

## Hydraulic analysis and effluent water quality assessment in physical green roof models with potential for energy recovery

### Analyse hydraulique et évaluation de la qualité de l'effluent dans des modèles physiques de toitures végétalisées avec potentiel de récupération d'énergie

Carlos Rey Mahia<sup>a</sup>, Juan Naves García-Rendueles<sup>b</sup>, Stephen J. Coupe<sup>c</sup>, Liz Trenchard<sup>c</sup>, Luis A. Sañudo Fontaneda<sup>a</sup>, José Anta Álvarez<sup>b</sup>, Acacia Naves<sup>d</sup>, Felipe P. Álvarez Rabanal<sup>a</sup> y María Alejandra Pimiento<sup>b</sup>

<sup>a</sup> Civil, Environmental and Geomatics Engineering Research Group (CEGE), Department of Construction and Manufacturing Engineering, Campus of Mieres, University of Oviedo - reycarlos@uniovi.es; sanudoluis@uniovi.es; alvarezfelipe@uniovi.es.

<sup>b</sup> Water and Environmental Engineering Group (GEAMA), Technological Innovation Center in Building and Civil Engineering (CITEEC), Universidade da Coruña - juan.naves@udc.es; jose.anta@udc.es.

<sup>c</sup> Centre for Agroecology, Water and Resilience, Coventry University - stephen.coupe@coventry.ac.uk; apy157@coventry.ac.uk.

<sup>d</sup> CICA - Interdisciplinary Center for Chemistry and Biology, E.T.S.E. Camiños, Canais e Portos, Universidade da Coruña- acacia.naves@udc.es

## RÉSUMÉ

Cette étude analyse le comportement hydraulique, la qualité de l'eau et le potentiel thermique de six prototypes de toitures végétalisées intégrant des échangeurs de chaleur. Divers matériaux (argile expansée, granulats et déchets mixtes) ont été testés sous pluies simulées, en évaluant la rétention d'eau, les propriétés physico-chimiques de l'effluent et la récupération thermique. Les résultats révèlent des différences de rétention, ainsi que des valeurs initiales élevées de turbidité et de conductivité liées aux particules fines du substrat. Les concentrations métalliques restent faibles, hormis quelques traces dans un modèle. L'échangeur restaure sa température après la pluie, montrant la faisabilité d'applications eau-énergie. Ce travail apporte des données pionnières sur le comportement hydrologique et thermique de toitures végétalisées multifonctionnelles.

## ABSTRACT

This study evaluates the hydraulic behaviour, water quality, and thermal potential of six green roof prototypes incorporating heat exchangers. To this end, different materials (such as expanded clay, aggregates, and mixed CDW) were tested under simulated rainfall events, assessing water retention, the physico-chemical characteristics of the effluent, and the thermal recovery of the system. The results show notable differences in retention capacity between models, as well as high turbidity and electrical conductivity values during the first events, associated with the washing-out of fines from the substrate. Metal concentrations were low, except for occasional traces in one model. The heat exchanger demonstrated the ability to restore its temperature after rainfall, indicating feasibility for combined water-energy applications. This work provides pioneering insights into the hydrological and thermal behaviour of multifunctional green roofs.

## KEYWORDS

Green roofs, Sustainable Urban Drainage Systems (SUDS), Thermal exchange, Water quality, Water-Energy Nexus

## 1 INTRODUCTION

Green roofs (GRs) enhance local biodiversity by providing productive habitats within urban environments (Shafique et al., 2018). In temperate climates, such as those in the United Kingdom and northern Spain, rainfall is distributed throughout the year but may be insufficient to supply irrigation water for GR vegetation year-round. Modifications to the subbase layers of GR cross-sections can help overcome this limitation by increasing storage capacity and improving contact between the water reservoir and the substrate (Rey-Mahia et al., 2023).

GRs are part of the set of techniques known as Sustainable Urban Drainage Systems (SUDS). These systems have gained prominence due to their ability to restore elements of the natural water cycle and to mitigate problems associated with flooding and runoff pollution (Sañudo Fontaneda et al., 2024). In this context, sustainable water management has been recognized as a priority by the United Nations, with SUDS being a key tool in achieving this objective (United Nations, 2018).

Traditionally, SUDS design criteria have focused on four main pillars: water quantity, water quality, biodiversity, and amenity (Woods Ballard et al., 2015). However, recent research has begun to explore more holistic approaches that incorporate the energy dimension, considering both the thermal benefits that these infrastructures can provide to urban buildings and their potential for energy generation or recovery (Rey-Mahia et al., 2023). Innovative proposals combining energy production technologies with SUDS have been developed, such as the geothermal exploitation of permeable pavements and green ditches (Faraj-Lloyd et al., 2017; Rey-Mahía et al., 2023).

In this research, the potential for thermal exploitation using heat exchangers was evaluated for the first time in the literature, for which an experiment based on the standardized Thermal Response Test (TRT) was designed (García Gil et al., 2020). This study aligns with ongoing efforts to optimize the use of urban space through multifunctional surfaces, integrating the water–energy nexus approach (Charlesworth et al., 2017). The possible impact of the heat exchange system on the biological performance of the green roof system was also assessed, representing the first time these aspects have been jointly addressed in the literature within the combined design of heat pumps and SUDS.

Furthermore, the hydraulic and hydrological performance of the system cross-sections was studied, as well as the effluent water quality of the models, evaluating the influence of the different materials and section configurations analysed. The present work constitutes a significant contribution to the understanding of the hydrological–thermal behaviour of vegetated SUDS, providing pioneering knowledge in this field.

## 2 MATERIALS AND METHODS

This research focused on various GR designs, testing a total of six different typologies. The GR models were constructed using different materials, including aggregate, expanded clay, substrate (comprising 25% biochar and 75% compost), recycled aggregate (mixed CDW), and geocells. The material distribution and layer thicknesses are shown in Figure 1. The designs were developed based on information available in the literature concerning the influence of materials on green roof structure (Rey-Mahía et al., 2022).

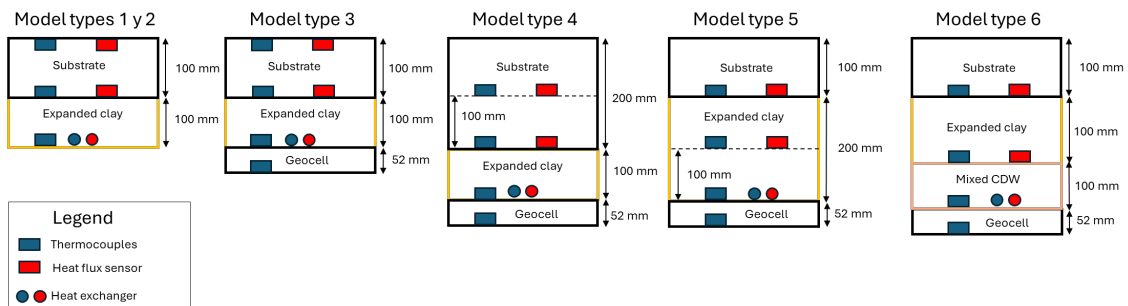


Figure 1. Cross-sections of the vegetated roofs.

As shown in Figure 1, a 20 mm diameter heat exchanger was installed at the bottom of the models, with a density of 5 m of pipe per square meter of roof area, arranged in a slinky configuration. Heat flux sensors (Hukseflux HFP-01) and type-K thermocouples were installed inside the models according to the layout shown in Figure 1. At the outlet of the testing boxes, which measured 111 × 91 × 61 cm, a water collection tank was installed for collecting

the effluent, as well as for measuring the outflow from the boxes using an ultrasonic sensor (see Figure 2).



Figure 2. View of one of the testing boxes.

The different tests carried out in this research were performed in the indoor rainfall simulator of the Hydraulics Laboratory at the Centro de Innovación Tecnológica en Edificación e Enxeñaría Civil (CITEEC), Universidade da Coruña, where rainfall events with an intensity of 30 mm/h were simulated. Three boxes were available for the physical roof models; therefore, the tests were structured in different batches.

First, two rainfall events (rainfalls 1 and 2) were conducted, each lasting 1 hour, with 96 hours between them. Subsequently, the impact of rainfall on the heat recovery capacity of the heat exchanger was assessed. For this purpose, the hot-water recirculation system was activated (recirculating water at  $50 \pm 2$  °C), and after 24 hours, two rainfall events were simulated, each with a duration of 30 minutes and separated by 90 minutes without rain (rainfalls 3 and 4). The heat exchange system ran from the beginning of the experiment for 48 hours and, after this period, ambient-temperature water was recirculated for an additional 24 hours. Water samples were collected from the outlet tank of each physical model at the end of each event, these being representative samples of the mean event concentration. The samples were analysed using a HI98194 multiparametric probe (Hanna Instruments), an LP 2000 turbidimeter (Hanna Instruments), and an Optima 5300DV optical emission spectrometer.

### 3 RESULTS

This communication presents the results associated with the analysis of effluent quantity and quality from the GR systems. Differences in the hydraulic retention capacity of the different models were observed. Expanded clay showed a higher initial hydraulic retention capacity until reaching the saturation point of the material. Water samples corresponding to the type-4 roof model presented the highest turbidity and electrical conductivity values, due to the washing-out of fines occurring in the substrate (this model having the greatest layer thickness, 20 cm). Table 1 presents the turbidity and electrical conductivity values of the mean event concentration samples.

	Turbidity (NTU)				Electrical conductivity ( $\mu\text{S}/\text{cm}$ )			
	Rain 1 (30 mm/h over 1h)	Rain 2 (30 mm/h over 1h)	Rain 3 (30 mm/h over 30 min)	Rain 4 (30 mm/h over 30 min)	Rain 1 (30 mm/h over 1 h)	Rain 2 (30 mm/h over 1 h)	Rain 3 (30 mm/h over 30 min)	Rain 4 (30 mm/h over 30 min)
<b>Model 1</b>	66	8	345	163	6979	216	7739	4965
<b>Model 2</b>	229	242	240	144	2204	1233	1665	1264
<b>Model 3</b>	34	171	274	174	7290	10510	7186	4234
<b>Model 4</b>	130	245	236	394	9755	12530	11970	10960
<b>Model 5</b>	177	341	478	298	9566	7310	5960	4120

Table 1. Turbidity and electrical conductivity values for each simulated rainfall.

With respect to metal concentrations in the leachates, a total of nine metals were analysed (Al, As, Cd, Cr, Cu, Hg, Mg, Pb, Zn). Concentrations were low in all samples, except for the type-6 model during the first rainfall events, where traces of Hg were detected, with measured values of 8 mg/L (rainfall 1) and 1.7 mg/L (rainfall 2).

Regarding the heat recovery capacity of the heat exchanger, it was observed that all models returned to their initial temperature conditions within  $12 \pm 2$  hours after the end of the second rainfall event (rainfall 4).

## 4 CONCLUSIONS

High turbidity and electrical conductivity values were observed in all models, which progressively decreased as the rainfall events proceeded. A similar trend was observed for metal concentrations. This behaviour is most likely due to the washing-out of fines present in the upper substrate layer. Furthermore, it was observed that the impact of rainfall on the heat exchange system was low, with the system showing a strong ability to restore the initial pre-rainfall temperature conditions. Future work will require evaluating the performance of the system under real operating conditions or in long-term testing.

## ACKNOWLEDGEMENTS

The present work was carried out in the CITEEC Research Infrastructure and is funded by EU funds under the Horizon 2020 program through the CO-UDlabs project ref. 101008626. Carlos Rey-Mahía acknowledges the University of Oviedo for the Predoctoral Scholarship reference PAPI-22-PF-8.

## LIST OF REFERENCES

- Charlesworth, S. M., Faraj-Llyod, A. S., & Coupe, S. J. 2017. Renewable energy combined with sustainable drainage: Ground source heat and pervious paving. *Renewable and Sustainable Energy Reviews*, 68, 912–919. <https://doi.org/10.1016/j.rser.2016.02.019>
- Faraj-Lloyd, A., Charlesworth, S. M., & Coupe, S. J. 2017. *Sustainable Drainage Systems and Energy: Generation and Reduction* (S. M. Charlesworth & C. A. Booth, Eds.; First Edition). John Wiley & Sons, Ltd.
- García Gil, A., Garrido Schneider, E. A., & Mejías Moreno, M. 2020. *Geotermia Somera: Fundamentos Teóricos y Aplicación*. Instituto Geológico y Minero de España (IGME).
- Naciones Unidas. 2018. La Agenda 2030 y los Objetivos de Desarrollo Sostenible: una oportunidad para América Latina y el Caribe.
- Rey-Mahía, C., Álvarez-Rabanal, F. P., Coupe, S. J., & Sañudo Fontaneda, L. Á. 2023. The Role of Geothermal Heat Pump Systems in the Water–Energy Nexus (D. Borge-Diez & E. Rosales-Asensio, Eds.). *Springer International Publishing*. <https://doi.org/10.1007/978-3-031-24524-4>
- Rey-Mahía, C., Álvarez-Rabanal, F. P., & Sañudo-Fontaneda, L. 2023. Experimental and Numerical Study of the Thermal Properties of Dry Green Swales to Be Used as Part of Geothermal Energy Systems. *Applied Sciences (Switzerland)*, 13(19). <https://doi.org/10.3390/app131910644>
- Rey-Mahía, C., Álvarez-Rabanal, F. P., Sañudo-Fontaneda, L. A., Hidalgo-Tostado, M., & Suárez-Inclán, A. M. 2022. An Experimental and Numerical Approach to Multifunctional Urban Surfaces through Blue Roofs. *Sustainability (Switzerland)*, 14(3). <https://doi.org/10.3390/su14031815>
- Sañudo Fontaneda, L. Á., Roces García, J., Allende Prieto, C., Rey Mahía, C., & Menéndez Suárez-Inclán, A. 2024. *Manual Técnico de Diseño de Sistemas Urbanos de Drenaje Sostenible (SUDS) y su Implementación en el Municipio de Gijón*. Ediciones Universidad de Oviedo
- Shafique, M., Kim, R., & Rafiq, M. 2018. Green roof benefits, opportunities and challenges – A review. In *Renewable and Sustainable Energy Reviews* (Vol. 90, pp. 757–773). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2018.04.006>
- Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., & Kellagher, R. 2015. *The SuDS Manual*. CIRIA. <https://doi.org/978-0-86017-760-9>