Chapter

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 sensoring 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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