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A HYDRUS model for irrigation management of green roofs with a water storage layer

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ABSTRACT

Green roofs suffer from water stress during prolonged dry periods. Periodically irrigation is usually needed to maintain the health of green roofs. This paper presents a green roof model for simulating the long term variation of soil moisture of green roofs with a storage layer. The model mainly incorporates a HYDRUS-1D model for the soil layer and an evaporation model for the storage layer. It explicitly accounts for the effects of evaporation from the storage layer on the soil moisture. After calibration and validation with the observed data of a pilot green roof, the model was implemented to evaluate the efficiency of various irrigation schemes for the green roofs built with different structural designs under typical weather conditions in Shenzhen, China. The results indicate that without irrigation the green roofs experience water stress (defined as soil moisture <60% of the field capacity) in more than 35% of days in a year. As the irrigation frequency increases, the days of water stress decrease but the total irrigation amount increases. Irrigation to the field capacity every 3 days and irrigation to the saturation moisture content every 7 days are two relatively efficient irrigation schemes, which can achieve optimal tradeoffs between the objectives of saving irrigation water and maintaining adequate soil water availability to the green roof plants. Furthermore, as the soil layer depth increases, the days of water stress decrease but the total irrigation amount increases. While as the storage layer depth increases, both the days of water stress and the total irrigation amount decrease. The study demonstrates that the model has the capacity to evaluating the efficiency of the irrigation schemes for the green roof. Therefore, it can help support the irrigation management of green roofs.

1. Introduction

Green roofs, a roofing system covered with soil and vegetation, are recognized as an economically and environmentally sustainable approach to urbanization. Many studies have demonstrated that green roofs have broad benefits on stormwater runoff mitigation (Fassman-Beck et al., 2013; Speak et al., 2013; Stovin et al., 2012; Versini et al., 2015; Voyde et al., 2010), runoff pollutant removal (Razzaghmanesh et al., 2014), energy conservation (Castleton et al., 2010; Chen, 2013; D'Orazio et al., 2012), mitigation of urban heat island effects (Kolokotsa et al., 2013; Susca et al., 2011), reduction of noise and air pollution (Rowe, 2011; Van Renterghem and Botteldooren, 2009), carbon sequestration (Getter et al., 2009; Li et al., 2010; Rowe, 2011), as well as increased biodiversity and landscape aesthetics (Brenneisen, 2006; Fernandez-Canero and Gonzalez-Redondo, 2010). Green roofs have become an increasingly attractive alternative to conventional roofs made of impervious materials (Carson et al., 2013). However, green roofs are difficult growing environments for vegetation because they have finite growing medium depths and volume (Lu et al., 2014; MacIvor et al., 2013; Nagase and Dunnett, 2010). Availability of water is another important limitation for vegetation on green roofs. The water demand of green roofs generally relies on natural precipitation events. However, periodically irrigation is still needed to maintain the healthy growth of vegetation in green roofs during the prolonged dry periods (Guo et al., 2014; MacIvor et al., 2013; Rowe et al., 2014). Moreover, an efficient irrigation scheme for green roofs can help mitigate water stress and save irrigation water.

The irrigation schemes and their efficiency for green roofs have previously been investigated through experiment on the test beds

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or measurement on the full scale of installations. VanWoert et al. (2005) reported that water should be applied at least once every 28 days to maintain the healthy growth of *Sedum* spp. in green roof substrates with a 6-cm media depth and more frequently for shallower substrates. Nektarios et al. (2014) also reported that the thinner substrates need the higher irrigation frequency, particularly for the extensive green roofs (depth of the substrate layer <15 cm). Papafotiou et al. (2013) investigated the synergistic effect of the type and depth of substrate layer and irrigation frequency on the growth performances of three Mediterranean aromatic xerophytes at an extensive green roof in Athens, Greece. They found that shallow compost-amended substrate with sparse irrigation resulted in similar or even bigger plant growth of all plant species compared with deep peat-amended substrate with normal irrigation. Rowe et al. (2014) compared the effectiveness of the irrigation methods (overhead, drip, and sub-irrigation) for extensive green roofs and found that overhead irrigation generally resulted in higher volumetric moisture content, less amount of runoff and better plant growth compared to drip and sub-irrigation. Schroll et al. (2011) evaluated green roof plant selections and the need for supplemental irrigation in the Pacific northwestern United States. They found that the grass roemer's fescue (*Festuca idahoensis* var. *roemeri*) and the shrub 'Lasithi' cretan rockrose (*Cistus creticus* ssp. *creticus*) suffered aesthetically under low irrigation; while irrigation had no effect on survival or growth of the succulents hardy iceplant and 'Cape Blanco' broadleaf stonecrop (*Sedum spathulifolium*) and the bulb small camas (*Camassia quamash*).

In addition, some green roofs are designed with an additional storage layer to increase the rain water storage capacity of the green roof system and to maintain proper soil moisture during dry periods. Vijayaraghavan (2016) classified the storage or drainage layer into drainage modular panels and drainage granular materials. The drainage modular panels are made of polyethylene or polystyrene with compartments to store water. Nophadrain 5 + 1 (Wong and Jim, 2014) and BioRemeGree drain cell (Vijayaraghavan and Joshi, 2014) are two examples of the commercial modular panels used for green roof systems. The drainage granular materials usually have some water retention capacity and large pore spaces to store water. The manufacturers focus on the development of lightweight drainage granular materials, such as expanded clay, expanded shale, pumice, natural puzolana and rubber crumbs, etc (Vila et al., 2012). Some manufacturers are experimenting with wicks and micropumps to enhance the water flux from the storage layer to the soil layer.

Many models have been developed to simulate the hydrological performance of green roofs during storm events, such as SWMM with the LID controls module (Alfredo et al., 2010; Burszta-Adamiak and Mrowiec, 2013; Palla and Gnecco, 2015), the HYDRUS-1D model (Hakimdavar et al., 2014; Hilten et al., 2008), the SWMS-2D model (Palla et al., 2009), and the Soil, Water Atmosphere and Plant model (SWAP) (Metselaar, 2012). Locatelli et al. (2014) presented a simple conceptual model for the hydrological performance of green roofs, which includes surface and subsurface storage components representing the overall retention capacity of the green roof. The models were usually applied to simulate the peak flow rates, retention volumes, or detention time for runoff from green roofs (Hakimdavar et al., 2014; Hilten et al., 2008; Li and Babcock, 2014).

In order to evaluate the irrigation requirement of green roofs during the inter-rainfall dry periods, the models should have the capacity to predict the variation of moisture content of the soil layer (Stovin et al., 2013). The effects of the storage layer should be taken into account in the model for a good irrigation management of green roofs. Some models, such as SWAP, HYDRUS-1D and SWMS-2D, can predict the variation of soil moisture given accurate evapotraspiration (ET), irrigation, and precipitation data (Hilten et al., 2008; Palla et al., 2009). In addition, Berretta et al. (2014) successfully simulated the temporal changes in moisture content in extensive green roofs during dry periods using a hydrologic model based on water balance, an estimate of potential ET and a soil moisture extraction function. However, their applications in green roofs are limited to monolithic green roofs without a storage layer at a site scale (Li and Babcock, 2014). Guo et al. (2014) applied an analytical probabilistic stormwater model (APSWM) to estimate the irrigation time fractions and the irrigation water requirements of green roofs with storage layers. For simplicity, the model treats a storage layer as an equivalent additional soil layer, which has the same hydraulic properties as the actual soil layer.

With respect to modelling studies of green roofs for stormwater management, relatively few have included the capability of modelling irrigation management of green roofs. Theoretically, the stormwater retained in the storage layer at the bottom of green roofs could evaporate into the upper soil layer and increase the moisture content of the media during dry periods. To date, the effects of evaporation from the storage layer on green roof irrigation requirement have not been explicitly considered in green roof modelling efforts.

The objectives of the present study are to (1) develop a green roof model, which incorporates the HYDRUS model and an evaporation model for the storage layer, to explicitly consider the effects of evaporation from the storage layer on the soil moisture during dry periods; (2) demonstrate the simulation accuracy of the proposed model by using data collected for a pilot green roof in Shenzhen, China; and (3) evaluate the efficiency of various irrigation schemes for the green roofs built with different structural designs under typical weather conditions in Shenzhen.

The present paper is organized as follows: Section 2 describes the experiments performed on a pilot green roof; the framework of the proposed green roof model; model calibration and validation as well as the design scenarios for modelling analysis. In Section 3, the efficiency of various irrigation schemes for the green roofs are presented and discussed. Finally, conclusions are presented in Section 4.

2. Material and methods

2.1. The green roof experiment

A pilot green roof was installed on a 1% slope terrace on Building E at the campus of the Peking University Shenzhen Graduate School (PKUSZ). The pilot green roof is a PVC box with the dimensions 2m × 2m × 0.3 m (length × width × height) (Fig. 1). The green roof consists of a vegetation layer, a soil layer, geotextile and a storage layer from top to bottom (Fig. 2). The vegetation layer is planted with sedum lineare, which is one of the most commonly used green roof plants (Dunnett and Kingsbury, 2008). The soil layer is filled with engineered light soil (10% yellow soil, 35% peat soil, 30% mushroom manure and 25% branches fertilizer) to a depth of 10 cm. The storage layer is 5 cm deep and filled with crushed gravels with a porosity of 0.43. There are two rows of drainage holes on one side of the PVC box: one is located on the top of the soil layer for drainage of surface runoff, the other is located at the top of the storage layer for drainage of bottom runoff.

The basic parameters of the soil matrix were measured by using laboratory soil-column experiments. The dry bulk density is 0.78 g/m^3, and the saturated water content, field capacity and residual water content are 0.32, 0.28 and 0.076, respectively. The saturated hydraulic conductivity of the engineered soil is 95 mm/h. The rainfall amount was recorded at an interval of 10 min by an automated weather monitoring system (DAVIS weather station, Hayward, CA, USA) installed at PKUSZ. The measured meteorolog-