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Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport

Ting Sun [a,b,*], Elie Bou-Zeid [b], Zhi-Hua Wang [c], Eileen Zerba [d], Guang-Heng Ni [a]

[a] Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
[b] Civil and Environmental Engineering Department, Princeton University, Princeton, NJ 08544, United States
[c] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, United States
[d] Princeton Environmental Institute, Princeton University, Princeton, NJ 08544, United States

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ABSTRACT

In this study, the Princeton ROof Model (PROM) is developed, validated and used to simulate the hygrothermal dynamics of green roof systems. PROM is embedded within the framework of the Princeton Urban Canopy Model, with a multi-layer spatially-analytical heat transfer scheme and an improved hydrological module. The model is validated by comparing simulated surface temperature and soil moisture to the measurements at two experimental sites, one in Beijing, China and the other in New Jersey, USA. The results demonstrate that PROM is able to capture the diurnal cycle of roof temperatures and the soil moisture dynamics of green roofs with high accuracy. Driven by a 30-day summertime meteorological forcing from July 2001, PROM is used to investigate the green roof thermal improvement to the urban indoor and outdoor environments, compared to conventional roofs. The impact of green roofs is significant in reducing surface temperatures, and outdoor and indoor heat fluxes during this summer period. To quantify this thermal improvement, three indices related to surface temperature, outdoor heat flux and indoor heat flux, are introduced; and the dependence of these indices on hydrological and meteorological conditions is investigated. The results indicate that incoming solar radiation and medium layer moisture are the main determinants of the green roof performance.

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1. Introduction

According to the United Nations [1], more than 50% of the world's populations are currently living in cities and the world is still undergoing rapid urbanization, especially in developing countries. In China, the urbanization rate has exceeded 50% [2] and is projected to continue growing in the next 30 years. Urbanization poses significant challenges to energy and water sustainability in cities, and exacerbates many environmental problems. Some of the adverse effects related to urbanization are: increased urban storm flood [3], increased building energy consumption [4], poor air quality [5], and urban heat island (UHI) effect [6]. Loss of green spaces in urban areas is one of the main triggers of the UHI effect, leading to human discomfort and increasing building energy consumption [7].

Green roofs, where an extra complex vegetation layer is added above the existing rooftop, have been demonstrated to be an effective method to alleviate some of these urban environmental problems [8]. There are two types of green roofs, intensive and extensive [9]. The intensive green roofs are also called roof gardens and feature a variety of vegetation species to increase their esthetic value, but they are usually more expensive mainly due to thick medium layer and frequent maintenance requirement [10]. Extensive green roofs are widely used in roof retrofit projects, owing to their low-cost and easy implementation. Most green roof studies are limited to extensive green roofs, and show that the benefits of these roofs mainly involve storm water retention [11–21], and thermal improvement to both ambient-air and roof-surface temperatures [7,22–31].

In particular, the thermal benefits of green roofs are highlighted by many studies due to their impact on the urban microclimate and building energy efficiency [32,33]. These benefits are also well documented through field observations under a wide range of climatic conditions in tropical [33], sub-tropical [16,27,34,35], Mediterranean [18,32,36], temperate [23,25] and sub-frigid regions [37]. The findings of these studies confirm that green roofs outperform conventional roofs in reducing surface temperatures and indoor heat flux.

* Corresponding author. Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China. Tel.: +86 133 8110 5136.
E-mail addresses: sunt05@mails.tsinghua.edu.cn, sunting.05@gmail.com (T. Sun).

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However, due to the variety of green roof designs, it is difficult to generalize the relationship between the thermal performance of green roofs and the site's meteorological conditions. In addition, one often has alternative options: cheaper white roofs, various configurations of green roofs, or increased roof insulation. Therefore, it is necessary to develop an accurate model for green and conventional roofs, that captures heat as well as moisture fluxes, if different roof options are to be compared or if the performance of a given design is to be assessed under specific climatic conditions. Such models have indeed been developed and used to investigate green roof systems; however, most of them focus on the building scale, are not constructed to be easily linked to meteorological simulations or data, and use simplified hydrological or thermal submodels (see for example the potential errors resulting from spatially-discrete solutions of the heat equation in Wang et al. [38]).

Therefore, in this paper we propose, validate and apply an improved model of green roofs that accurately solves the full equations for heat conduction and water transport in soils and couples them to the atmosphere using widely-tested similarity theories. The new model, referred to as the Princeton ROof Model (PROM), is developed based on the simplified version included in the Princeton Urban Canopy Model (PUCM), which is a full urban surface energy budget scheme that can be easily coupled to atmospheric models such as the Weather Research and Forecasting (WRF) model [39]. PUCM [38–40] was the first UCM to introduce multiple urban characteristic facades, including green roofs. Another feature of PUCM is the Green's function-based solutions for surface temperatures and conductive heat fluxes, which has the advantage of spatial continuity and improved accuracy [41]. Although green roofs are included as a part of the PUCM, the green roof in the PUCM has only one layer, while actual green roofs are usually composed of several layers with distinct thermal properties [38]. In addition, the parameterization of soil water retention and flux for green roofs is simplified in the PUCM, with a bucket model used for describing the hydrologic processes.

Therefore, to more accurately depict thermal dynamics involved in the composite structure of green roofs, a multi-layer heat transfer scheme is implemented by combining Green's function-based solutions for each functional layer with distinct thermal properties, while maintaining the advantages of this spatially-analytical approach (continuity and accuracy). The other major improvement is the replacement of the bucket water content module with a Richards' equation-based hydrologic module, which can better capture the hydrologic dynamics and vertical variability in green roofs. The improved roof model, PROM, is then validated offline by comparison with observation results from two green roof sites. In addition to model presentation and validation, this paper aims to apply PROM to assess the thermal performance of green roofs in summertime under different climatic conditions. Our study is restricted to summertime due to the significant impact of green roofs on urban microclimate and building energy efficiency in the summer [23,37] (in the winter, they simply serve as an extra insulation layer). With PROM and real-time datasets of July 2011, a 30-day simulation is then performed to investigate the thermal improvement by green roofs in comparison with conventional ones. In addition, three thermal performance indices of green roofs are introduced to evaluate their effectiveness. Finally, the sensitivity of these indices to different meteorological forcing conditions are investigated.

2. Model description and validation

2.1. Princeton ROof Model (PROM)

PROM is developed under the framework of PUCM as shown in Fig. 1. PUCM adopts the most common single canyon representation for urban areas [42–44] and further divides each urban facet into different types to incorporate the surface heterogeneity. For instance, ground surfaces include asphalt, concrete pavement and lawns; wall materials can be a mixture of brick or glass; roofs comprise conventional and green covers. However, the existing green roof component in PUCM does not resolve the vertical transport and distribution of water and represents the roof as a single homogeneous layer.

In this work, we improve the PUCM by implementing a multi-layer heat transfer scheme and a Richards' equation based hydrological module. The combination of the PUCM and the PROM now has the capability to very accurately simulate hygrothermal processes involved in green roofs.

2.1.1. Multi-layer heat transfer scheme

The thermal dynamics of green roof systems are characterized by the one-dimensional (1D) heat conduction equation:

$$\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \quad (1)$$

with a spatially continuous thermal field in the spatial domain $x \in [0, d]$, where ρ is the density, c_{p} the specific heat capacity, k the

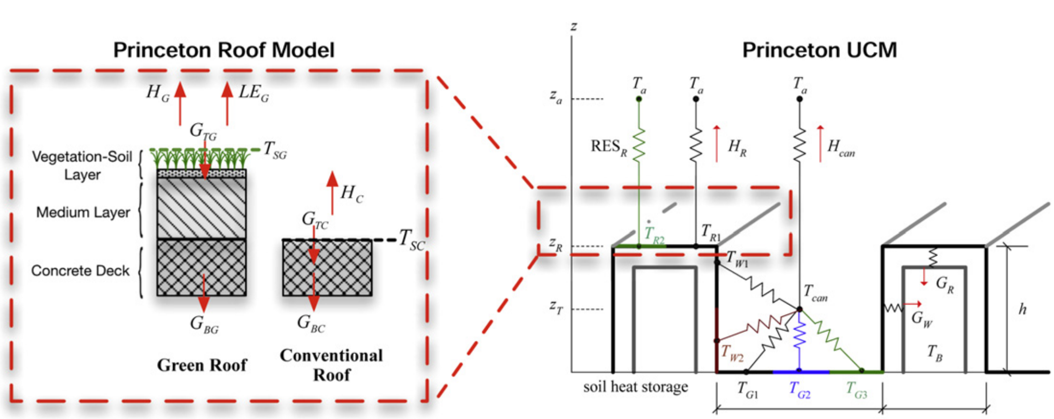

Fig. 1. Schematic of Princeton ROof Model (PROM, left side) under the frame of Princeton UCM (PUCM, right side). In the schematic of PROM, dissipative heat fluxes are denoted with red arrows, along with notations: H for sensible heat flux, LE for latent heat flux, G for heat flux through surface. Dashed line aligned with roof surface denote surface temperature with notation T_s. Subscript G is for green roof, C for conventional roof, T for top surface and B for bottom surface (for notations employed in PUCM schematic refer to Ref. [38]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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