Evaluating SUDS performance to support stormwater reuse strategies in Madrid Nuevo Norte urban development

Évaluation du fonctionnement des SUDS pour soutenir les stratégies de réutilisation des eaux pluviales dans le développement urbain Madrid Nuevo Norte

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RÉSUMÉ

Ce travail présente les résultats initiaux du suivi d'un projet pilote de Systèmes Urbains de Drainage Durable (SUDS) déployé dans le nord de Madrid afin d'analyser le potentiel de réutilisation locale des eaux pluviales dans le futur développement Madrid Nuevo Norte. Deux typologies – un pavé perméable et un jardin de biorétention – ont été monitorées parallèlement à un avaloir conventionnel. Douze épisodes pluvieux ont été étudiés, comprenant des analyses de qualité d'eau, l'enregistrement continu des débits et la caractérisation des substrats. Une grande partie des paramètres se situe dans les plages de valeurs issues des cadres réglementaires espagnols pertinents, qui ne sont pas obligatoires pour ce type de dispositif mais constituent ici un référentiel utile pour évaluer l'aptitude à la réutilisation. Les résultats montrent que les SUDS atténuent significativement les débits de pointe et améliorent la qualité de l'eau, ce qui suggère qu'après un post-traitement adapté, ces eaux pourraient être valorisées pour des usages non potables dans une approche urbaine circulaire.

ABSTRACT

This study presents the first-year monitoring results of a Sustainable Urban Drainage Systems (SUDS) pilot facility implemented in northern Madrid to inform stormwater reuse strategies within the forthcoming Madrid Nuevo Norte urban development. A permeable pavement area and a bioretention zone were monitored alongside a conventional gully used as control. Twelve rainfall events were analyzed through water-quality monitoring, continuous hydraulic measurements, and soil characterization. Results show that both SUDS significantly attenuate peak flows and enhance stormwater quality through filtration, sorption, and biogeochemical interactions. Most parameters fall within reference values drawn from relevant Spanish regulatory directives which, although not legally binding for this type of system, provide an informative benchmark for assessing reuse suitability. This suggests that, with appropriate post-treatment, SUDS-treated runoff could constitute a non-potable water resource viable for reuse. The findings offer evidence-based guidance for integrating decentralized stormwater capture and treatment into new urban districts, supporting Madrid's transition toward a circular and resource-oriented approach to sustainable rainfall management.

KEYWORDS

Bioretention, permeable pavement, stormwater reuse, SUDS monitoring, water quality.

Bioretention, Pavement perméable, Réutilisation des eaux pluviales, Suivi des SUDS, Qualité de l'eau.

1 INTRODUCTION

Urban developments are increasingly recognizing stormwater as a potential local water resource rather than merely drainage waste (Fletcher et al., 2015). This shift is especially relevant in Mediterranean cities such as Madrid, where seasonal water scarcity and high urban-water demand make the recovery of rainfall a valuable opportunity (European Environment Agency, 2020). Within this context, Madrid Nuevo Norte (MNN) urban development intends to incorporate Sustainable Urban Drainage Systems (SUDS) to support decentralized water capture, preliminary treatment, and potential non-potable reuse.

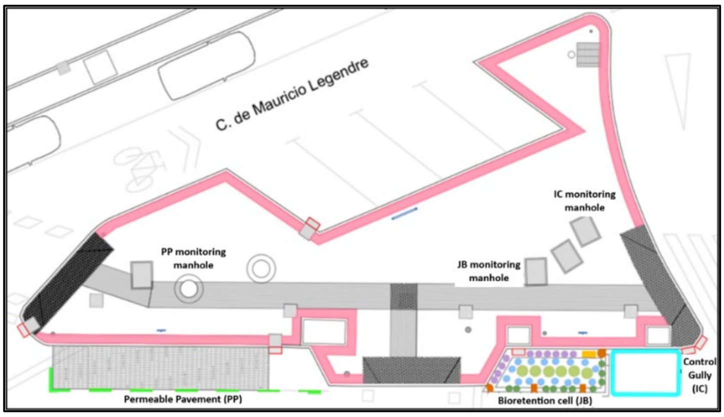

Figure 1 – Layout of the pilot installation

To provide technical evidence for these decisions, a pilot installation was built on Agustín de Foxá Street, consisting of a permeable pavement (PP), a bioretention zone (JB), and a conventional gully (IC) used as a hydraulic and quality baseline (Figure 1). The pilot aims to characterize the performance of these SUDS under real urban conditions, assess their capacity to improve stormwater quality, and determine the feasibility of recovering SUDS-treated runoff as a usable local resource.

This article presents the results of the first year of monitoring. The study focuses on a pilot level, evaluating how SUDS can act as capture and treatment elements that reduce hydraulic loads and enhance water quality, thus enabling realistic reuse pathways within MNN.

2 METHODS

Monitoring was conducted between October 2024 and October 2025. Twelve rainfall events were characterized by water sampling at IC, JB and PP. From these, two storms were sampled with increased temporal resolution to capture pollutant dynamics at the onset of runoff and evaluate potential first-flush effects. Water was collected at 0, 5 and 30 minutes from both IC and JB. The following physical, chemical and microbiological parameters were characterized, due to their relevance to stormwater treatment and reuse:

pH, total phosphorus, turbidity (UNT), dissolved oxygen, alkalinity, total suspended solids, saturated oxygen, sulphates, volatile suspended solids, chemical oxygen demand, chlorides, conductivity/total dissolved solids, biological oxygen demand (BOD_5), calcium (Ca_{2+}), *Escherichia coli*, total organic carbon, total coliforms, total nitrogen, aliphatic and aromatic hydrocarbons HTPs, enterobacter aerogenes, ammonium ($N\text{-}NH_{4+}$), PAHs, helminth eggs/intestinal nematodes, nitrite ($N\text{-}NO_{2-}$), pesticides, legionella, nitrate ($N\text{-}NO_{3-}$) and metals contents (Pb, Cu, Cd, Zn, Ni, Cr, Fe, Al, As, Mn, Sb, Se).

Furthermore, hydraulic performance was evaluated through level sensors converting depth to flow, using a V-notch weir. Since contributing drainage areas differ among the structures, discharge values were normalized per hectare for comparison. Also, meteorological variables were measured using a weather station and a rain gauge.

Finally, bioretention substrate was sampled before installation and twice during the monitoring period, analyzing the same set of parameters listed previously. Also, permeability tests were performed on the PP and JB using falling-head infiltration, thermography-based EPC tests, and ASTM ring infiltration method.

3 RESULTS AND DICUSSION

3.1 Stormwater quality and implications for reuse

As previously identified in relevant studies (Davis *et al*., 2009), the comparative analysis of the three monitoring chambers reveals clear differences in water quality linked to their respective drainage pathways and dominant sources of runoff. The conventional gully consistently showed the highest organic and microbiological loads, with elevated COD, BOD_5, ammonium, and indicator organisms such as *E. coli*, enterobacter aerogenes and total coliform, reflecting direct exposure to polluted urban surfaces. In contrast, the bioretention runoff samples exhibited higher concentrations of calcium, magnesium, phosphates and nitrates, indicating strong influence of the soil medium and occasional fertilizer residues from green-area maintenance. The permeable pavement chamber presented elevated levels of sodium, potassium, chlorides, sulphates, alkalinity and total carbon, consistent with leaching from construction materials and washing off from surrounding paved areas. Pesticides appeared only sporadically and at low concentrations, while metal patterns differed between systems: bioretention samples were dominated by soil-associated metals (Fe, Al, Zn, Mn, Cu), permeable pavement showed higher urban-derived metals contents, such as arsenic and antimony, and the gully exhibited intermediate values that reflect a mixture of surface wash-off and sediments accumulation.

Comparisons with earlier monitoring periods show a general decrease in contaminant concentrations in SUDS-treated runoff, suggesting progressive flushing of construction residues and stabilization of the systems. Pollutograph analyses confirmed first-flush behavior for parameters such as organic matter and metals contents, although this pattern was less evident for solids and some nutrients, likely due to differences in catchment response times and pollutant mobilization processes (Deletic & Orr, 2005).

3.2 Hydraulic performance and runoff attenuation

The analysis of flow quantity reveals clear contrasts in hydraulic behavior between the conventional drainage system and the SUDS. The Control Gully (IC) consistently exhibited an immediate and pronounced response to rainfall, with high peak discharges occurring shortly after precipitation onset. This behavior reflects the limited retention and infiltration capacity of impermeable road surfaces, which rapidly convey runoff towards the drainage network. In contrast, permeable pavement (PP) and the bioretention zone (JB) showed attenuated and delayed hydrographs, demonstrating their ability to infiltrate, store, and gradually release stormwater. This hydraulic moderation remained evident not only during moderate rainfall but also under high-intensity events and storms characterized by multiple rainfall pulses. Such consistency across diverse storm conditions confirms the robustness and efficiency of both SUDS typologies in controlling runoff. As an example, Figure 2 presents the normalized hydrograph ($L \cdot s^{-1} \cdot ha^{-1}$) and corresponding hyetograph of one the characterized events.

Overall, comparisons of total discharge and normalized flow further emphasize the distinction between conventional drainage and SUDS, underscoring the contribution of the latter to urban hydraulic regulation. By reducing and delaying peak flows, SUDS help mitigate local flood risk and improve the management of stormwater in densely impervious environments, thereby supporting more resilient and resource-oriented urban drainage strategies. A methodological limitation identified during the project relates to the need for refining catchment calibration to obtain more accurate flow estimates. Improving this calibration will help reduce uncertainties in peak flows and response times, enabling more reliable comparisons between events and across drainage systems.

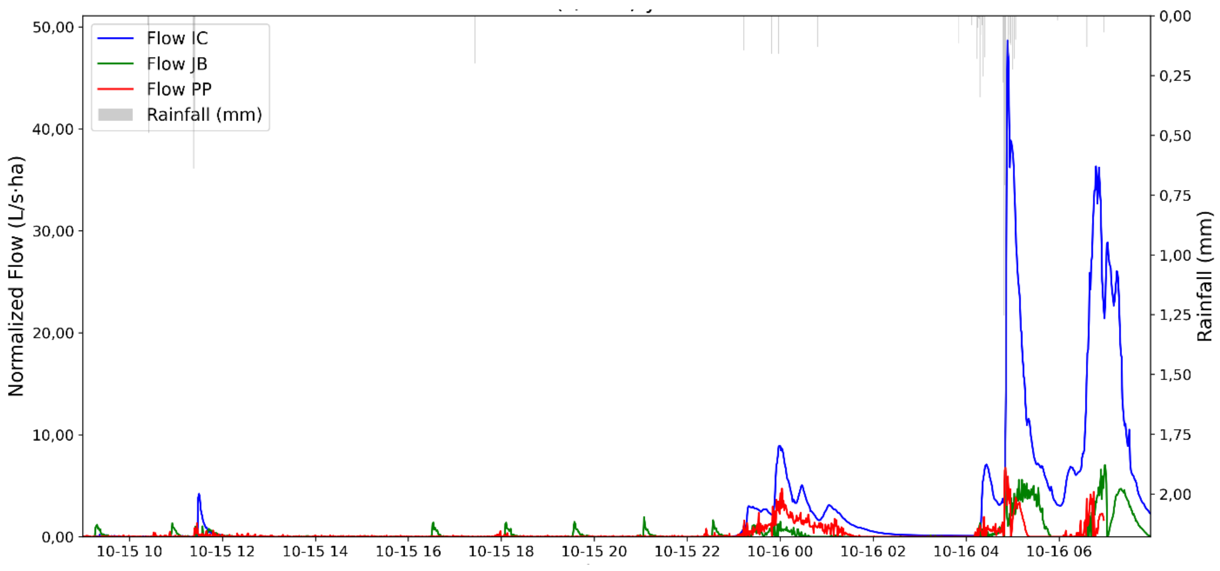

Figure 2. Example of hyetograph and corresponding normalized hydrographs for IC, JB and PP.

3.3 Substrate evolution and pollutant retention

Soil analyses revealed increasing concentrations of metals, such as Cu, Zn, Fe and Mn over time, indicating that the bioretention soil may be acting as an effective sink for pollution. This behavior aligns with the expected treatment functions of bioretention systems while emphasizing the need for long-term monitoring to anticipate possible media renewal.

Permeability tests showed stable infiltration capacity in SUDS typologies across the monitoring period. The EPC method confirmed that the permeable pavement maintained homogeneous infiltration behavior over the year, and the bioretention soil displayed adequate infiltration rates without signs of clogging. Maintaining permeability is essential for stormwater capture and the reliability of resource-oriented drainage design.

3.4 Implications for stormwater reuse and resource-oriented urban planning

Monitoring results demonstrate that SUDS can serve as decentralized capture and preliminary treatment units that support stormwater reuse strategies within new urban developments such as MNN. While no regulatory requirements apply to water discharged from SUDS, the use of established Spanish regulatory (Gobierno de España, 2015) benchmarks provides a valuable frame of reference to assess potential reuse pathways at district scale. By attenuating flows, reducing pollutant loads and maintaining infiltration capacity, SUDS help produce a partially treated stormwater resource that can be integrated into a local circular-water framework, reducing dependence on potable supplies for irrigation and street-cleaning activities.

The herein reported empirical results illustrate planners and designers with realistic expectations to work with, decreasing uncertainty in the selection, sizing and placement of SUDS within each particular district case. This helps ensure that SUDS are not only drainage elements, but also contributors to resource recovery and sustainable urban-water management.

4 CONCLUSIONS

The first year of monitoring confirms that the installed SUDS pilot facility performs effectively in both the hydraulic and quality dimensions. The permeable pavement area and bioretention system consistently attenuate and delay runoff peaks, reducing hydraulic stress and facilitating opportunities for local water capture. Water-quality results show substantial improvement compared with direct runoff, with most parameters falling within reference ranges derived from relevant Spanish regulation thresholds. Although this regulation is not mandatory for SUDS, they offer a practical benchmark to understand the degree of post-treatment that would be required before potential reuse application.

Substrate analyses demonstrate that the bioretention substrate retains pollutants without compromising infiltration capacity, while both SUDS maintained stable permeability throughout the year. These findings provide a robust empirical basis for guiding the design and implementation of SUDS within Madrid Nuevo Norte urban development, particularly regarding stormwater reuse feasibility. The second year of monitoring will further refine these insights and support the development of resource-oriented drainage strategies in Mediterranean urban districts.

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