Building and Environment 75 (2014) 250–263

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Physical parameterization and sensitivity of urban hydrological models: Application to green roof systems

Jiachuan Yang, Zhi-Hua Wang*

School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, USA

ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form
12 February 2014
Accepted 15 February 2014

Keywords:
Hydrological model
Sensitivity
Green roof
Monte Carlo simulations
Parameter uncertainty
Urban heat island

ABSTRACT

Rapid urbanization has emerged as the source of many adverse environmental effects and brings cities to a vulnerable situation under future climate challenges. Green roofs are proven to be an effective solution to alleviate these effects by field observations under a wide range of climate conditions. Recent advances in modeling urban land-atmosphere interactions provide a useful tool in capturing the dynamics of coupled transport of water and energy in urban conies, thus bridge the gap of modeling at city to regional scales. The performance of urban hydrological models depends heavily on the accurate determination of the input parameter space, where uncertainty is ubiquitous. In this paper, we use an advanced Monte Carlo approach, viz. the Subset Simulation, to quantify the sensitivity of urban hydrological modeling to parameter uncertainties. Results of the sensitivity analysis reveal that green roofs exhibit markedly different thermal and hydrological behavior as compared to conventional roofs, due to the modification of the surface energy portioning by well-irrigated vegetation. In addition, statistical predictions of critical responses of green roofs (extreme surface temperature, heat fluxes, etc.) have relatively weak dependence on climatic conditions. The statistical quantification of sensitivity provides guidance for future development of urban hydrological models with practical applications such as urban heat island mitigation.

1. Introduction

To date, more than 50% of the world's populations are living in cities and the percentage continues to increase with undergoing urbanization process, especially in developing countries [1]. Rapid urbanization has emerged as the source of many adverse effects such as urban heat island (UHI) [2], storm floods [3], air pollution [4], increased building energy consumption [5], disruption of ecosystem [6], etc. These effects pose stringent constraints on energy and water sustainability and bring cities to a vulnerable situation under future climate challenge [7,8]. Green roofs, rooftop structures with vegetation, have been proved as an effective solution to alleviate some of these adverse effects, by improving stormwater management, reducing energy usage, mitigating heat island, improving air quality, and accommodating native wildlife habitat [9,10,56,57]. These benefits have been observed under a wide range of climate conditions through field observations [11–14].

Broadly, green roofs can be classified into two major types by their characteristics: intensive and extensive roofs. Intensive green roofs are usually associated with roof gardens and feature a variety of vegetation species [15]. A relatively deep layer of soil and frequent maintenance are required for this type. Extensive green roofs have relatively thin layers of soil and are designed to be virtually self-sustaining with minimum maintenance [16]. Popular across Europe over the last few decades, green roofs are now becoming more familiar to North Americans with studies and implementations of green roof projects in a number of cities [9]. While recent years have seen rapidly increasing number of studies on green infrastructure, particularly green roofs, nearly all of them have been limited to either field measurements at very small (e.g. a single roof) or simulation results at very large (continental or global) scales, leaving the gap widely open at city and regional scales. Pioneering work on studying city and regional scale cooling effect to reduce UHI has resorted to remotely sensed imagery using, e.g. Landsat TM [17]. The lack of city scale modeling of green roofs is partly owing to the sensitivity of green roof performance to a variety of parameters, such as ambient environments, vegetation specie and soil property, etc. Therefore, for city planners or decision makers to develop general guidance on green roof implementation

---

* Corresponding author. Tel.: +1 480 727 2933; fax: +1 480 965 0577.
E-mail addresses: zhwang@asu.edu, wzh.wang@gmail.com (Z.-H. Wang).

http://dx.doi.org/10.1016/j.buildenv.2014.02.006
0360-1323/

at large scales, accurate models that well capture energy as well as water budgets on green roofs are necessary.

As green roofs are installed in the built environment, their numerical simulations necessarily require a good representation of urban surface processes and land-atmosphere interactions. During the past decade, numerous urban canopy models (UCM) have been developed focusing on the dynamics of energy transport in the urban canopy layer [18–21]. By explicitly resolving urban geometry as a big "street canyon" [22], most of the UCMs are generally good in reproducing energy budgets but are inevitably inadequate in capturing the dynamics of urban water budgets owing to the oversimplified representation of complex urban hydrological processes [23–25]. For example, *Kusaka* et al. [19] used hypothesized saturated surface with an evaporative parameter to represent vegetated surfaces in cities. *Lee* [20] included tall trees and grass surface in his hydrological model but subsurface water transport was neglected. In this paper, we adopt a physical urban hydrological model, developed recently by *Wang* et al. [26], to simulate green urban infrastructure. Compared to previous schemes [19–21], main developments in the model include detailed description of natural and engineered surfaces, consideration of subsurface water transport and sub-facet heterogeneity resolution. *Sun* et al. [27] replaced the homogeneous single-layer roof module within the model to enable the simulation of hygrothermal dynamics in multi-layer green roof system. Vertical transport and distribution of soil water content in a green roof were then resolved in discretized layers. Inter-layer heat fluxes in a green roof system are computed by a spatially-analytical scheme using Green's function approach [28]. Spurious numerical oscillation due to temperature discontinuities at the interface can be avoided with this scheme. This hydrological model was integrated into a single-layer UCM to fully capture the surface and subsurface energy and water transport in the built environment. Capability of the model had been validated by field measurements under different climate conditions [26–28].

Though the coupled UCM-hydrology framework is generally suitable for modeling various green roof designs, its performance depends largely on the accuracy of the input parameters [29,30]. Currently detailed field measurements of all input parameters of the model at various scales of applications are rarely possible. Input parameters related to vegetation types and soil properties in urban hydrological modeling vary widely for different green infrastructure. In addition, manufacturers of green roofs usually keep the technical information confidential to achieve competitive advantage. As a result, uncertainties inherent in the input parameter space of the hydrological model inevitably impair the quality of model performance.

This paper seeks to shed new light on the impact of parameter uncertainties on green roof modeling with two main objectives: (1) to investigate the sensitivity of the integrated UCM-hydrology model to various uncertain input parameters; and (2) to evaluate critical responses of green roofs under different scenarios (geographical locations, weather conditions, and vegetation cover fractions). The challenge of characterizing unsaturated hydraulic properties of soils adds to the complexity of numerical modeling. *Cuenca* et al. [31] showed that for bare soils, the parameterization of soil water transport had significant effect on evaporation process. Accurate estimates of soil hydraulic properties are of paramount importance in regulating land-atmosphere interactions and determining the land surface states [32,33]. In particular, properties such as hydraulic diffusivity and conductivity are highly nonlinear to soil moisture θ, which can vary by several orders of magnitude even for very small changes in θ, especially under relatively dry condition [34]. In this study, we adopt two widely used unsaturated soil hydraulic models and compare their performance in the integrated UCM-hydrology framework before the sensitivity analysis, namely the van Genuchten model (hereafter referred to as the vG model) [34] and the empirical soil hydraulic model developed by *Clapp and Hornberger* [35] and *Cosby* et al. [36] (hereafter referred to as the CHC model). Note that the CHC model has been adopted for modeling soil hydraulics in the Weather Research and Forecasting (WRF) model [32].

Analyzing model sensitivity to parameter uncertainty is common in environmental studies [37,38]. In conventional approach, the sensitivity of model output to an individual parameter is obtained by changing the values of that particular parameter while the rest parameters remain fixed. However, statistical correlations between the uncertain parameters from such approach can be biased towards the chosen base scenario [30]. In this paper, we use an advanced Monte Carlo simulation tool, i.e. the Subset Simulation [39], to conduct the sensitivity analysis. Subset Simulation is an adaptive stochastic simulation procedure that is particularly efficient in capturing critical events associated with small probabilities (i.e. risk analysis) and the uncertain parameter space of large dimensions. It has been applied over a broad range of engineering problems such as seismic risk analysis [40], fire risk analysis [41] and dynamics [42]. In the context of green roof study, assessment of critical responses of a roof system under local climate conditions manifests its effectiveness and is of great interest to manufacturer, city planner and households.

In the next section, we describe the basis of the urban hydrological model, unsaturated soil hydraulic models, and the advanced Monte Carlo simulation. Statistics of uncertain parameters in this study are summarized in Section 3. Model evaluation against observational dataset is demonstrated in Section 4. Section 5 shows the comparison between performances of two soil hydraulic models integrated in the hydrological model. Sensitivity of green roof modeling to uncertain parameters and critical performance under different weather conditions are discussed in Section 6, followed by concluding remarks in Section 7.

2. Methodology

2.1. Urban hydrological model

In this section, the urban hydrological model and the embedded unsaturated soil hydraulic models are briefly explained. Only parameterizations relevant to this study are discussed below, while detailed description can be found in original papers [26,27,34,36]. A schematic of the UCM is shown in Fig. 1(b). Building arrays are represented as one-dimensional (1D) infinite street canyons with equal heights on both sides. In Fig. 1(b), it clearly illustrates that the UCM takes the surface heterogeneity of urban terrain into account by dividing urban facets (roof, wall and ground) into sub-facets. In this paper, we categorize roof surface into two types: the green roof and the engineered roof (schematic is shown in Fig. 1(a)). As shown in Fig. 1(a), the green roof has three additional layers of various materials on top of the concrete deck, namely the vegetation-soil, the growing media and the drainage layers. These layers consist of porous materials and their volumetric water content θ is computed by vertically discretizing the layer. At the top layer, the infiltration I is calculated by:

$$I = \min[P, K(\theta)], \tag{1}$$

where P is the precipitation and $K(\theta)$ denotes the θ-dependent hydraulic conductivity. The surface runoff R is then calculated as the residual water budget:

$$R = P - I - ET, \tag{2}$$