Development of a simplified proxy based on soil moisture sensors to quantify stormwater infiltration in a bioretention area

Développement d'un proxy simplifié basé sur des capteurs d'humidité du sol pour quantifier l'infiltration des eaux pluviales dans une zone de biorétention

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RÉSUMÉ

Les Solutions fondées sur la nature, comme les Systèmes urbains de drainage durable (SuDS), sont de plus en plus utilisées pour gérer les eaux pluviales urbaines et limiter les inondations liées au changement climatique. En améliorant l'infiltration sur site, elles réduisent la pression sur les réseaux d'égouts et soutiennent le développement de « villes éponges ». La Ville métropolitaine de Milan (3.25 millions d'habitants sur 1575 km², densité de 2064 hab./km²) a réalisé 90 interventions SuDS dans 32 communes grâce au Plan national de relance et de résilience (PNRR). Ces systèmes atténuent les inondations et peuvent recharger les nappes superficielles, fournissant une Ressource en Eau Alternative pour l'irrigation urbaine. Pour vérifier ce potentiel, une zone de bioretention à Solaro a été équipée de capteurs d'humidité du sol et d'un pluviomètre. Deux ans de données ont permis d'évaluer les capteurs et de comparer les mesures aux attentes de conception. Un indicateur simplifié a ensuite été élaboré pour estimer l'infiltration réelle. Il montre que ces capteurs peuvent servir d'outils économiques pour la gestion intégrée de l'eau, l'évaluation des performances, les alertes de maintenance et l'irrigation d'urgence en période de sécheresse.

ABSTRACT

Nature-based Solutions (NbS), such as Sustainable Drainage Systems (SuDS), are increasingly promoted to manage urban stormwater and reduce flooding linked to climate change. SuDS enhance on-site infiltration, alleviating pressure on sewer networks and supporting the development of "sponge cities" that safely manage rainwater in densely urbanized areas. The Metropolitan City of Milan (3.25 million inhabitants spread across an area of 1575 km², with a population density of 2064 inhabitants per km²) has implemented 90 SuDS interventions across 32 municipalities under Italy's National Recovery and Resilience Plan (PNRR). These systems mitigate urban flooding and can act as distributed recharge for shallow aquifers, which — though unsuitable for drinking — can supply water for urban irrigation, functioning as an Alternative Water Resource (AWR). To validate this AWR pathway, a bioretention area in Solaro was equipped with soil-moisture sensors and a rain gauge to monitor infiltration dynamics. Two years of data were analyzed to validate sensor performance and compare observed behavior with theoretical design expectations. A simplified proxy was then developed to quantify actual infiltration from sensor and rainfall data. This proxy demonstrates the feasibility of using soil-moisture sensors as low-cost tools for integrated water management and therefore the urban flooding hazard, enabling performance evaluation, maintenance alerts, and emergency irrigation during droughts.

KEYWORDS

Alternative Water Resource, Soil Moisture Sensors, Sponge City, Stormwater Infiltration Quantification, Sustainable Drainage Systems

1 INTRODUCTION

In recent years, urban planners have increasingly promoted the adoption of Nature-based Solutions (NbS) for stormwater management, driven by the growing frequency of urban flooding linked to climate change. Sustainable Drainage Systems (SuDS) provide an effective strategy for reducing the load on existing sewer networks by enhancing on-site stormwater infiltration. The widespread implementation of these in highly urbanized areas supports the development of so-called "sponge cities," which are designed to absorb, retain, and safely manage rainwater, thereby reducing flood risk in densely built environments.

The Metropolitan City of Milan (3.25 million inhabitants spread across an area of 1575 km², with a population density of 2064 inhabitants per km²) has adopted this approach to prevent floods and manage stormwater across the region. Through a project financed by Italy's National Recovery and Resilience Plan (PNRR), 90 SuDS interventions have been designed and are currently being implemented across 32 municipalities within the Metropolitan City. The sponge city approach mitigates urban flooding by temporally attenuating stormwater flows or infiltrating them into the ground. SuDS can therefore act as a distributed recharge mechanism for shallow aquifers. Although the shallow aquifer of the Metropolitan City of Milan is diffusely contaminated and unsuitable for potable use, the infiltrated water can nonetheless be recovered for irrigating urban green spaces. SuDS that promote infiltration may thus be considered an infrastructure of an Alternative Water Resource (AWR) for irrigation purposes.

A key step in validating this AWR pathway is quantifying the volume of rainwater that a SuDS can effectively infiltrate. The infiltrated water can, in principle, be estimated from rainfall data combined with soil characteristics and SuDS geometry. To address this challenge, one of the SuDS interventions—located in Solaro and consisting of a bioretention area and infiltration shafts—has been equipped with soil-moisture sensors and a rain gauge to monitor system performance during rainfall events and infiltration dynamics. A two-year series of data was analyzed. First, the correct performance of the sensors was validated by examining SuDS behavior through soil-moisture profiles during events with different return periods (RPs) and comparing the observed response with the theoretical behavior expected from design parameters. Once validated, a simplified proxy was developed—based on soil-moisture sensor data and rainfall measurements—to quantify the volume of water infiltrated by the system.

This simplified proxy demonstrates the feasibility of using soil-moisture sensors within SuDS as low-cost tools for integrated water-management services. Such an approach would facilitate both the evaluation of system performance, quantifying the stormwater volumes infiltrated and so diverted from the sewer network, and the operation and maintenance, permitting to set alert for controlling SuDS functioning and eventually emergency irrigation during drought periods.

2 CASE STUDY

The case study examined in this investigation is located in Solaro. The SuDS intervention, implemented under a Life Project (Life Metro Adapt), consists of an impermeable parking area drained by infiltration shafts and a bioretention area. Specifically, a 2900 m² portion of the parking area is drained by six infiltration shafts, while a 450 m² catchment area is directed toward a 150 m² bioretention area. The infiltration shafts are hydraulically connected to the bioretention area to manage rainfall events with high RPs.

A soil-moisture sensor was installed within the bioretention area. The sensor measures volumetric water content at six depths, from 5 cm to 55 cm at 10 cm intervals, with a data acquisition frequency of 10 minutes. In addition to soil-moisture data, rainfall records were collected from the rain gauge closest to the site. The analysis conducted in this study uses two years of soil-moisture and rainfall data, covering the period from March 2023 to February 2025.

A schematic of the intervention, including the configuration of the drainage systems and the location of the soil-moisture sensor, is shown in Figure 1.

3 RESULTS AND DISCUSSION

The first step of the study was to verify the relationship between the cumulative rainfall and the soil moisture, and to validate the reliability of the sensors. Several rainfall events were therefore analyzed. Figure 2 presents the results for three representative events: the first with a RP of less than 2 years, the second with a RP between

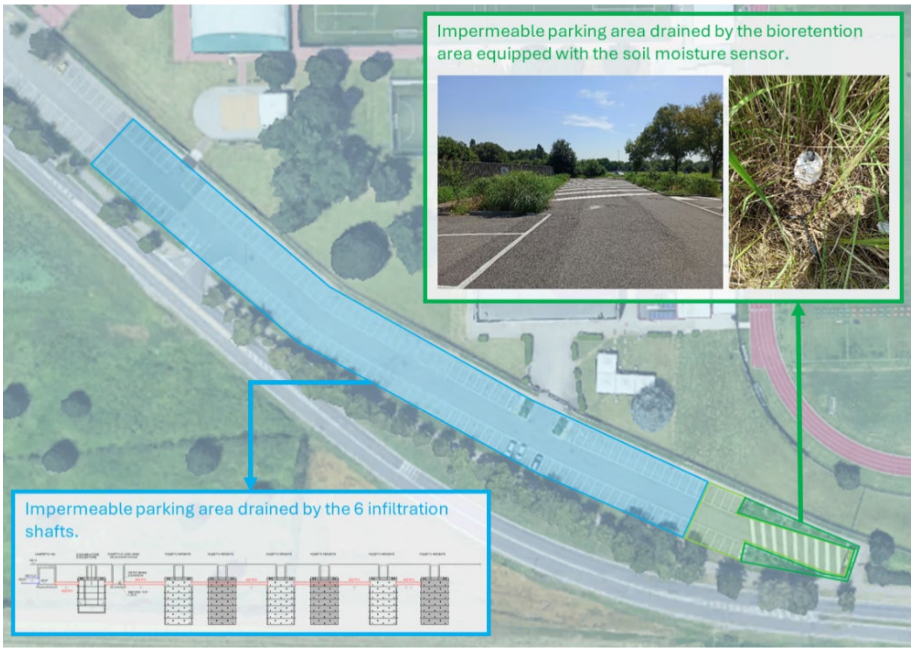

Figure 1 – Schematic representation of the case study area located in Solaro with the SuDS details and the soil moisture sensor.

2 and 5 years, and the third with a RP between 10 and 20 years. The first row of subpanels in Figure 2 shows the cumulative rainfall over time for the different events; the second row of subpanels illustrates the average soil moisture dynamics; and the third row of subpanels displays the soil-moisture profiles at three key time points—before the rainfall, during the rainfall, and after the rainfall. These moments are indicated by circles in both the cumulative rainfall and average moisture plots.

This analysis confirms that the sensors are performing correctly, as a progressive increase in soil moisture from the surface downward is observed during rainfall events. This effect is particularly evident for the event with a RP of less than 2 years. For events with longer RPs, a moisture increase is also detected at the deepest sensor in addition to the top-down wetting. This behavior is due to the hydraulic connection between the infiltration shafts and the bioretention area: for events with RPs greater than 5 years, the shafts are unable to drain the entire volume of stormwater, causing the bioretention area to receive and infiltrate the excess water.

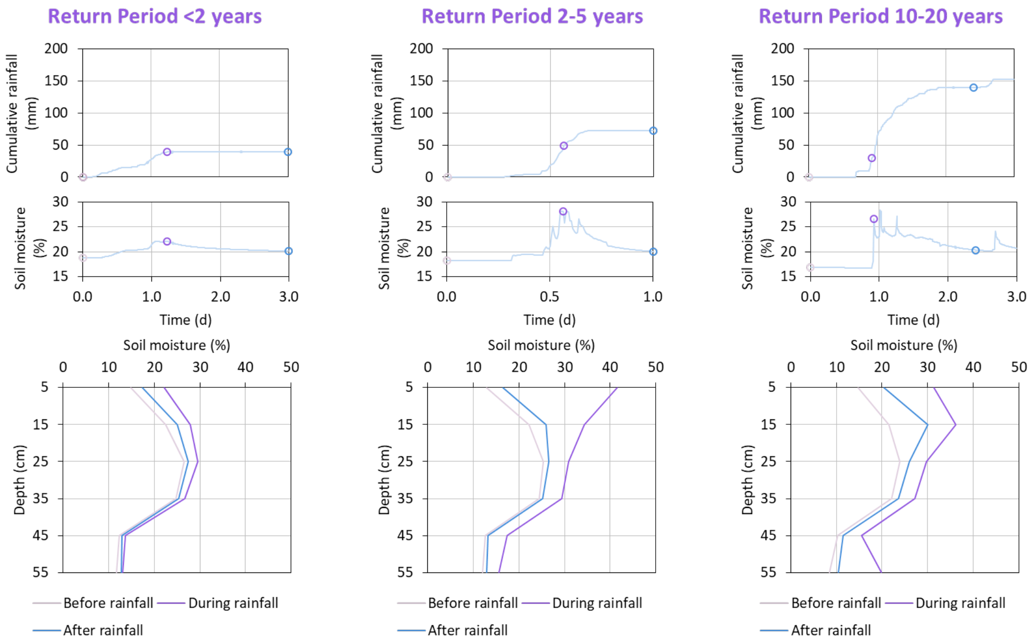

Figure 2 - Cumulative rainfall over time, average soil moisture over time and soil moisture profiles over depth for three

rainfall events (RP <2 years, 2-5 years, 10-20 years).

The second step was to develop a robust method for estimating the volume of water infiltrated by the bioretention area using the soil-moisture sensor installed within it, and to identify whether— and for which rainfall events— the system activates, indicating that infiltration occurs. The simple assumption underlying the proxy is the following: if a rainfall event is recorded by the nearest rain gauge and an increase in soil moisture is observed in the bioretention area in 24 h, then rainfall water is infiltrating; conversely, if a rainfall event is recorded but soil moisture does not increase in 24 h, infiltration is not taking place. The scheme of the proposed proxy is illustrated in Figure 3.

By applying the proposed approach to the analyzed dataset, it was possible to determine that, of all rainfall events recorded by the rain gauge—and therefore of all the precipitation that fell over the study area—73% of the stormwater was infiltrated by the bioretention area. Of this infiltrated volume, 28% was temporarily retained within the bioretention system and subsequently released slowly into the soil and evapotranspired, while the remaining 72% infiltrated directly. The same proxy also supports operation and maintenance activities and allows the detection of various anomalies, such as a malfunction of the sensor itself or a problem in the SuDS.

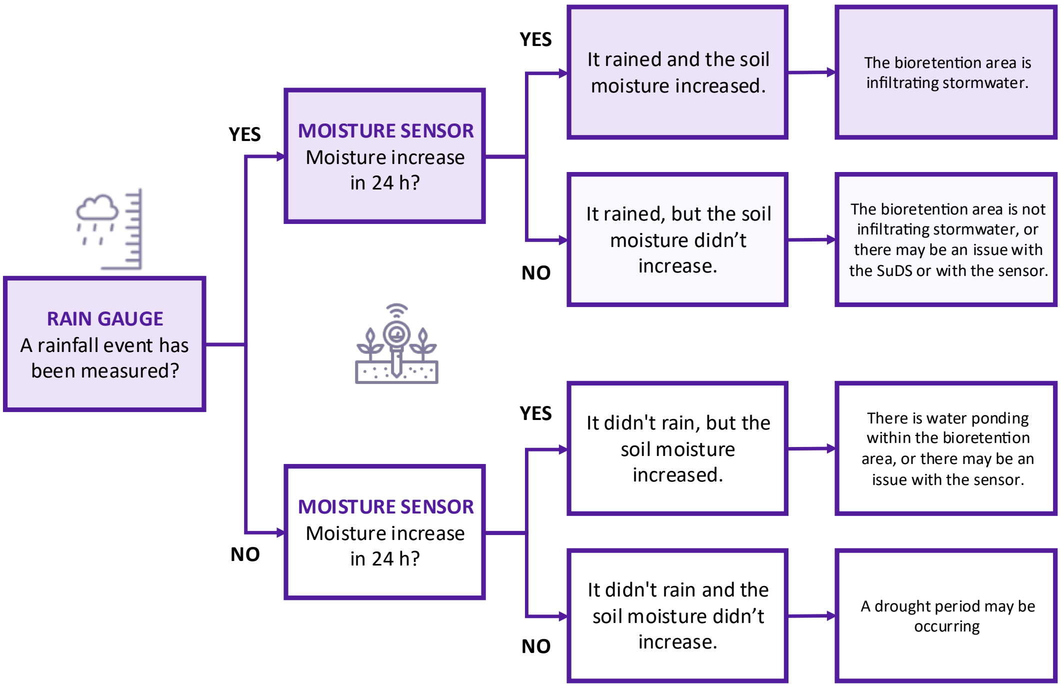

Figure 3 – Proxy scheme for estimating the amount of water infiltrated by the bioretention area.

4 CONCLUSIONS

The installation of soil moisture sensors within SuDS provides valuable insights into the dynamics of stormwater infiltration and the behavior of bioretention areas. In this study, a simple proxy combining rainfall data from rain gauges with soil moisture measurements was developed to estimate the volume of water infiltrated by a bioretention system. The results demonstrate the feasibility of using soil-moisture sensors as low-cost tools for integrated water-management services, enabling both the evaluation of system performance—by quantifying infiltrated stormwater and, consequently, the volume diverted from the sewer network—and the support of operation and maintenance activities, including alerts for system monitoring and emergency irrigation during drought periods. While the proposed proxy shows promising results, further analyses are required to fully validate its reliability and applicability under different climatic and hydrological conditions.

ACKNOWLEDGMENTS

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