Pilot-scale assessment of Sustainable Drainage Systems (SuDS) for urban runoff treatment at experimental facility

Évaluation à l'échelle pilote de systèmes urbains de drainage durable (SuDS) pour le traitement du ruissellement sur le site expérimental

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RÉSUMÉ

Les systèmes urbains de drainage durable (SuDS) sont de plus en plus promus comme alternative ou complément aux réseaux unitaires et séparatifs pour gérer les eaux pluviales urbaines, réduire les débits de pointe et améliorer la qualité des rejets. Toutefois, les données de performance à l'échelle pilote dans les climats méditerranéens restent limitées, en particulier pour des configurations en chaîne combinant plusieurs unités. Cet article présente l'installation expérimentale du CEIC à Meco (Espagne), conçue pour tester différentes techniques de drainage durable sous des conditions de pluie réelles. Le banc d'essai comprend plusieurs unités représentatives (par exemple noues, pavés perméables, tranchées drainantes et dispositifs de bio-rétention) intégrées dans un train de traitement. L'instrumentation permet de suivre en continu les pluies, les débits et la qualité de l'eau à l'entrée et à la sortie. Les premiers résultats montrent une atténuation significative des débits de pointe et une amélioration de la qualité des eaux de ruissellement, en particulier pour les polluants particulaires. Le retour d'expérience sur la conception, l'exploitation et la maintenance de l'installation met en évidence des recommandations pour le dimensionnement et le suivi de SuDS dans les contextes méditerranéens.

ABSTRACT

Sustainable Drainage Systems (SuDS) are increasingly promoted as an alternative or complement to conventional combined and separate sewer systems to manage urban stormwater, reduce peak flows and improve effluent quality. However, pilot-scale performance data under Mediterranean climate conditions remain limited, especially for treatment trains combining several devices. This paper presents the CEIC experimental SuDS facility in Meco (Spain), designed to test different sustainable drainage techniques under real rainfall conditions. The pilot plant includes several representative units (e.g. swales, permeable pavements, filter drains and bioretention systems) arranged in a treatment train. The site is instrumented to continuously monitor rainfall, flows and water quality at inlet and outlet control points. Preliminary results indicate a significant attenuation of peak discharges and a clear improvement of stormwater quality, particularly for particulate-bound pollutants. Operational experience from the first monitoring campaigns is used to identify key design, operation and maintenance aspects that are critical for SuDS performance in semi-arid and Mediterranean contexts. The CEIC facility provides a robust platform to support future optimisation of SuDS design guidelines and to promote their wider implementation in Spanish cities.

KEYWORDS

biorétention, revêtement perméable, eaux pluviales, SuDS (systèmes urbains de drainage durable), ruissellement urbain, bioretention, permeable pavement, stormwater, SuDS, urban runoff

1 INTRODUCTION

Rapid urbanisation and climate change are intensifying pressures on conventional urban drainage systems. Increased imperviousness leads to higher runoff volumes and peak flows, while more frequent short and intense storms can overload existing sewer networks and receiving waters. At the same time, regulatory frameworks and public expectations are evolving towards improved environmental protection, flood risk reduction and more liveable urban spaces (Carmo & Campos, 2021).

Sustainable Drainage Systems (SuDS), also known as Sustainable Urban Drainage Systems (SUDS) or, in Spanish, Técnicas de Drenaje Urbano Sostenible (TDUS), have emerged as a key component of integrated urban water management. By promoting infiltration, retention, detention and treatment of runoff close to where it is generated, SuDS can reduce peak flows, enhance groundwater recharge and improve stormwater quality, while providing co-benefits such as urban greening and heat-island mitigation.

Despite extensive international experience, the implementation of SuDS in Spain and other Mediterranean countries is still limited compared to Northern Europe or other regions. Barriers include a lack of locally validated design criteria, limited performance data under Mediterranean rainfall patterns, and uncertainties regarding operation and maintenance responsibilities. Demonstration and research facilities at pilot scale are therefore essential to build confidence among practitioners and decision makers.

The CEIC experimental facility in Meco (Spain) was conceived to address this gap by providing a flexible pilot-scale platform to:

- test different SuDS configurations under controlled but realistic conditions,
- quantify hydraulic and water quality performance for local rainfall and runoff characteristics,
- evaluate practical aspects of construction, operation and maintenance, and
- generate data to support the development of national and municipal guidelines for TDUS.

This paper has three main objectives:

1. to describe the design and configuration of the CEIC SuDS pilot plant;
2. to present the monitoring strategy and data analysis approach; and
3. to discuss preliminary performance results and lessons learnt, with a focus on implications for SuDS design in Mediterranean climates.

2 MATERIALS AND METHODS

2.1 Site description and layout

The CEIC facility is located in Meco, near Madrid (Spain), in a continental Mediterranean climate with moderate annual rainfall, strong inter-annual variability and frequent short, intense events in spring and autumn. Summers are typically dry (AEMET, 2020).

The pilot plant receives runoff from a controlled contributing area representing typical urban surfaces (roofs, parking areas, roads). Runoff is conveyed to a pre-treatment and distribution chamber and then directed to different SuDS units operating in parallel or in series. The layout allows:

- comparison of SuDS typologies under similar inflow conditions,
- evaluation of combined treatment trains with different rain conditions
- testing of different hydraulic loading and bypass options, as well as quality parameters

A schematic layout (Figure 1) shows the main units, flow paths and monitoring points.

2.2 SuDS units

The facility incorporates SuDS representative for Spanish urban developments, for example:

- **Permeable pavement** with structural surface, bedding and storage layer with underdrain, designed for infiltration and temporary storage;
- **Filter drain** (gravel trench with perforated pipe), providing conveyance, storage and basic filtration;
- **Vegetated swale**, functioning as a linear detention and treatment unit with adapted vegetation;
- **Bioretention cell / rain garden** with layered filter media and underdrain, aimed at enhanced removal of particulates and dissolved pollutants;
- **Detention/retention basin** for additional peak flow attenuation and sedimentation, when required.

Inlet and outlet structures control distribution of flows, water levels and bypass. Geometry, storage volumes, media and vegetation are defined according to international practice and adapted to local materials and climate.

2.3 Instrumentation and monitoring

The plant is instrumented for continuous hydraulic monitoring and event-based water quality sampling. The system includes:

- rain gauge(s),
- flow measurement at main inlets and outlets,
- water level sensors in storage layers and basins,
- basic physico-chemical probes at selected locations,
- automatic samplers triggered by flow or level.

For selected events, composite samples are collected at the inflow and outflow of each unit or treatment train. Analyses typically include TSS, COD/DOC, nutrients and, when relevant, metals and microbiological indicators.

2.4 Data analysis

Hydraulic performance is characterised by event runoff volume reduction, peak flow attenuation, hydrograph delay and inferred infiltration/storage behaviour.

Water quality performance is assessed using event mean concentrations and loads. Removal efficiencies are calculated as relative reductions between inflow and outflow. Non-parametric statistics are used to describe performance, and, when enough events are available, relationships with rainfall depth, intensity and antecedent dry period are explored.

3 RESULTS AND DISCUSSION

3.1 Rainfall and inflow

The initial monitoring period includes a range of events representative of the local Mediterranean regime: frequent small events and fewer high-intensity storms. Runoff coefficients at the plant inlet are consistent with typical impervious urban catchments, confirming the representativeness of inflow conditions (Pascual, et al., 2025).

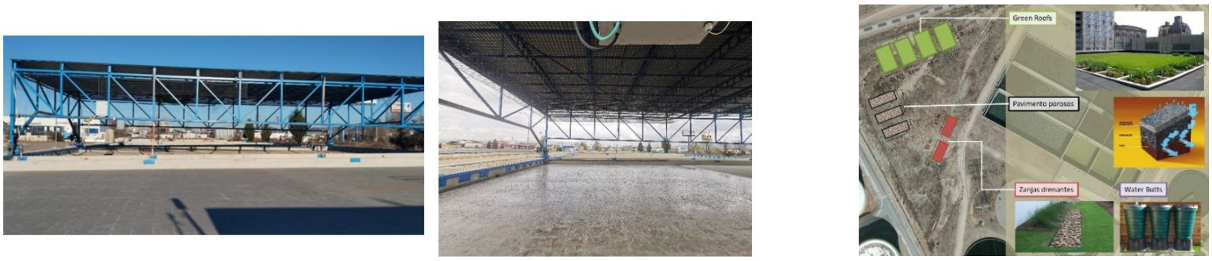

***Imagen 1**. Structure (left) and a rainfall simulation (right), and parts of the CEIC SuDS.*

3.2 Hydraulic performance

The SuDS units and treatment trains consistently attenuate peak flows and reshape hydrographs. For small and medium events, a substantial share of inflow volume is retained through infiltration and storage; for larger events, detention and controlled release dominate.

Permeable pavements and bioretention cells provide strong delay and damping of hydrographs when storage layers are not saturated. Swales and filter drains add storage and reduce velocities. At facility scale, the combined effect is lower and smoother outlet discharges, reducing hydraulic stress on downstream systems. Observed attenuation is consistent with international findings for similar systems.

3.3 Water quality performance

Preliminary trends can be summarised as:

- **TSS:** high reduction of suspended solids, indicating effective sedimentation and filtration; particulate-bound pollutants are expected to follow similar patterns.
- **Organic matter:** moderate COD/DOC reductions, enhanced when vegetated or bioretention units are present.
- **Nutrients:** variable performance depending on configuration and media; specific amendments improve phosphorus retention, while nitrogen removal depends on moisture regime and residence time.
- **Metals:** when monitored, dissolved and particulate metals tend to decrease, especially in fine, organic-rich media.

These results confirm the potential of SuDS to improve stormwater quality under local conditions, and highlight the need for tailored media where nutrient removal is a priority.

3.4 Operational aspects

The pilot plant also provides insight into practical implementation.

Inlet and overflow detailing is crucial to avoid short-circuiting and scour, and has a direct influence on the hydraulic performance of the SuDS units. Surface clogging appears where fine sediments accumulate, but this can be managed with simple and regular maintenance operations. Vegetation establishment in swales and bioretention systems may require temporary irrigation during the initial period; once established, however, vegetation contributes significantly to both hydraulic and water-quality performance. Combined hydraulic and quality monitoring has proven effective for characterising system behaviour, although it is resource-demanding, and the experience gained helps to optimise future monitoring programmes..

4 CONCLUSIONS AND OUTLOOK

The CEIC experimental SuDS facility in Meco demonstrates the feasibility and interest of pilot-scale platforms to support TDUS deployment in Mediterranean cities. Based on the first monitoring period, the pilot plant reproduces typical urban runoff conditions and allows testing of relevant SuDS typologies and alternative treatment systems. The SuDS configurations achieve robust attenuation of peak flows and beneficial modification of hydrographs, especially for frequent events. Clear stormwater quality improvements are obtained for TSS and particulate-bound pollutants, with potential for nutrient and metal reduction depending on the media and design adopted. With appropriate detailing and basic maintenance, the systems operate reliably under local climate and loading conditions.

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