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To irrigate or not to irrigate: Analysis of green roof performance via a vertically-resolved hygrothermal model

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ABSTRACT

In this study, the performance of an irrigation-integrated green roof (GR) system is analyzed through numerical simulations using the vertically-resolved Princeton ROof Model (PROM). The simulations are driven by a 63-day series of summertime meteorological forcing measured at a GR site in Beijing, China. Due to the importance of the medium layer depth of GR systems, its effect on the dynamics of heat and moisture transports and consequently on the thermal performance is first examined under a no-irrigation scenario. The results confirm that the medium layer depth affects heat and moisture transports significantly, but non-monotonic trends emerge. A deeper layer is found to redistribute more water into the bottom section, thus limiting surface evaporation, while a thin layer does not store enough water, dries up fast, and decreases performance too. This indicates that an optimal layer thickness exists somewhere in the middle. Given a fixed medium layer depth, different irrigation scenarios are then investigated. Higher irrigation control limits (i.e. the soil moisture at which irrigation is initiated) enhance the thermal performance of the GR, but this enhancement plateaus at high limits. Based on these findings, a GR (constructed over an un-insulated concrete slab roof in Beijing) is simulated and a simplified operational cost-benefit analysis is performed by comparing the cost of irrigation to that of the energy saved due to lower air-conditioning (AC) requirement when the GR is wetted. The analysis indicates that the irrigated GR system costs are lower than the AC costs for an unirrigated GR. For instance, an irrigated GR system with an area of 100 m^2 under an irrigation control limit of 0.3 m^3 m^{-3} will save ¥ 110 (18 USD) for the chosen 63-day simulation period in Beijing. Therefore, irrigation-integrated GR systems emerge as potentially viable solutions for improving building energy efficiency in a temperate climate.

1. Introduction

Green roof (hereinafter GR) systems are widely adopted in urban areas to mitigate urban environmental problems such as urban heat islands (UHIs) (see e.g. Refs. [1,2]), urban storm water runoff (see e.g. Refs. [3–5]), and air pollution (see e.g. Refs. [6–8]). GR systems are also helpful in reducing building energy consumptions (see e.g. Refs. [9,10]). As a result, quantifying and improving the thermal performance of GR systems in terms of mitigating UHIs and improving building energy efficiencies are becoming increasingly important for engineers, architects, urban planners, and building owners and operators.

A typical GR system is composed of several layers: vegetation layer, medium layer, filtering layer, drainage layer and deck layer. The medium layer is considered to impact the thermal performance of GRs the most through its characteristics for thermal insulation and water retention [11]. Of these two functions, the thermal insulation is mainly inherited from the material composing the medium layer and thus serves as a relatively static factor [12]. Water retention on the other hand is fulfilled by the porous structure of medium layer and has strong linkages to the various physical dynamics taking place within GRs. Many studies have examined the impact of the water content in the medium layer and find that it plays a crucial role in regulating the heat transported across GR systems through its influence on evaporative cooling at the external surface [13]. By performing a sensitivity analysis using an analytical model, Tsang and Jim [14] found that an increase of available water in soil from 30% to 60% can reduce the heat storage in their GR system by 24%. Also from simulation results, Feng et al. [9] found that a quasi-saturated medium layer can result in 58.4% of

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net radiation being dissipated in evaporative latent heat and thus improves the thermal performance of GR. However, despite agreement that the water content in the medium layer is a primary factor that controls the thermal performance of GRs, the hydrological processes in the medium layer and how they are affected by layer thickness and irrigation remain not fully understood. For example, the role of the depth in regulating the dynamic water content profile, which has a direct impact on the actual evapotranspiration from GR surfaces, has not been comprehensively studied. Furthermore, the complex interplay between the hydrological and thermal processes to regulate the thermal performance also requires further investigation using observations or models that can capture this interplay. As such, the basic physical processes governing the performance of GRs, the interaction between these processes, and the effects of hydrometeorological conditions and design variables, need to be investigated more comprehensively.

Previous studies illustrate how the water content in the medium layer plays a crucial role in improving the thermal performance of GRs, suggesting that the effect of irrigation becomes a major determinant of this performance. Feng et al. [9] suggested that proper irrigation may be an effective way to improve the thermal performance of GR systems. This was confirmed by Sailor [15] who conducted building energy simulations in less humid climates. Dvorak and Volder [16] further note that improvements on the thermal performance of GR systems resulting from irrigation are modulated by local climatic conditions. Lin and Lin [17] found that an irrigation frequency of twice a week improves the thermal performance of their GR in Kaohsiung (a subtropical place). However, Jim and Peng [18] analyzed the experimental data from a GR site in Hong Kong (also a subtropical place) and observed limited effect of soil moisture on the thermal performance of their GR, which is probably due to the fact that evapotranspiration is predominately controlled by energy availability rather than water availability. Consequently, the improvement of thermal performance of GR systems by irrigation was found to depend on the local climate and should be assessed for each site; however, general trends and climatic indicators that control the role of irrigation could still be developed. Furthermore, while previous studies considered irrigation as means of improving the thermal performance of GR by increasing water availability, detailed investigation of the irrigation strategy and its relationship with the hygrothermal processes within GR remains to be performed.

Apart from the physical and environmental conditions regulating the GR performance, socio-economic factors (e.g. energy price, operation of water supply, etc.) may also impact the overall GR performance and the suitability of irrigation as a means to improve this performance. For instance, Ascione et al. [19] examined the economic viability of GR systems of various European cities under local climatic and pricing conditions by conducting building energy simulations. They found that the extra costs of irrigation may overcome the benefits from energy saving due to the limited precipitation and the price of water and energy. As for cities in Australia, Williams et al. [20] suggested that using of gray water for irrigating GR systems should be considered due not only to economic concerns, but also to water scarcity. Beijing has undergone very rapid urbanization in the past three decades. As this trend continues, the city is facing increasingly severe environmental problems [21]. It is also noteworthy that Beijing has a relatively dry and temperate climate. The temporal distribution of precipitation is uneven, with most of the rain concentrated in July and August as shown in Fig. 1(a). While the daily maximum air temperature is high throughout the summer (from May to September), as shown in Fig. 1(b). This implies that high cooling loads occur during the summer and thus improving the thermal performance of GR systems by introducing irrigation might be particularly beneficial. In addition, given that China is a developing country and the labor costs are relatively low, the initial cost of including irrigation in GR systems in Beijing might not influence the cost-effectiveness of this option significantly.

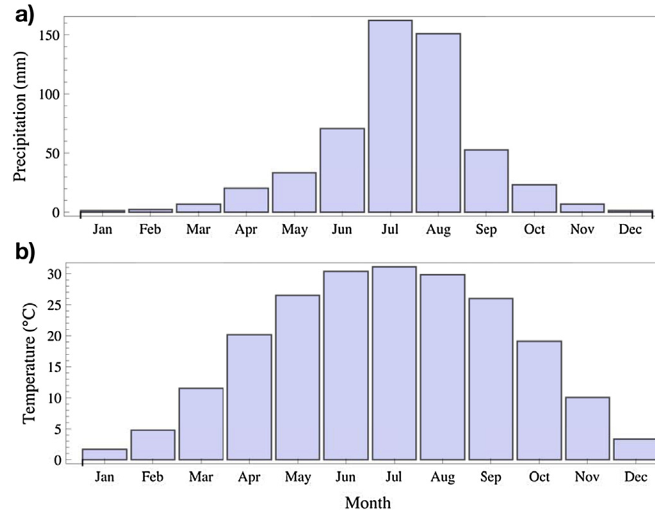

Fig. 1. Monthly mean values of a) precipitation and b) daily maximum air temperature in Beijing based on 1950–2010 daily dataset collected by China's National Meteorological Administration.

The aim of this paper is thus to develop a physical understanding of the processes that control the thermal performance of GR systems, and how they are altered by the two main physical attributes of GR: its depth (a measure of its thermal and hydrological inertia) and its moisture content (a measure of its ability to produce evaporative cooling), which can be controlled through irrigation. The study uses the state-of-the-art roof simulation tool PROM (Princeton ROof Model), which has been thoroughly validated for GR studies [22]. We start by briefly describing and validating the model. Then we detail the "smart irrigation" module that is developed in this study and is coupled to PROM for examining the

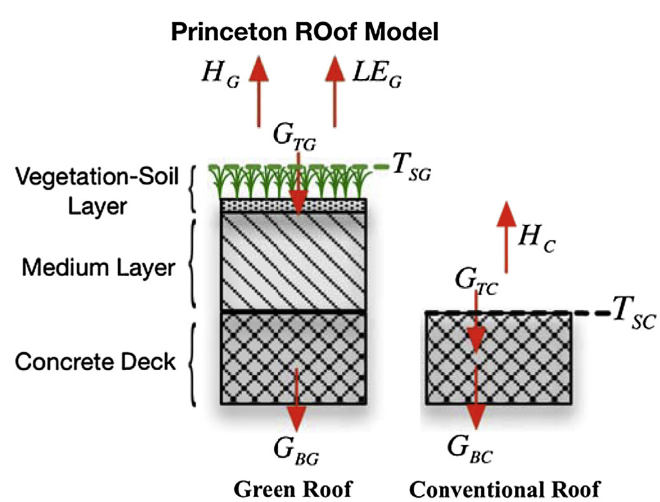

Fig. 2. Schematic of Princeton ROof Model (PROM). In the schematic of PROM, heat fluxes are denoted by red arrows, along with their notations: *H* for sensible heat flux, *LE* for latent heat flux, *G* for heat flux into the surface. Dashed lines aligned with roof surface denote various surface temperatures with notation T_S. Subscript G is for green roof, C for conventional roof, T for top surface and B for bottom surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)