotranspiration and yield of maize in an arid area. Scientific Reports. 2017;**7**:43122

[67] Dietz ME, Clausen JC. A field evaluation of rain garden flow and pollutant treatment. Water, Air, and Soil Pollution. 2005;**167**(1):123-138

[68] Li H, Sharkey LJ, Hunt WF, Davis AP. Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering. 2009;**14**(4):407-415

[69] Zhang K, Chui TFM. Evaluating hydrologic performance of bioretention cells in shallow groundwater. Hydrological Processes. 2017;**31**(23):4122-4135

[70] de la Mota Daniel FJ, Day SD, Owen JS Jr, Stewart RD, Steele MK, Sridhar V. Porous-permeable pavements promote growth and establishment and modify root depth distribution of *Platanus* × *acerifolia* (Aiton) Willd. in simulated urban tree pits.

Urban Forestry & Urban Greening. 2018;**33**:27-36

[71] Eger CG, Chandler DG, Roodsari BK, Davidson CI, Driscoll CT. Water budget triangle: A new conceptual framework for comparison of green and gray infrastructure. In: 2014 International Conference on Sustainable Infrastructure: Creating Infrastructure for a Sustainable World, ICSI. **2014**; 2014

[72] Eger C,G, Chandler D,G, Driscoll C,T. Hydrologic processes that govern stormwater infrastructure behaviour. Hydrological Processes. 2017;**31**(25):4492-4506

[73] Göbel P, Stubbe H, Weinert M, Zimmermann J, Fach S, Dierkes C, et al. Near-natural stormwater management and its effects on the water budget and groundwater surface in urban areas taking account of the hydrogeological conditions. Journal of Hydrology. 2004;**299**(3):267-283

[74] Johannessen BG, Hanslin HM, Muthanna TM. Green roof performance potential in cold and wet regions. Ecological Engineering. 2017;**106**:436-447

[75] Soulis KX, Ntoulas N, Nektarios PA, Kargas G. Runoff reduction from extensive green roofs having different substrate depth and plant cover. Ecological Engineering. 2017;**102**:80-89

[76] Leng G, Huang M, Tang Q, Gao H, Leung LR. Modeling the effects of groundwater-fed irrigation on terrestrial hydrology over the conterminous United States. Journal of Hydrometeorology. 2014;**15**(3):957-972

[77] Garza PR, Welker A, Rife S. Forensic analyses of two failed rain gardens in a tract development in Glasgow, Delaware. Geoenvironmental Engineering: Honoring David E. Daniel (GSP 274). 2016:60-68

[78] Starry O, Lea-Cox JD, Kim J, van Iersel MW. Photosynthesis and water use by two Sedum species in green roof substrate. Environmental and Experimental Botany. 2014;**107**:105-112

[79] Denich C, Bradford A. Estimation of evapotranspiration from bioretention areas using weighing lysimeters. Journal of Hydrologic Engineering. 2010;**15**(6):522-530

[80] Hess A, Wadzuk B, Welker A. Evapotranspiration in rain gardens using weighing lysimeters. Journal of Irrigation and Drainage Engineering. 2017;**143**(6):04017004

[81] Marasco DE, Culligan PJ, McGillis WR. Evaluation of common evapotranspiration models based on measurements from two extensive green roofs in New York City. Ecological Engineering. 2015;**84**:451-462

[82] Heusinger J, Weber S. Surface energy balance of an extensive green roof as quantified by full year eddy-covariance measurements. Science of the Total Environment. 2017;**577**:220-230

[83] DiGiovanni K, Montalto F, Gaffin S, Rosenzweig C. Applicability of classical predictive equations for the estimation of evapotranspiration from urban green spaces: Green roof results. Journal of Hydrologic Engineering. 2013;**18**(1):99-107

[84] Jahanfar A, Drake J, Sleep B, Gharabaghi B. A modified FAO evapotranspiration model for refined water budget analysis for Green Roof systems. Ecological Engineering. 2018;**119**:45-53

[85] Brown RA, Borst M. Quantifying evaporation in a permeable pavement system. Hydrological Processes. 2015;**29**(9):2100-2111

[86] Nemirovsky EM, Welker AL, Lee R. Quantifying evaporation from pervious concrete systems: Methodology and hydrologic perspective. Journal of Irrigation and Drainage Engineering. 2013;**139**(4):271-277

[87] Syrrakou C, Pinder GF. Experimentally determined evaporation rates in pervious concrete systems. Journal of Irrigation and Drainage Engineering. 2013;**140**(1):04013003

[88] Fletcher TD, Deletic A, Mitchell VG, Hatt BE. Reuse of urban runoff in Australia: A review of recent advances and remaining challenges. Journal of Environmental Quality. 2008;**37**(5_Supplement):S-116-S-127

[89] Marasco DE, Hunter BN, Culligan PJ, Gaffin SR, McGillis WR. Quantifying evapotranspiration from urban green roofs: A comparison of chamber measurements with commonly used predictive methods. Environmental Science & Technology. 2014;**48**(17):10273-10281

[90] Starry O, Lea-Cox J, Ristvey A, Cohan S. Parameterizing a water-balance model for predicting stormwater runoff from green roofs. Journal of Hydrologic Engineering. 2016;**21**(12):04016046

[91] Koc CB, Osmond P, Peters A, Irger M. A methodological framework to assess the thermal performance of green infrastructure through airborne remote sensing. In: International High-Performance Built Environment Conference—A Sustainable Built Environment Conference 2016 Series SBE16, iHBE; 2016; 2017

[92] Dotto CBS, Mannina G, Kleidorfer M, Vezzaro L, Henrichs M, McCarthy DT, et al. Comparison of different uncertainty techniques in urban stormwater quantity and

quality modelling. Water Research. 2012;**46**(8):2545-2558

[93] Berretta C, Poë S, Stovin V. Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics. Journal of Hydrology. 2014;**511**:374-386

[94] Wong GKL, Jim CY. Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning. Landscape and Urban Planning. 2015;**143**:173-182

[95] Jim CY, Peng LLH. Weather effect on thermal and energy performance of an extensive tropical green roof. Urban Forestry & Urban Greening. 2012;**11**(1):73-85

[96] Stratigea D, Makropoulos C. Balancing water demand reduction and rainfall runoff minimisation: Modelling green roofs, rainwater harvesting and greywater reuse systems. Water Science and Technology: Water Supply. 2015;**15**(2):248-255

[97] Hakimdavar R, Culligan PJ, Guido A, McGillis WR. The soil water apportioning method (SWAM): An approach for long-term, low-cost monitoring of green roof hydrologic performance. Ecological Engineering. 2016;**93**:207-220

[98] Brunetti G, Šimůnek J, Piro P. A comprehensive analysis of the variably saturated hydraulic behavior of a green roof in a mediterranean climate. Vadose Zone Journal. 2016;**15**(9):1-17

[99] Herrera J, Flamant G, Gironás J, Vera S, Bonilla CA, Bustamante W, et al. Using a hydrological model to simulate the performance and estimate the runoffcoefficient of green roofs in semiarid climates. Water (Switzerland). 2018;**10**(2):198

[100] Avellaneda PM, Jefferson AJ, Grieser JM, Bush SA. Simulation of the cumulative hydrological response to green infrastructure. Water Resources Research. 2017;**53**(4):3087-3101

[101] Brunetti G, Šimůnek J, Piro P. A comprehensive numerical analysis of the hydraulic behavior of a permeable pavement. Journal of Hydrology. 2016;**540**:1146-1161

[102] Mobilia M, Longobardi A, Sartor JF. Including a-priori assessment of actual evapotranspiration for green roof daily scale hydrological modelling. Water (Switzerland). 2017;**9**(2):72

[103] Lizárraga-Mendiola L, Vázquez-Rodríguez GA, Lucho-Constantino CA, Bigurra-Alzati CA, Beltrán-Hernández RI, Ortiz-Hernández JE, et al. Hydrological design of two low-impact development techniques in a semi-arid climate zone of central Mexico. Water (Switzerland). 2017;**9**(8):561

[104] Carson T, Keeley M, Marasco DE, McGillis W, Culligan P. Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models. Urban Water Journal. 2017;**14**(6):589-603

[105] Allen RG, Pereira LS, Raes D, Smith M. FAO Irrigation and Drainage Paper No. 56. Vol. 56(97). Rome: Food and Agriculture Organization of the United Nations; 1998. p. e156

[106] Walter IA, Allen RG, Elliott R, Jensen M, Itenfisu D, Mecham B, et al. ASCE's standardized reference evapotranspiration equation. Watershed Management and Operations Management 2000; FortCollins, Colorado, US: American Society of Civil Engineers. 2000. pp. 1-11

[107] Eliasson I, Offerle B, Grimmond CSB, Lindqvist S. Wind fields and

turbulence statistics in an urban street canyon. Atmospheric Environment. 2006;**40**(1):1-16

[108] Thom A, Oliver H. On Penman's equation for estimating regional evaporation. Quarterly Journal of the Royal Meteorological Society. 1977;**103**(436):345-357

[109] Figuerola PI, Berliner PR. Evapotranspiration under advective conditions. International Journal of Biometeorology. 2005;**49**(6):403-416

[110] Jarvis P. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society of London B. 1976;**273**(927):593-610

[111] Brutsaert W, Stricker H. An advection-aridity approach to estimate actual regional evapotranspiration. Water Resources Research. 1979;**15**(2):443-450

[112] Landeras G, Ortiz-Barredo A, López JJ. Comparison of artificial neural network models and empirical and semi-empirical equations for daily reference evapotranspiration estimation in the Basque Country (Northern Spain). Agricultural Water Management. 2008;**95**(5):553-565

[113] Gao J, Pan J, Hu N, Xie C. Hydrologic performance of bioretention in an expressway service area. Water Science and Technology. 2018;**77**(7):1829-1837

[114] Mancipe-Munoz NA, Buchberger SG, Suidan MT, Lu T. Calibration of rainfall-runoff model in urban watersheds for stormwater management assessment. Journal of Water Resources Planning and Management. 2014;**140**(6):05014001

[115] Tao J, Li Z, Peng X, Ying G. Quantitative analysis of impact of

green stormwater infrastructures on combined sewer overflow control and urban flooding control. Frontiers of Environmental Science & Engineering. 2017;**11**(4):11

[116] Yang Y, Chui TFM. Optimizing surface and contributing areas of bioretention cells for stormwater runoff quality and quantity management. Journal of Environmental Management. 2018;**206**:1090-1103

[117] Feng Y, Burian S. Improving evapotranspiration mechanisms in the U.S. Environmental Protection Agency's storm water management model. Journal of Hydrologic Engineering. 2016;**21**(10):06016007