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Runoff reduction from extensive green roofs having different substrate depth and plant cover

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ABSTRACT

The current study aims to systematically analyze the relationship between runoff reduction from different types of shallow green roof systems, and the initial substrate moisture conditions, and total rainfall depth. The experimental study comprised of 30 specialized lysimeters equipped with green roof layering. The lysimeters had two different substrate depths (8 cm or 16 cm) and three different plant covers [either succulent plants (*Sedum sediforme* (Lacq.) Pau), or xerophytic plants (*Origanum onites* L.), or turfgrasses (*Festuca arundinacea* Shreb.)]. In addition unplanted lysimeters and lysimeters without a green roof system were utilized as controls. The results of the experimental study were used in order to formulate a mathematical expression, which effectively described the relationship between all the above mentioned parameters (runoff reduction, initial substrate moisture conditions and rainfall depth). The derived relationship was then utilized to provide effective estimations of the rational method runoff coefficients, which constitutes one of the main prescribed methodologies for water resources planning, and management, as a function of initial moisture content and total rainfall depth. Furthermore, the Soil Conservation Service Curve Number model was calibrated using the collected rainfall–runoff data in order to estimate the corresponding curve number (CN) values. Finally, the applicability of a simple linear relationship between total rainfall depth and total runoff depth was investigated. The observed runoff reduction ranged between 2% and 100% for the total runoff depth and between 17% and 100% when the peak runoff rate was considered. Higher reductions were observed in deeper substrates (16 cm) combined with *O. onites* vegetation cover as well as in cases with lower initial substrate moisture contents and smaller rainfall depths. A strong multiple correlation between rainfall depth, runoff reduction and initial substrate moisture was observed. The developed equation describing this correlation was successfully fitted to the experimental data. In addition, the SCS-CN model was successfully calibrated using the experimental rainfall–runoff data of this study. The obtained CN values were generally high and varied from 88 to 95.5. The lowest CN value was obtained for *O. onites* vegetation cover combined with deeper substrate depth (16 cm), indicating an increased runoff mitigation potential for such vegetation cover types.

1. Introduction

Green roofs are emerging as one of the most promising management practices aiming to ameliorate the environmental problems and hydrological risks associated with urbanization (Booth and Jackson, 1997; Carbone et al., 2014, 2015; Hilten et al., 2008). One of the most important services provided by green roof systems is related to their ability to retain a portion of the rainfall and to distribute runoff over a longer period of time. In this way, green roofs are considered as an effective methodology for reducing hydrological risks in urban regions.

Green roof systems typically consist of three major components: a vegetation layer, a lightweight substrate medium and a water storage/drainage layer placed on top of a waterproof membrane (Carbone et al., 2015; Carson et al., 2013; Yang et al., 2015). According to the depth of the growing substrate layer, green roofs are commonly classified as extensive or intensive. Generally, green roofs with substrate depth less than 15 cm are classified as extensive and their vegetation consists of shallow rooting, drought

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resistant plants. In contrast, intensive green roofs have a substrate depth exceeding 15 cm which can support the sustainable growth of deeper rooting plants such as shrubs and trees. Due to the above mentioned characteristics, extensive green roofs are lighter, cheaper, and require less maintenance. Accordingly, they have wider applicability, especially on older building retrofitting where rooftop weight is the outmost limiting factor (Carson et al., 2013; Nektarios et al., 2011, 2015; Yang et al., 2015).

The hydrologic performance of green roof systems is characterized by the rainfall depth retained and the runoff release rate. They both depend on several factors, such as rainfall specific characteristics, anteceded rainfall conditions, substrate depth and its hydraulic characteristics, storage/drainage layer capacity, vegetation cover characteristics, and slope of the green roof (Carbone et al., 2015; Speak et al., 2013; Teemusk and Mander, 2007; Wong and Jim, 2014). Several studies have reported that green roofs can retain up to 90% of the total rainfall depth when individual rainfall events are considered, with the observed retention being reduced as the rainfall depth increased (Carson et al., 2013; Carter and Rasmussen, 2006; Getter et al., 2007; Mentens et al., 2006; Morgan et al., 2013; Simmons et al., 2008; Spolek, 2008; Stovin et al., 2012; Teemusk and Mander, 2007; Van Woert et al., 2005; Wong and Jim, 2014). Furthermore, reductions of 60–80% have been reported in peak flow rates from green roof systems compared with conventional roof tops (Bliss et al., 2009; Carter and Jackson, 2007; Palla et al., 2012; Villarreal et al., 2004). When the total annual rainfall depth is considered, green roofs may significantly reduce runoff generation from 15% to 80% (Bliss et al., 2009; Carter and Jackson, 2007; Palla et al., 2012; Villarreal et al., 2004). However, several studies showed that the observed retention depends on the rainfall pattern (Carter and Rasmussen, 2006; Teemusk and Mander, 2007; Wong and Jim, 2014). More specifically, in larger rainfall events, the maximum green roof storage capacity is reached, resulting in temporary retainment of the remaining rainfall which is then slowly released from the green roof system. Thus, the rainfall surge becomes significantly smoothed compared with the conventional impervious rooftops (Hilten et al., 2008; Wong and Jim, 2014). In addition, the ability of green roofs to reduce runoff is greatly affected by the initial moisture conditions as well as by the total rainfall depth. Consequently, the capacity of green roof systems to reduce runoff when it is mostly needed, namely during wet periods and for large rainfall events, has been questioned.

In practice, water resources planning guidelines necessitate the use of simple methods for estimating runoff volumes and peak flows from green roof systems. For instance, existing regulations often demand hydrologic calculations to be performed using the Soil Conservation Service Curve Number (SCS-CN) method (NRCS, 2009) or by utilizing the runoff coefficient of the rational method. Therefore, several researchers have studied the empirical relationships for green roof runoff based on curve number and runoff coefficient (Alfredo et al., 2010; Carter and Rasmussen, 2006; Fassman-Beck et al., 2016; Getter et al., 2007; Moran et al., 2005). Yang et al. (2015), analyzed the possible runoff generation mechanisms in green roofs, which involve either the runoff resulting from substrate saturation (saturation-excess) or runoff generated when the rainfall intensity is larger than the infiltration rate (infiltration-excess). They suggested that due to the highly conductive substrate materials that are utilized in extensive or semi-intensive green roofs, saturation-excess is the dominant mechanism. Accordingly, they proposed a simple linear relationship between total rainfall depth and total runoff depth based on a simple water balance applied on an event by event basis.

The current study included four different vegetation covers [either succulent plants (*Sedum sediforme* (Lacq.) Pau), or xerophytic plants (*Origanum onites* L.), or turfgrasses (*Festuca arundinacea* Shreb.), or bare substrate without any vegetation] and two green roof substrate depths (either 8 cm or 16 cm). The aim of such detailed study was to systematically analyze the relationship between runoff reduction, initial substrate moisture conditions, and total rainfall depth as well as to formulate a mathematical expression effectively describing the above-mentioned relationship. This relationship is expected to provide effective estimations of the rational method runoff coefficient (C), which is one of the main standardized methodologies for water resources planning and management. Furthermore, the Soil Conservation Service Curve Number (SCS-CN) model, which is one of the most popular techniques among engineers and practitioners for estimating runoff volumes and peak flows (NRCS, 2009; Soulis et al., 2009; Soulis and Valiantzas, 2012, 2013), was calibrated using the experimental rainfall–runoff data obtained in the present study in order to estimate the corresponding curve number (CN) values. Finally, the applicability of a simple linear relationship between total rainfall depth and total runoff depth was investigated.

2. Materials and methods

2.1. Experimental setup and data acquisition

The study period initiated from 15 Jan. 2015 and lasted until 15 Jan. 2016. The study included thirty (30) orthogonal thermally insulated lysimeters (Fig. 1) having external dimensions of 110 cm wide × 210 cm long × 35 cm height (internal dimensions were 100 cm wide × 200 cm long × 30 cm in height) that were placed on the roof of the library building at the Agricultural University of Athens, Greece (37°59′ lat., 23°42′ long). The lysimeters were constructed from 2 mm thick galvanized metal sheets and were based on metal bases having the ability to alter their inclination from 0.5° to 30°. The lysimeters and their inclination system were designed and manufactured by Kinematik SA (Metamorphosi, Athens, Greece). Each lysimeter was thermally insulated at the bottom and from all four sides by 5 cm extruded polystyrene slabs (300 L, Fibran SA, Thessaloniki-Oreokastro, 56010, Greece). The lysimeters were set at an inclination of 5° with the use of a laser leveling instrument.

A complete extensive green roof layering system was simulated within each lysimeter, starting with a protection mat placed on top of the water proofing membrane (Sarnafil®, TG 66-15; Sika Hellas, Krioneri, Athens, Greece) that was lined with the use of heated air. An outflow opening was constructed in the middle of the lowest part of the lysimeters. The outflow opening was lined with the same waterproofing material and was connected to a PVC pipe leading the runoff to a tipping bucket system. The size of the opening was sufficiently large to avoid the possibility of bottleneck effect even at extreme rainfall intensities. The waterproofing membrane was protected with a 3 mm protection mat made of non-rotting synthetic polyester fibers, weighing 0.30 kg m^{-2}, able to retain 3 L m^{-2} water as manufacturing instructed (VLS-300, DIADEM, LANDCO LTD Athens, 14341, Greece). On top of the protection mat a 25 mm high, 1.36 kg m^{-2} drainage board (DIADRAIN 25H, DIADEM, LANDCO LTD Athens, 14341, Greece) with 11.8 L m^{-2} water storing capability was laid. The drainage layer was covered by a non-woven geotextile (VLF-150, DIADEM, LANDCO LTD Athens, 14341, Greece) made of thermally strengthened polypropylene.

The substrate for plant growth was placed on top of the non-woven geotextile. Fourteen (14) lysimeters were filled with 8 cm substrate depth, and another 14 lysimeters with 16 cm substrate depth. The substrate comprised pumice, attapulgite clay, zeolite and grape marc compost at volumetric proportions of 65:15:5:15 respectively, according to the patent #1008610. The physical and chemical capacities of the utilized substrate are listed in Table 1. Each lysimeter was equipped with autonomous automated