The hydrological performance of a green roof: an experimental study in the University of Calabria, Italy

M. Carbone, G. Nigro, G. Garofalo & P. Piro
Department of Civil Engineering, University of Calabria, Italy

Abstract

In an urban environment, the progressive increase of impermeable surfaces has produced drastic changes in the natural hydrological cycle. Heavy rainfall-runoff events may overwhelm urban drainage systems, causing consequent flooding, which may be dangerous to human life and urban infrastructures. The reduction of green areas and the surface ‘sealing’ do not only produce negative effects from a hydrological-hydraulic perspective, but also from an energy point of view, contributing to modifying the urban microclimate.

In the urban environment the use of green roofs may represent a sustainable solution to abate urban runoff quantity and quality, by retaining a portion of drained rainwater, and to reduce a heated island effect. The innovative green roof at the University of Calabria consists of light-weight layers and is covered by Mediterranean plant species. The green roof is monitored with an intensive system to retrieve hydrological and hydraulic parameters across the stratigraphy and in the surrounding environment.

The objective of this study is to show the hydraulic response of a green roof in the Mediterranean climate during dry and wet weather conditions. The hydrological performance evaluation was based on water content data monitored across the entire stratigraphy and the flow rates released at the outflow for three rainfall-runoff events and for three dry weather events. The study shows the advanced monitoring system and the temporal distribution of effluent flow rate and water content for the investigated green roof and the bar roof.

Keywords: stormwater, retention rainwater, low impact development, green roof, soil water content.
1 Introduction

In the urban environment, the progressive increase of impermeable surfaces has produced drastic changes in the natural hydrological cycle. During rainfall events, the infiltration rate and evapotranspiration in highly urbanized watersheds have significantly dropped and, as a result, an increase of runoff volumes and peak flow rates has occurred. Heavy rainfall-runoff events may overwhelm the urban drainage systems, causing consequent flooding, which may be dangerous to human life and urban infrastructures. The reduction of green areas and surface ‘sealing’ not only produce negative effects from a hydrological-hydraulic perspective, but also from an energy point of view and contribute to modifying the urban microclimate and generating heat islands in our cities. During rainfall events, the discharge of pollutants such as heavy metals, nutrients, organic matter and particulate matter washed-out from roads, parking lots, and rooftops into local waterways, impairs the water quality of the receiving water bodies [1–3].

Compared to traditional grey infrastructures, green infrastructures (GI) represent small-scale engineered facilities, belonging to green stormwater infrastructure practices which mimic the pre-development hydrological cycle [4, 5]. GI offers a wide range of benefits to people and wildlife, incorporates both the natural environment and engineered systems and preserves ecosystem values and functions [5, 6].

Green roofing is a GI practice, which is particularly advantageous where land area is unavailable for other BMPs [7, 8]. A green roof consists of three major components: a vegetative/surface layer; a substrate (soil); a storage/drainage layer [9]. Green roofs mitigate runoff since the substrate and vegetation absorb precipitation, providing rainfall retention.

A green roof has been designed and engineered at the University of Calabria in an European Project (PON – Integrated and sustainable management service for the water – energy cycle in urban drainage systems) funded by EU and MIUR (Ministry of University and Research – Italy), along with other sustainable water-green solutions, such as a permeable pavement and a biofiltration system. The main objective of the project is the development of an integrated and sustainable management service for the water–energy cycle in the urban environment.

Specifically, the green roof is covered by autochthon vegetal species (Mediterranean climate) and is characterized by innovative stratographies. The data have been collected by advanced and ad-hoc instrumentation since September 2013. The green roof is designed and built based on the local climate conditions. Specifically, autochthon vegetal species, adapted to grow in a Mediterranean climate condition, are utilized, instead of commercial types of species such as Sedum, widely used in Germany and UK.

The objective of this study is to evaluate the hydrological performance of a full-scale green roof in the Mediterranean climate during dry and wet weather conditions. The hydrological performance evaluation is based on the water content data monitored across the entire stratigraphy in dry and wet weather conditions as well as the flow rates released from the green roof for three rainfall-runoff events.
2 Methodology

The research was conducted at the University of Calabria, Italy. The test site is situated on a fifth-floor terrace of a campus building and consists of four green roof compartments, which vary in their stratigraphy, composition elements and vegetal species. The site is located in a Mediterranean climate region, characterized by a hot-dry summers and cool-wet winters.

The study refers to three rainfall-runoff events and three dry weather periods selected from a three-month monitoring program (from September to December 2013). The study is based on the data retrieved from two of the four green roof compartments. The first compartment represents the reference roof (conventional roof), covered by a pre-existing waterproofing layer and equipped with four temperature sensors and a flow meter device at the outlet section. The second green roof with an area of 40 m² and a slope of 1% consists of the following layers: (1) a soil substrate of 8 cm; (2) an ‘egg box’ drainage and storage layer in polystyrene. The storage capacity of the drainage layer is equal to 11 L/m² as reported in the technical data sheet provided by the industrial company. The entire package has a thickness of 14 cm. The roof itself was protected by a tough geotextile membrane. A fibrous membrane was also placed between the drainage layer and the substrate. A transversal section of the green roof is shown in Figure 1.

![Figure 1: Transversal section of the green roof (stratigraphy).](image)

The substrate consists of a mineral terrain built to comply with Italian regulation (UNI 11235): (1) anchoring the root; (2) preventing standing water on the surface; (3) water and nutritional supply (due to the ability to retain water in the cavities, the terrain requires less water and due to the zeolite, nutrients remain firmly anchored inside); (4) root respiration and life of the microorganisms present (the natural cavities in the minerals and spaces between the grains ensure a significant supply of oxygen to the roots). The material is highly draining and clay-free. The particle size distribution (PSD) of the soil substrate is reported in Figure 2.
Figure 2: Particle size distribution of the mineral soil substrate.

The PSD is a hetero-disperse gradation ranging from 0.08 to 10 mm with a $d_{50}$ of 4 mm. The soil is classified according to Unified Soil Classification System (USCS) as silt sand. A fine filter membrane separates the substrate from the underlying ‘egg box’ drainage layer. The green roof is covered by pioneered vegetal species.

A data acquisition monitored thermo-physical parameters in the four compartments of the green roof (GR) and the building’s rooms underneath [10]. The water content was measured with a relative humidity sensor, consisting of 4-fork detectors. Across the entire stratigraphy, four sampling points in the GR were set up to measure water content in the soil. For each sampling point two relative humidity sensors were installed vertically across the substrate stratigraphy, for a total of 8 sensors in the GR.

Rainfall depth was measured every one minute using a 0.2 mm resolution tipping bucket rain gauge. With regard to the hydraulic parameters, flow meter devices, installed at the outlet of each compartment, were used to measure the effluent flow rates. The flow meter device was ad-hoc designed to measure a large range of flow rates (0.1–2 L/s) and was based on stage-flow rate relationship through an opening. The water level was measured by a level sensor.

3 Results

The results depicted in Figure 3 (A, B, C) show the distribution of effluent flow rate observed in three rainfall events occurring at September 16th, November 11th, December 1st 2013, respectively from the reference roof (R) and the green roof (GR). As expected, the effluent hydrograph from GR exhibits a lag with regard to the hydrograph from the R for each rainfall event.
Figure 3: Effluent flow rate and water content from the bare roof (R) and the green roof (GR) for three rainfall events (A, B, C). Cumulative effluent volume distribution for the bare roof (R) and the green roof (GR) for the three rainfall events (D, E, F).

Such delay is most likely due to the infiltration process through the soil (water retention) and the storage/drainage in the “egg box” layer, which also provides water retention. The water content results are averaged across the entire stratigraphy and the four sampling points in the GR. The temporal distribution of water content during the three rainfall events is reported in Figure 3 (A, B, C). The variation of water content in soil is dependent from complex interactions between the antecedent dry weather period (ADWP), monthly weather trends, and rainfall duration, quantity and peak intensity.
The initial water content value is observed to be relatively low in the event of September 16th 2013 since the ADWP is fairly long. The distribution of the water content closely mirrors the distribution of the effluent flow rate. However, towards the end of the event the water content slowly decreases until it reaches an asymptotic value of 8%. This suggests that the decrease of water content in the soil is a very slow phenomenon, which requires several dry weather days to return to its initial values.

The initial water content value in the event of November 11th 2013 is also pretty low, due to the fact that, during the ADWP, around 20 days long, small rainfall showers occurred. The distribution of the water content rapidly rises corresponding to the first event peak and then increases to an asymptotic value, which remains consistent after the rainfall event stops. Towards the end of the rainfall event the water content slowly decreases to a value of 10%. Throughout the entire event the variation of water content is negligible.

The event of December 1st is characterized by a higher initial water content in the soil with regard to the other events. Since the water content in the soil is already high, the water retention efficiency provided by the soil is significantly reduced. The water content remains fairly constant throughout the entire event, showing some slightly delayed peaks corresponding to the rainfall peaks.

The cumulative distributions of effluent volume from R and GR for each event are reported in Figure 3 (D, E, F). As expected, the total volume delivered from the GR is significantly smaller than that from R. The water volume reduction is due to the presence of the “egg box” layer, which provides water storage. A proportion of the water volume loss is also due to the presence of vegetation at the top layer, which triggers the evaporation process (solely evaporation, not transpiration, due to the low plant coverage).

The average volume retention of the green roof is around 30% with regard to the bare roof. Figure 4 reports the water content distribution for three dry-weather days as well as the solar radiation.

The results show that the peak of water content loss is slightly lagged with regard to the peak of solar radiation for the three dry days selected. These results suggest that the effect of solar radiation on the reduction of water content in the soil occurs during the afternoon hours after the maximum solar radiation (around noon). The reduced water content is considered to be mainly due to evaporation since the plant coverage was very low at the time of the monitoring.

4 Conclusions

A comparative monitoring program was carried out at the University of Calabria, Italy since September 2013 to characterize the hydraulic behavior of a green roof in Mediterranean climate conditions. The results obtained for a bare roof (R) and a green roof (GR) were compared. The GR consists of a soil substrate, with a thickness of 8 cm and an ‘egg box’ drainage/storage layer in polystyrene. The effluent flow rate and the water content behavior during wet weather events were analyzed. Also, the temporal distribution of water content for three dry weather days was investigated.
Figure 4: Water content and solar radiation for the green roof (GR) for three dry days.

The results were based on three rainfall events occurring on September 16th, November 11th, December 1st 2013 and three dry weather days. The GR produced a lag in the hydrograph with regard to the R due to the infiltration process through the soil (water retention) and the water retention in the storage layer.
The initial water content highly influenced the stormwater retention capacity of the soil and, thus, the hydrological performance of the green roof. A low value of initial water content is typical of the events with a fairly long antecedent dry weather period (ADWP). The temporal distribution of water content closely follows the effluent flow rate distribution, regardless of the rainfall event. The water content slowly drops, even after the end of the rainfall events, suggesting that a long ADWP is required to bring the water content to its original value. As expected, the findings also showed that, when the initial value of water content in soil is already fairly high, the water retention provided by the soil is significantly reduced throughout the entire event.

The total volume reduction provided by GR is, on average, around 30% due to the presence of the “egg box” layer, which provides water storage. A portion of the water volume loss is also due to the presence of vegetation on the top layer, which triggers the evaporation phenomena (solely evaporation, not transpiration due to the low plant coverage).

The findings demonstrated the positive effect in volume reduction of the lightly weighted green roof, especially when the initial water content is relatively low. Further studies will analyze the results from long-term monitoring and study diverse design configurations to enhance the hydraulic performance of this green roof package.

Acknowledgements

The study was co-funding from the Italian National Operative Project – Research and Competitiveness for the convergence regions 2007/2013 – I Axis “Support to structural changes” operative objective 4.1.1.1. “Scientific-technological generators of transformation processes of the productive system and creation of new sectors” Action II: “Interventions to support industrial research”.

References


