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Multi-level numerical and statistical analysis of the hygrothermal behavior of a non-vegetated green roof in a mediterranean climate

Giuseppe Brunetti[a,b,c,*], Michele Porti[c], Patrizia Piro[c]

[a] Department of Civil Engineering, Architecture, Land, Environment and Mathematics, University of Brescia, Brescia 25123, Italy
[b] Department of Land, Air and Water Resources, University of California, Davis, Davis 95616, United States
[c] Department of Civil Engineering, University of Calabria, Rende, CS 87036, Italy

HIGHLIGHTS

- A numerical description of the hygrothermal behavior of a green roof is provided.
- The model is combined with advanced statistical/numerical methods.
- The model is calibrated against measured data from an experimental facility in Italy.
- The cooling efficiency of a combined stormwater reuse-green roof system is examined.
- The watering regime is optimized using a Response surface methodology.

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ABSTRACT

Green Roofs (GR) represent a sustainable technological solution for reducing the environmental footprint of urban areas. Despite their benefits, traditional GRs have been criticized regarding their economic feasibility, suggesting to develop advanced hybrid engineering solutions able to simultaneously maximize their hydrological and energetic benefits. In this view, there is a need of numerical models able to describe their complete hygrothermal behavior. Thus, the main aim of this study was to assess the suitability of the one-dimensional mechanistic model HYDRUS-1D in providing an accurate and comprehensive description of the coupled water-heat-vapor transport in a field-scale Non-Vegetated Green Roof (NVGR) in the south of Italy. A complete calibration framework, which encompassed the Particle Swarm Optimization (PSO) algorithm and the combined Global Sensitivity Analysis-Generalized Likelihood Uncertainty Estimation (GSA-GLUE) method, was used to estimate the substrate thermal properties and assess the model predictive uncertainty. The calibrated model was exploited to examine the cooling efficiency of a combined Stormwater Reuse-NVGR system in the warm season. The analysis revealed that deeper substrates are positively correlated with thermal lag and attenuation, and that the irrigation can be properly designed to trigger the evaporative and convective cooling of the NVGR. The Response Surface methodology was finally used to optimize the watering regime on an 8 cm-deep NVGR. The exploitation of the evaporative cooling effect of the NVGR by means of a model-based irrigation optimization led to a reduction of the average soil bottom temperature of 4 °C. The coupled system was able to maximize the energetic benefits of GR.

1. Introduction

During the last century, cities have expanded their boundaries as a consequence of the demographic growth and urbanization. The urban population is constantly increasing, and future projections estimate that it will represent 66% of the total word population by 2050 [1]. The unplanned urbanization of undeveloped lands leads to rapid sprawl, environmental pollution, and unsustainable resources utilization [2,3]. Energy consumption and water resources management are among the key aspects in the mitigation of the environmental footprint of urban areas. In the early 2000s, Santamouris et al. [4] highlighted how urban areas were already representing the major source of energy consumption, in particular for heating and cooling offices and residential buildings, and the importance to develop sustainable solutions able to reduce energy demand and improve the urban climate. Nevertheless, buildings are not only energy-intensive, but their rooftops represent

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[*] Corresponding author at: Department of Land, Air and Water Resources, University of California, Davis 95616, United States.
E-mail address: giusep.bru@gmail.com (G. Brunetti).

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40–50% of impervious surfaces in urban areas. Impervious surfaces alter the natural hydrological cycle by reducing the infiltration and evapotranspiration capacity of urban catchment, and increasing the surface runoff.

Green roofs (GR) belong to the class of Low Impact Development techniques (LID), a 'green' approach to stormwater management that aims to restore the natural hydrological cycle of urban areas. A vast literature support the role of GRs as a sustainable solution. A comprehensive and exhaustive review of the environmental benefits of GRs was provided by Berardi et al. [5], who also highlighted how cross-disciplinary approaches are fundamental in the analysis of such systems. In our opinion, this represents a critical point for a more widespread adoption of GRs, and LIDs in general. Several valuable studies have focused on providing an assessment of the hydrological and energetic benefits of green roofs in urban areas. For example, Brunetti et al. [6] investigated the hydrological behavior of a 8 cm-deep extensive GR coupled with a reuse system in a Mediterranean climate. In that study, the GR exhibited significant stormwater retention capacity and was able to reduce peak flow rate with values ranging from 7 to 60%. In another work, Stovin et al. [7] analyzed the hydrological performance of a green roof test bed in UK. Based on a 29-months monitoring campaign, the authors reported an annual retention capacity of 50.2%, with a total volumetric retention equivalent to 30% during the significant rainfall events. These and other scientific studies have clearly proven the hydrological gain of GRs, which are able to retain and evapotranspirate stormwater, thus reducing the surface runoff.

Similarly, further researches provided a clear evaluation of the energetic benefits of GR. In a recent study, Bevilacqua et al. [8] demonstrated how extensive GRs can effectively reduce surface temperature during summer and mitigate the daily temperature excursion during winter, thus providing an active thermal insulation effect on the underlining building. In another work, Santamouris et al. [9] investigated the energy saving potential of green roofs on a nursery school in Greece. The analysis revealed that GRs were able to significantly reduce the cooling load during summer, with values ranging from 12 to 87%. As reported by Jim [10], GRs can serve as a surrogate thermal insulation to limit the amount of heat entering the indoor space. The thermal performance of GRs can be further improved by carefully selecting their materials. In this perspective, Perez et al. [11] experimentally investigated the use of rubber crumps as drainage layer in green roofs. Their analysis confirmed that GRs can enhance the energy savings during summer in Mediterranean climate, and revealed that rubber crumps can be used as a drainage layer without affecting the functioning of the GR.

Despite the environmental benefits, some criticisms have been moved to GRs regarding their economic feasibility. Ascione et al. [12] evaluated the technical and economic feasibility of green roofs applied to a modern office buildings, considering various vegetation covers and different external coatings. In that study, the analysis revealed how, in case of scarce precipitations, the watering cost can nullify the savings in energy demand for air-cooling. Although, the authors pointed out that the combination of water reuse systems and smart irrigation devices could increase the thermal benefits of GR. However, it must be emphasized that the analysis of Ascione et al. [12] neglected the economic impact of a reduced flood risk operated by GRs. This suggests that more research is needed to investigate the thermal behavior of GRs, in all its variants (e.g., vegetated and non-vegetated), and to propose engineering solutions able to merge and maximize the energetic and hydrological benefits of GRs. In this perspective, Berardi et al. [13] investigated the thermal benefits obtained by combining a water-to-air heat exchanger with a green roof. In that study, the coupled system was able to reduce the indoor temperature in the test cells by almost 10 °C when the exterior temperatures were above 35 °C. In another work, Chemisana et al. [14] focused on the experimental evaluation of Photovoltaic – Green Roofs (PV) under Mediterranean climate summer conditions. Their analysis revealed that the combined PV-GR system led to an average increase of the maximum power output of the PVs (ranging from 1.29% to 3.33% depending on the plant), indicating a good synergy between the PVs and the plants.

Numerical models represent a fundamental tool for the analysis of the hygrothermal behavior of GRs. As pointed out by Ouldboukhitine et al. [15], the numerical modeling of the dynamic thermal behavior of a GR is essential to build useful tools for the prediction of energy savings intended for engineering construction. In this view, several studies have focused on developing and validating numerical models able to provide a comprehensive description of the hygrothermal behavior of GRs. For example, Lazzarin et al. [16] developed a model able to calculate the thermal and energy effect of a green roof on a building under varying meteorological condition. However, the proposed model extremely simplified the unsaturated hydraulic behavior of the substrate by neglecting the role of the soil hydraulic properties. It is worth noting that, in the same study, the authors emphasized the role of the latent flux of evapotranspiration on the thermal behavior of the green roof. In particular, a wet substrate cancels entering energy fluxes, and produces outgoing fluxes acting as a passive cooler. This aspect has been deeply investigated in the present work. In another study, Sailor [17] coupled the building energy simulation program EnergyPlus® [18] with a physically based model of the energy balance of the green roof. The model was validated against measured temperatures with satisfactory results. In that study, the author highlighted how the building energy consumption was strongly affected by vegetation density, soil substrate depth and irrigation. EnergyPlus® [18] has been used in several studies dealing with the numerical modeling of GRs' thermal behavior. For example, it was later used by Chan et al. [19] to simulate the hygrothermal behavior of four GRs installed on the rooftop of a commercial building in Hong Kong, China. The model was validated with good results and later used to calculate the overall thermal transfer value, a widely adopted measure in many countries for enhancing energy-efficient building design. However, the proposed model do not provide a physically based description of the unsaturated water flow in the growing medium. Ouldboukhitine et al. [15] highlighted how an accurate description of the water flow in the soil substrate is fundamental for correctly simulating the energy transfer through the building envelope. In this view, some studies have recently focused on providing a more detailed description of the water flow in the soil substrate. Sun [20] used an updated version of the PROM model [21] to analyze the hygrothermal behavior of a green roof in China. The proposed model coupled the Richards equation with an analytical solution of the heat transport in the porous medium, and was validated with good results against measured data. However, the analytical solution was based on the pure heat conduction equation, thus neglecting the contribution of the heat convection operated by fluid, which becomes significant in nearly saturated conditions. Furthermore, the modified PROM model used in that study included only the Brooks-Corey function for the description of the soil hydraulic properties, which can be unsuited for soils exhibiting bimodal behavior [6]. A recent attempt to provide a detailed analysis of the hygrothermal behavior of a non-vegetated green roof is reported in Sandoval et al. [22]. In that study, the hydrological model HYDRUS-2D has been used to assess the impact of different soil properties on the thermal and hydraulic behavior of a hypothetical green roof. However, the effect of vapor flow was neglected, as well as no numerical validation against field scale data was carried out.

This brief literature review highlighted how there was a need of numerical models able to provide a reliable description of the deeply linked thermal and hydrological processes happening in GRs. This is confirmed by the high number of scientific studies dealing with GRs. As reported by Li and Babcock [23], in 2014 there were already more than 600 papers involving green roofs published worldwide (Web of Science), with a significant portion of them related to modeling. Thus, the main aim of this study was to assess the suitability of the one-dimensional hydrological model HYDRUS-1D [24] in providing an accurate