Journal of Hydrology 564 (2018) 416–423

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Green roof aging: Quantifying the impact of substrate evolution on hydraulic performances at the lab-scale

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ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Giorgio Mannina, Associate Editor

Keywords:
Hydrodynamic
Substrate
Pedogenesis
Hydrological performance
Inverse modelling
Numerical simulation

ABSTRACT

Green roofs are valuable solutions for rain management improvements in urban areas as they can partly store and delay rainfall water. Here, we point out that green roofs cannot be considered as static systems, which performances remain constant over time. This work is based on the cross-use of a lab-scale experiment and a modelling approach to evaluate the hydraulic performances of a green roof substrate over time. Experiments were conducted on new and aged materials, after 30 months of *in situ* aging. The experimental device was designed and implemented to simulate irrigation or rainfall and accurately monitor hydraulic fluxes. An estimation of hydraulic parameters was obtained by using inverse modelling of experimental data with HYDRUS-1D software. Comparisons between measured and modelled data demonstrated the reliability of the model for simulating the hydraulic behavior of the green roofs. Considering an incoming water event – which mimics a heavy rainfall – of 43 mm h^{-1} and similar water content initial conditions, our simulations indicate that the retention capacity and the delay effect were always higher for the new substrate than for the aged one. Both of these performance indicators strongly vary with the initial water content of the substrates. Whereas the relation is linear for the retention capacity ranging from 100% of retention for the drier conditions to 0% for the saturated substrates, it is more complex for the delay effect. Such performances were comparable to analogous data from the existing literature. Furthermore, this comparison confirmed that green roofs are submitted to an early aging in terms of structure, *i.e.* porosity. In our study, the aged substrate presented less favorable performances thus highlighting the key role of the composition of green roof substrate not only on the initial performances but also on their sustainability.

1. Introduction

Urbanization leads to increasing sealed surfaces, poorly covered with vegetation, thus limiting the amount of water that can infiltrate soils in comparison to rural areas (Lazzarin et al., 2005). As a result, during major rain events _peak runoff_ occurrence can lead to the release of high water volumes in urban areas that require adapted strategies to release storm-water. Among regulation devices, green roofs (GR) can be used to store, to evapotranspire and to delay the release of storm-water in sewers (Mentens et al., 2006). GR retention systems can retain and evapotranspire from 40 to 80% of the total annual rainfall volume (Bengtsson et al., 2005; Moran and Smith, 2005). However, this figure may vary significantly depending on: the local climatic conditions, the weather conditions over the year and the GR design (Villarreal et al., 2004; Jahanfar et al., 2018). Better performances are even obtained during rain peak events (60–80%) or at the individual rain event scale (Berndtsson, 2010; Hakimdavar et al., 2014; Palla et al., 2012; Stovin, 2010).

Abbreviations: GR, Green Roof; FLL, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (German Landscape Research, Development and Construction Society); TDR, Time Domain Reflectometer; nRMSD, normal Root Mean Square Deviation; ET, Evapotranspiration, RC, Retention Capacity; NSE, Nash-Sutcliffe model Efficiency

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https://doi.org/10.1016/j.jhydrol.2018.07.032
Received 15 May 2018; Received in revised form 9 July 2018; Accepted 14 July 2018
Available online 17 July 2018

Such performances at least depend on three intrinsic parameters: (i) the GR substrate moisture state prior to a rain event (Berretta et al., 2014; Palla et al., 2008; Uhl and Schiedt, 2008), (ii) the nature, the geometry and the organization of GR constituent layers (Carter and Jackson, 2007; Mentens et al., 2006; Teemusk and Mander, 2009) and (iii) the age of the GR (Getter et al., 2007). Concerning the first point, water content in the substrates is mostly influenced by previous meteorological events and local evapotranspiration rates (Hakimdavar et al., 2014; Hilten et al., 2008). In this way, vegetation type and abundance appear also as crucial factors (Buccola and Spolek, 2011). For the second point, the retention capabilities of extensive GR are mainly ensured by the substrate. Several studies emphasize the importance of its properties (thickness, characteristics and proportion of its organic and mineral components, etc.) on its hydraulic behavior (Berndtsson, 2010).

Regarding the third point, GR should be considered as reactive media that can be submitted to an evolution of their physical and chemical properties. As a consequence, significant evolution with time of the substrates physical properties, like their pore network, should lead to changes in their hydraulic parameters (Cannavo et al., 2014; Séré et al., 2012; Kutilek, 2004). A study on a 5-year-old substrate showed that the water holding capacity has increased compared to a new one (Getter et al., 2007). Several authors (Bouzouidja et al., 2018; De-Ville et al., 2015, 2017, 2018; Getter et al., 2007) demonstrated an evolution of the substrate structure, with variations of grain size and bulk density over time. They also highlighted an increasing number of micro-pores and macro-pores and greater connectivity between them, they did not quantify it though. For example, De-Ville et al. (2017, 2018) observed that a substrate based upon a light expanded clay aggregate increases the maximum water holding capacity, which was notably correlated with an increase of finer particles. Other works have monitored long term hydraulic performances of GR but did not study the physical evolution of the substrates (Berretta et al., 2014; Locatelli et al., 2013) or mentioned the lack of influence of the age of GR on their hydraulic behavior (Mentens et al., 2006). Consequently, there is a need for an increasing knowledge about the relation between hydraulic parameters evolution over time and hydraulic performances.

Considering the importance of intrinsic (e.g. nature of the constituents, physical properties, depth) and external factors (e.g. intensity and frequency of rainfall) on hydraulic performances of GR, tools to simulate hydrodynamics are required to forecast their behavior under various situations. Models of water transport in porous media (physical models as opposed to reservoir models) are considered to be relevant approaches to assess the GR hydraulic performances in various situations (Berretta et al., 2014; Charpentier, 2015, 2011; de Munck et al., 2013; Guo, 2012; Hakimdavar et al., 2014; Hilten et al., 2008; Metselaar, 2012; Palla et al., 2009; Stovin, 2010). Through the resolution of the general Richards equation (Richards, 1931), these authors were able to describe very accurately the water transport in unsaturated porous media such as GR and then demonstrated the interest of such an approach even though they did not measure the real hydraulic properties (hydraulic conductivity and water retention curve) required by the equations (Hilten et al., 2008; Palla et al., 2009). In their studies, these hydraulic parameters were evaluated based on a few physical characteristics (*i.e.* bulk density, particle size distribution, moisture at the field capacity and wilting point) thanks to pedo-transfer functions or by using neural networks prediction tools, like the rosetta module (Schaap et al., 2001). However, GR substrates are notably different in composition and structure from natural soils due to their coarse texture and the anthropogenic nature of their constituents (e.g. crushed brick, light expanded clay). Consequently, approaches based on natural soils databases should be used with caution. Thus, other authors carried out the experimental determination of those hydraulic parameters (Babilis and Londra, 2011; Hakimdavar et al., 2014). They measured hydraulic parameters in order to evaluate the impact of GR size (0.09–310 m^2) on hydraulic performances using a one-dimensional hydrologic model, HYDRUS-1D. Their prediction of the performance of a small GR (0.09 m^2) improved with the total rainfall amounts during a storm, but was generally not well captured. In addition, De-Ville et al. (2017) characterized their substrate using FLL testing physical measurements and non-invasive X-ray micro-tomography imaging. By coupling conceptual modeling and finite element meshing to determine retention and detention performances, De-Ville et al. demonstrated a small increase in terms of retention capacity of the 5-year-old GR. This enhancement was attributed to an increase of maximum water holding capacity in the aged substrate by 7% compared with the virgin substrate, which was also correlated to an increase of smaller pore size.

In this study, a GR laboratory setup was designed and implemented to monitor hydrodynamics and to highlight the substrate aging over thirty (30) months and its consequence on water transfer. This approach does not intend to represent any realistic behavior but aims at comparing, under similar controlled conditions, the hydrodynamics of a new (S0) substrate with an aged (S30) one. Another goal is to evaluate the accuracy of a water transport physical model to estimate the hydraulic performances over time and indicate some evolution of the properties of such an artificial medium.

2. Material and methods

2.1. Material

The first layer of a green roof is the vegetation plants, usually composed of sedum. These plants do not exceed 15 cm in height, including 5 cm of roots. Their contribution was not directly assessed in this study. The layer underneath is the substrate or growing medium. Here, we used a man-made mixture of 80% pozzolana and 20% organic matter. The specified pozzolana aggregate size distribution based on manufacturer specifications was 25% from 3 to 6 mm, and 75% from 7 to 15 mm. In France, pozzolana aggregates, extracted in the volcanic region of Massif Central, have a wide range of uses, including the creation of green roof substrates. Such a material exhibits interesting properties such as low bulk density, mechanical resistance and high water storage capacity (Yilmaz et al., 2016). It was already used for various published studies (Charpentier, 2015; Bevilacqua et al., 2016; Bouzouidja et al., 2018; Coma et al., 2016). The organic part is composed of 50% of peat dust and 50% of maritime pine barks. The present study focuses on the same substrate sampled at two different times. The first sample is called "new" substrate (S0) because it was never exposed to climatic aging, and the second sample is called "evolved" substrate (S30). S30 was sampled 30 months after implementation on an *in situ* GR located in Nancy (France) (N48°41′11.8716″, E6°13′7.0716″), which exhibits a temperate climate without dry seasons (Class Cfb according to the Köppen-Geiger classification). S30 was collected with roots and vegetation, preserving the organization of each layer, and then stored in a container before further lab-experiments. A bottom layer, geotextile, is used to prevent the leaching of the substrate. It was a thin synthetic non-woven polyester geotextile (about 2 mm) with apparent opening size about 90 μm.

2.2. Solid characterizations

Bulk density (ρ_a) was measured by filling and weighting the substrate in a stainless-steel cylinder (h = 30 cm; Ø = 20 cm) in accordance with the NF-EN 12,580 norm. Real solid density (ρ_r) was measured on three replicates using a helium pycnometer (Micromeritics AccuPyc 1130). Total porosity (δ) was then calculated after (Eq. (1)).

$$\delta = 1 - \frac{\rho_a}{\rho_r} \tag{1}$$

where ρ_a and ρ_r are respectively apparent and real soil density (kg m^{-3}).