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Evaluation of the hydraulic performance of a permeable pavement built in the city of Recife-PE (Brazil)

Avaliação do desempenho hidráulico de um pavimento permeável executado na cidade do Recife-PE (Brasil)

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ABSTRACT

The increase in impervious surfaces in urban areas compromises the soil's infiltration capacity and intensifies surface runoff, worsening environmental impacts, especially when associated with climate change. This study evaluated the implementation of a permeable pavement as a Nature-Based Solution (NbS) to promote more sustainable urban drainage. The intervention took place in the city of Recife, Brazil, in a previously impervious area where 840 m² of permeable pavement with interlocking concrete blocks was installed. The solution aimed to increase rainwater infiltration, reduce surface runoff, and mitigate local flooding. Geotechnical characterization and soil permeability tests were conducted at the site. The hydraulic performance was analyzed through monitoring of the water level inside the system, in conjunction with rainfall data collected between 2023 and 2024, as well as the determination of the permeability coefficients of the newly constructed pavement. The results indicated good infiltration capacity, with the system effectively managing rainfall volumes. Variations in the water level observed in the permeable pavement system were related to local precipitation, with no surface water accumulation recorded during the monitoring period. The NbS was able to manage several intense rainfall events, such as 122.8 mm (May 24, 2023) and 137.6 mm (June 15, 2024). The study contributes to the monitoring of NbS typologies in a tropical Brazilian city, highlighting the importance of experimental research and confirming the effectiveness of permeable pavement in the sustainable management of stormwater. This demonstrates its potential to mitigate flooding impacts in densely urbanized areas.

Keywords: nature-based solution (NbS); urban drainage; rainwater management.

RESUMO

O aumento da impermeabilização nas áreas urbanas compromete a capacidade de infiltração do solo e intensifica o escoamento superficial, agravando os impactos ambientais, especialmente quando associado às mudanças climáticas. Este estudo avaliou a implantação de um pavimento permeável como Solução Baseada na Natureza (SBN) para promover uma drenagem urbana mais sustentável. A intervenção ocorreu na cidade do Recife, Brasil, em uma área anteriormente impermeável, onde foram instalados 840 m² de pavimento permeável com blocos intertravados de concreto. A solução visou aumentar a infiltração de águas pluviais, reduzir o escoamento superficial e mitigar os alagamentos locais. Foram realizados ensaios de caracterização geotécnica e de permeabilidade do solo local. O desempenho hidráulico foi analisado por monitoramento do nível d'água no interior do sistema, associado a dados pluviométricos coletados entre 2023 e 2024, além da determinação dos coeficientes de permeabilidade do pavimento recém-construído. Os resultados indicaram boa capacidade de infiltração, com o sistema gerenciando volumes de água da chuva. As variações do nível da água observadas no sistema do pavimento permeável têm relação com a precipitação local, sem registro de acúmulo na superfície durante o período monitorado. A SBN foi capaz de gerenciar diversos eventos pluviométricos intensos, como 122,8 mm (24/05/2023) e 137,6 mm (15/06/2024). O estudo contribui para o monitoramento de tipologias SBN em uma cidade tropical brasileira. Evidencia-se a importância de pesquisas experimentais e confirma-se a efetividade do pavimento permeável na gestão sustentável das águas pluviais, demonstrando seu potencial para mitigar os impactos dos alagamentos em áreas densamente urbanizadas.

Palavras-chave: solução baseada na natureza; drenagem urbana; gestão de águas pluviais.

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Introduction

Over the past decades, Brazilian cities have undergone profound transformations, characterized by significant changes in land use and land cover (Lapa et al., 2022). The urbanization process, characterized by rapid population growth in urban areas, has generated increasingly detrimental environmental impacts (Koomen et al., 2023). Among the most recurring problems, urban flooding and inundations stand out, exacerbated by soil sealing and the lack of adequate planning for stormwater management (Pérez-Morales et al., 2021). Thus, urban flooding constitutes a highly relevant issue from both environmental and social perspectives, directly affecting the quality of life of urban populations (Nipassa et al., 2023).

According to Oliveira (2017), the transformations driven by the increasing impermeabilization of soils compromise the infiltration capacity and the soil's potential to retain precipitation, resulting in larger volumes of surface runoff. As infiltration is reduced, peak flows become more intense and frequent, contributing to the aggravation of urban flooding. In this context, solutions that incorporate infiltration structures play a fundamental role in reducing surface runoff volumes and minimizing the magnitude of flood events. Among the possible alternatives are Nature-Based Solutions (NbS), which constitute innovative multifunctional tools that maximize benefits within urban systems (Kasprzyk et al., 2022).

Over the last decade, NbS have proven to be an adaptive strategy that offers multiple advantages for stormwater management, garnering significant research interest worldwide (Qiu et al., 2024). NbS comprise different types of blue–green infrastructure inspired by, supported by, or mimicking natural processes, simultaneously delivering environmental, social, and economic benefits while contributing to urban resilience (UNESCO, 2021). When implemented in urban areas, NbS are generally designed to promote sustainable urban development and assist in mitigating and adapting to climate change (Somarakis et al., 2019). The primary objective of NbS for urban stormwater management is to control the volume and timing of surface runoff, restore infiltration capacity in the urban environment, and thereby reduce the risk of flooding during intense rainfall events (Wang et al., 2021; Koiv-Vainik et al., 2022; Glick et al., 2023; Aghaloo et al., 2024).

Despite the growing number of studies highlighting the use of NbS for flood mitigation, significant knowledge gaps remain. Herath et al. (2025) emphasized the need for quantitative assessments of NbS performance, as well as a deeper understanding of implementation challenges across different environments and contexts. The limited adoption of NbS in developing countries, such as Brazil, is associated with multiple barriers, including investment constraints, technological limitations, and the need for experimental studies adapted to local contexts (Zyoud and Zyoud, 2025).

Zoghi et al. (2025) reported varying levels of NbS performance across different climatic and precipitation conditions in Canada, indicating the need for differentiated and context-specific analyses in other countries. In Brazil, some experimental initiatives have demonstrated reductions in urban flooding; however, broader implementation is needed, particularly given the importance of quantitative metrics for flood risk management (Pachouri et al., 2025; Rotimi et al., 2025).

Among the typologies of NbS, permeable pavement is one prominent example (Koiv-Vainik et al., 2022). This technology simultaneously meets the mechanical requirements for load resistance and the need for water infiltration through its layers. According to ABNT (2015), permeable pavements operate by reducing surface runoff without compromising structural integrity. Marchioni (2018) describes these systems as structures incorporating voids that allow the passage of water and air, with the surface layer designed to directly support mechanical loads while efficiently and continuously promoting water infiltration.

The hydraulic performance assessment of permeable pavements focuses on quantifying parameters related to the accumulation of stormwater through infiltration and its residence time within the system's layers (Kamali et al., 2017; Rodríguez-Rojas et al., 2018). In addition, the comparison of peak flow reduction relative to conventional pavement is an important indicator of hydraulic performance (Kamali et al., 2017; Rodríguez-Rojas et al., 2018; Madrazo-Uribeetxebarria et al., 2023). Rodríguez-Rojas et al. (2018) identified a substantial reduction in water flow in permeable pavements during multiple rainfall events, demonstrating the suitability of this type of system for more sustainable stormwater management. The study by Zhao et al. (2023) further highlighted the importance of quantitatively analyzing infiltration characteristics of permeable pavements through experimental evaluation.

This study aimed to demonstrate the transformation of an impermeable area into a space with permeable pavement, emphasizing its contribution to sustainable urban drainage, with a focus on evaluating hydraulic performance and exploring how the implemented NbS enhances infiltration potential and stormwater storage capacity. Research on NbS is critical in countries where many vulnerable areas and populations are exposed to flood risks (Lopes et al., 2025). Therefore, critical assessments of the benefits of NbS, grounded in consolidated practical experiences within Brazilian cities, are necessary (Rodrigues et al., 2023). Thus, this study contributes relevant information regarding the local monitoring of an NbS typology in a Brazilian tropical city, highlighting the importance of experimental research in Brazil on a topic of global relevance.

Methodology

Study area

The permeable pavement area analyzed in this study was constructed in the city of Recife, the capital of the state of Pernambuco, Brazil. The city is located within the coastal Atlantic forest physiographic zone and is characterized by a hot and humid climate. The rainiest period occurs between March and August, with climatological normals

(1991–2020) from the National Institute of Meteorology (INMET) ranging from 186.7 mm in August to 390.5 mm in June (INMET, 2025). The mean annual precipitation is 2,155.5 mm. Among the 76 meteorological stations with climatological normals in INMET across the nine states of Northeastern Brazil, this value is surpassed only by a single station — Turiaçu, in Maranhão — which records an annual mean precipitation of 2,175.1 mm (INMET, 2025).

Recife's coastal plain lies slightly above sea level, and in some areas, elevations are comparable to spring tide levels, which hinders natural drainage during rainy periods and increases the city's vulnerability to urban flooding (Cabral and Alencar, 2005).

The permeable pavement is located within the facilities of the Polytechnic School of the University of Pernambuco (POLI-UPE), at the Benfica University Campus, in the Madalena neighborhood of Recife (Figure 1), at coordinates 8°03′31.8″ S and 34°54′12.7″ W. Land use and land cover in the microbasin where the system is situated correspond to a fully urbanized area with a low slope (MAPBIOMAS, 2023).

The stratification of soil layers in the study area was previously carried out by Barros et al. (2024), who identified the presence of silty sand and silty–clayey sand down to a depth of 1.25 m. Figure 2 presents a detailed view of the intervention area, indicating the location of the monitoring point for groundwater level within the permeable pavement (installed piezometer).

Prior to the renovation works, the entire area was impermeable, and a large portion of it was used for vehicular traffic and parking (Figure 3). To implement the NbS, it was necessary to adapt the original renovation project, which included replacing part of the external pavement, among other interventions. In the initial design, conventional pavement with concrete interlocking blocks was planned.

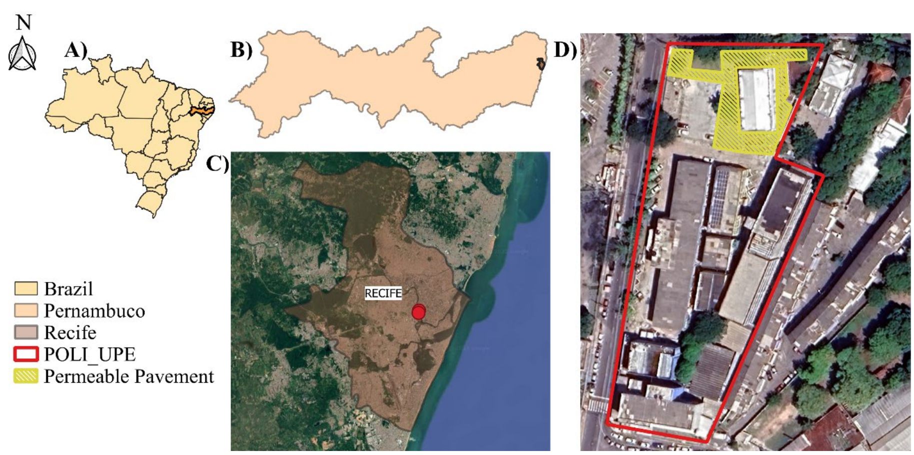

Figure 1 – Location of the study area. (A) Brazil, with emphasis on the state of Pernambuco. (B) Pernambuco, with emphasis on the city of Recife. (C) Recife with reference to the POLI-UPE Campus. (D) Location of the permeable pavement on the POLI-UPE premises.

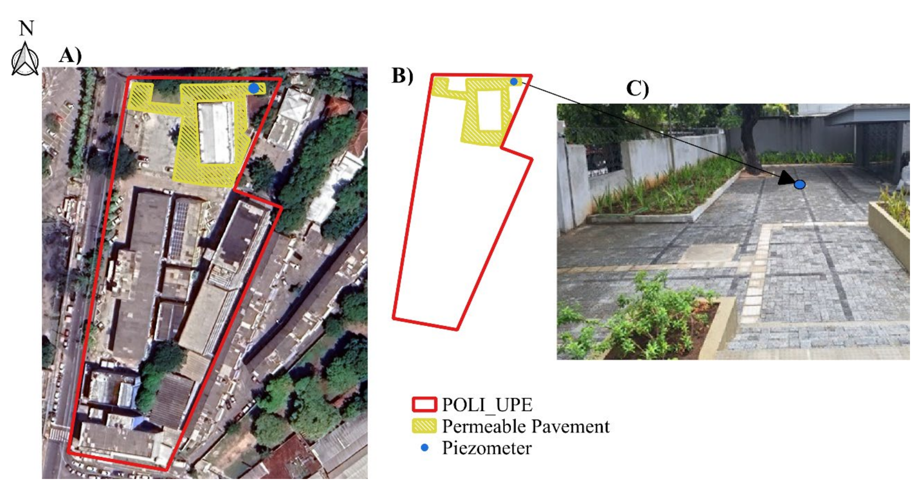

Figure 2 – Detailed view of the study area. (A) Location of the permeable pavement within the POLI-UPE campus. (B) Outline of the POLI-UPE area and the intervention area with the permeable pavement. (C) Location of the piezometer used for monitoring.

The approved design modification transformed the conventional pavement typology into a permeable system, utilizing permeable interlocking concrete blocks, and the area was designated exclusively for pedestrian use. It is important to note that the POLI-UPE campus has a history of flooding, with recurrent episodes occurring each winter. Significant rainfall events leading to flooding in the study area have been recorded; for instance, precipitation intensities over 24 h reached 102.1 mm on May 10, 2016, and 137.4 mm on May 25, 2022 (APAC, 2023).

Experimental development

Approximately 840 m² of permeable pavement were constructed — one of the decentralized, nature-based measures within the scope of NbS implementation (Qiu et al., 2024). Figure 4 shows an area with a location similar to that shown in Figure 3. However, Figure 4 corresponds to the period after the renovation of the campus pavement, meaning the permeable pavement typology had already been implemented.

Figure 3 – POLI-UPE area in 2020, with impermeable pavement prior to the renovation.

Figure 4 – POLI-UPE area, with permeable pavement in 2024.

The permeable pavement profile adopted in this study is illustrated in Figure 5. The surface layer consists of permeable interlocking concrete blocks (8 cm thick), followed by a bedding layer of crushed stone (5 cm thick), and finally, a 30 cm granular base layer composed of 19 mm aggregate, which is entirely enveloped in geotextile fabric. As shown in Figure 5, the full pavement structure has a total thickness of 43 cm, under which lies the natural subgrade soil that supports the permeable system.

The use of geotextile fabric in permeable pavement construction aims to minimize clogging within the voids of the base layer, where water storage occurs (Jabur et al., 2015). The decision to envelop the entire base layer was made to prevent clogging caused either by fine particles migrating upward from the subgrade soil or by particles moving downward from the upper layers during pavement use (Fassman and Blackbourn, 2010).

According to Brazilian Standards (NBR) 16416 (ABNT, 2015), the Brazilian standard for permeable concrete pavements, the infiltration system used in this project is a full-infiltration system; thus, all rainfall infiltrates into the subgrade without the use of drains. As established in the standard, the installation of permeable interlocking concrete blocks was performed without widened joints and, consequently, without jointing material (dry joints). The designated use typology corresponds to pedestrian traffic.

Soil characterization

To characterize the subgrade soil on which the permeable pavement was constructed, laboratory tests were performed for grain size distribution — NBR 7.181 (ABNT, 2025), California Bearing Ratio (CBR) — NBR 9.895 (ABNT, 2017), and permeability — NBR 13.292 (ABNT, 2021). A disturbed soil sample was collected at a depth of 0.45 m (subgrade of the permeable pavement), and subsamples were prepared for each test following the procedures established in NBR 6.457 (ABNT, 2024). Field tests included a permeability test using a single-ring infiltrometer and an auger-based investigation to identify the groundwater table level.

Given the granular classification of the soil, the constant-head permeameter method — NBR 13.292 (ABNT, 2021) — was used to determine the subgrade permeability. In conducting the test, a subgrade compaction degree of 90% was adopted, based on the in situ findings of Almeida (2017) and Silva (2022) for areas adjacent to the installed permeable pavement and at similar depths. The equation defined in NBR 13.292 (ABNT, 2021), based on Darcy's law, was applied to determine the numerical value of the subgrade permeability.

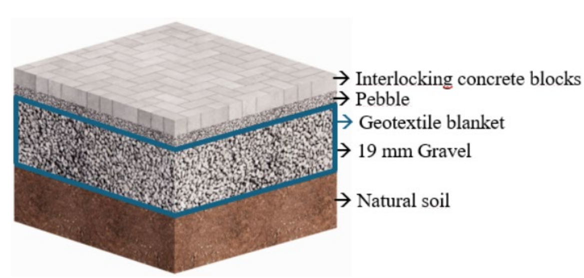

Figure 5 – Permeable pavement profile.

Hydraulic performance assessment

The hydraulic performance assessment of the permeable pavement was conducted by analyzing the system's behavior through the association of local precipitation data and water level data within the permeable pavement structure. The analysis sought to evaluate the pavement system over a sequence of rainfall events (Menezes, 2023). Additionally, permeability coefficient tests were performed on the newly constructed pavement according to the methodology proposed in NBR 16.416 (ABNT, 2015), using an infiltration ring.

The installation point of the piezometer (a 100 mm diameter Polyvinyl Chloride (PVC) tube driven from ground level to a depth of 2.5 m), into which the water level sensor was inserted, was selected based on feasibility criteria. These criteria were related to suitable locations for sheltering the datalogger connected to the sensor and ensuring adequate protection of the equipment. The locations chosen for determining the permeability coefficient consisted of three points near the installed piezometer.

Between March 5, 2023, and July 31, 2024, water level data were collected within the permeable pavement at the POLI-UPE. Using an automatic water level recorder (AMPEQ brand, model DALO 105) installed inside the piezometer, measurements were taken automatically and continuously at 1-min intervals. The data were stored in the datalogger, which was integrated with the automatic recorder.

Rainfall data were collected using a meteorological station installed at POLI-UPE. The station, manufactured by DAVIS, monitors several atmospheric parameters, including precipitation. Thus, it was possible to build the analytical dataset (water level and rainfall) for evaluating the hydraulic performance of the permeable pavement.

In determining the permeability coefficient of the newly constructed pavement, the methodology established in NBR 16.416 (ABNT, 2015) highlights that the minimum admissible value for the coefficient is 10^{-3} m/s for newly built permeable pavement. The standard proposes on-site permeability tests as the acceptance criterion for pavement implementation.

The tests were performed at three selected points on the pavement on the following dates, shortly after construction was completed: March 3, 2023; March 10, 2023; and March 17, 2023. For each point, the tests were conducted with a single repetition, as specified by the standard, resulting in six valid measurements per point.

Results and Discussion

Subgrade soil of the permeable pavement

The grain size distribution test performed on the soil sample collected at a depth of 45 cm (permeable pavement subgrade) indicated a predominance of the sand fraction, totaling approximately 80% of the soil composition. Additionally, regarding consistency limits, the soil was classified as non-liquid (NL) and non-plastic (NP). According to the textural triangle, the overall soil classification was loamy sand.

With respect to subgrade permeability, the test result was 6.38×10^{-5} m/s, which does not comply with NBR 16.416 (ABNT, 2015) for the adopted full-infiltration system (minimum normative value of 10^{-3} m/s). NBR 16.416 (ABNT, 2015) establishes a minimum coefficient that is considered excessively restrictive when compared to the American standard ACI 522R (2010), which requires, for the same infiltration system, a minimum soil permeability coefficient higher than 3.6×10^{-6} m/s, provided that this permeability extends to a depth of at least 1.20 m.

A new constant-head permeability test was therefore conducted on a soil sample collected at a depth of 1.20 m, which was also granulometrically classified as granular. The new permeability value obtained was 8.76×10^{-6} m/s, which complies with the American standard for full-infiltration systems, exceeding the required minimum. This result supports the choice of the full-infiltration system.

The single-ring infiltrometer test was conducted in the field at the subgrade depth (45 cm), at three distinct points. At point 1, the maximum infiltration rate was 925.99 mm/h (2.57×10^{-4} m/s), and the minimum stabilized rate was 111.2 mm/h (3.12×10^{-5} m/s). At point 2, infiltration rates were 702.48 mm/h (1.95×10^{-4} m/s) and 118.44 mm/h (3.29×10^{-5} m/s), and at point 3, 885.73 mm/h (2.46×10^{-4} m/s) and 82.48 mm/h (2.29×10^{-5} m/s). According to NBR 16.416 (ABNT, 2015), these values correspond to a medium permeability soil [> 36 mm/h (1.00×10^{-5} m/s) and ≤ 3,600 mm/h (1.00×10^{-3} m/s)].

Based on the results obtained, it can be stated that the subgrade soil presents suitable conditions for the implementation of compensatory infiltration techniques, given its grain size distribution, adequate load-bearing capacity indicated by the CBR value of 34%, and permeability consistent with the infiltration requirements of permeable pavement systems.

Hydraulic performance of the permeable pavement

All 18 permeability coefficients calculated from the tests (three points, one repetition each, over three different days) were above the minimum normative limit. Figure 6 shows the mean permeability coefficients for each test point, with the red line indicating the minimum required value.

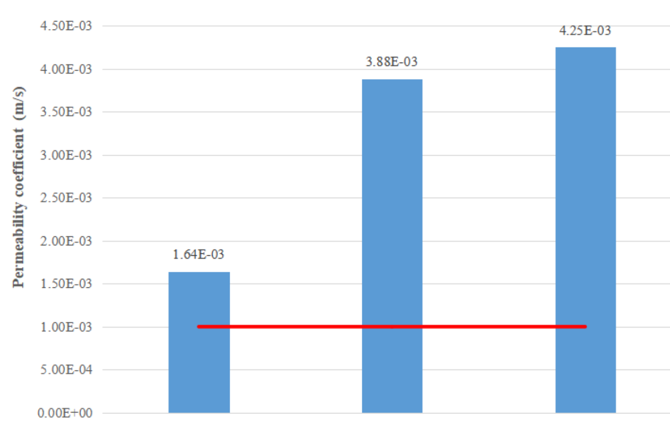

Figure 6 – Permeability coefficients of the newly constructed permeable pavement.

The final permeability coefficient for the newly constructed permeable pavement was 3.26×10^{-3} m/s, indicating suitable permeability for hydraulic performance (Zhu et al., 2021), equivalent to 3.26 mm/s.

The hydraulic performance assessment, conducted through the analysis of water-level data within the permeable pavement and local precipitation, covered the period from March 5, 2023, to July 31, 2024. No gaps occurred in the water-level data collection. Rainfall data were collected using a DAVIS-brand meteorological station installed on May 18, 2023, on the campus of the Polytechnic School, with recordings at 10-min intervals.

Figure 7 presents the graphs combining water-level data inside the permeable pavement system and local precipitation. The data have a temporal resolution of 10 min. The graphs display the time intervals on the horizontal axis and two independent vertical axes: on the left, water-level depth (in meters), and on the right, precipitation (in millimeters). The orange line represents the interface between the base layer and the subgrade (the bottom of the permeable pavement base and the top of the natural soil), located at a depth of 43 cm.

Regarding the analysis of the permeable pavement behavior, cycles of water-level rise and decline were observed according to precipitation events. The system water level rises during rainfall due to infiltration through the pavement. After rainfall ceases, the water level continues to rise for a period as the upper layers drain into the system. Once this process ends, no further increase in water level is observed. Exceptions — unexpected peaks — occurred when water accumulated within the base layer of the permeable pavement (above 0.43 m, corresponding to the base–subgrade interface) for certain periods.

To analyze the hydraulic behavior in greater detail, the days with the highest rainfall intensities were examined. In 2023, the most intense event occurred on May 24, with 122.8 mm of rainfall. In 2024, the peak occurred on June 15, with 137.6 mm (Figure 8).

Figure 9A shows the rainfall event of May 24, 2023. Since most of the daily precipitation occurred within a short time window, Figure 9b details the critical 4-h interval of the event. This interval lasted from 04:20 to 08:20 and accumulated 116.6 mm of the total 122.8 mm recorded that day.

Analysis of Figures 8 and 9 confirms that the water level within the pavement's storage layer increased during rainfall due to infiltration. The cyclical behavior is evident in the rising and receding hydrographs. The permeable pavement performed satisfactorily throughout the entire monitoring period, as it successfully infiltrated the required stormwater volumes during successive rain events.

This study highlights the relationship between increased water entry into the system, due to higher precipitation, and higher soil saturation. Increased saturation influences hydraulic processes within the pavement, slowing down the overall infiltration and storage dynamics. As noted by Madrazo-Uribeetxebarria et al. (2023), hydraulic processes are influenced by various subsurface characteristics, and the hydraulic properties of permeable pavements are fundamental to system performance.

Huang et al. (2016) emphasize that hydraulic performance in permeable pavements is mainly related to flow attenuation, peak-flow reduction, and surface infiltration capacity. According to Song (2022), areas where permeable pavements were implemented showed reduced runoff coefficients, decreases in peak flow, and delayed peak discharge in Nanjing (China); runoff control in Zhenjiang (China); and a reduction in effective impermeability from 45% to less than 5% in Menly (Australia).

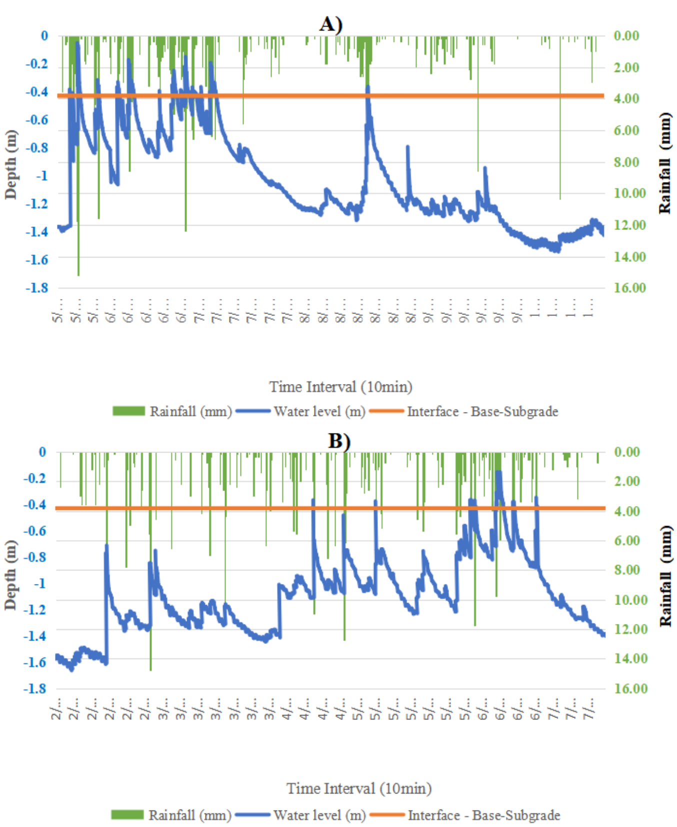

Figure 7 – Water level in the permeable pavement system × local precipitation. (A) 05/18/2023 to 10/24/2023; (B) 02/02/2024 to 07/31/2024.

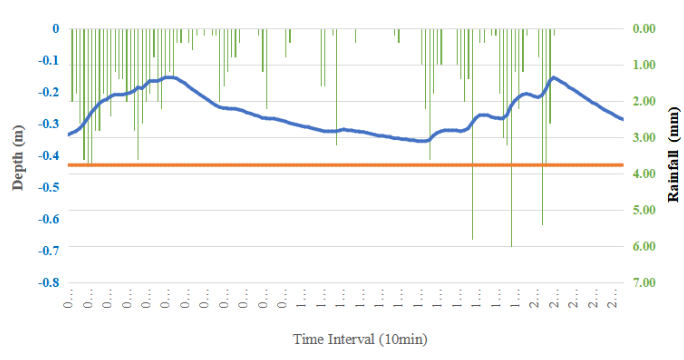

Figure 8 – Water level in the permeable pavement system × precipitation — 06/15/2024.

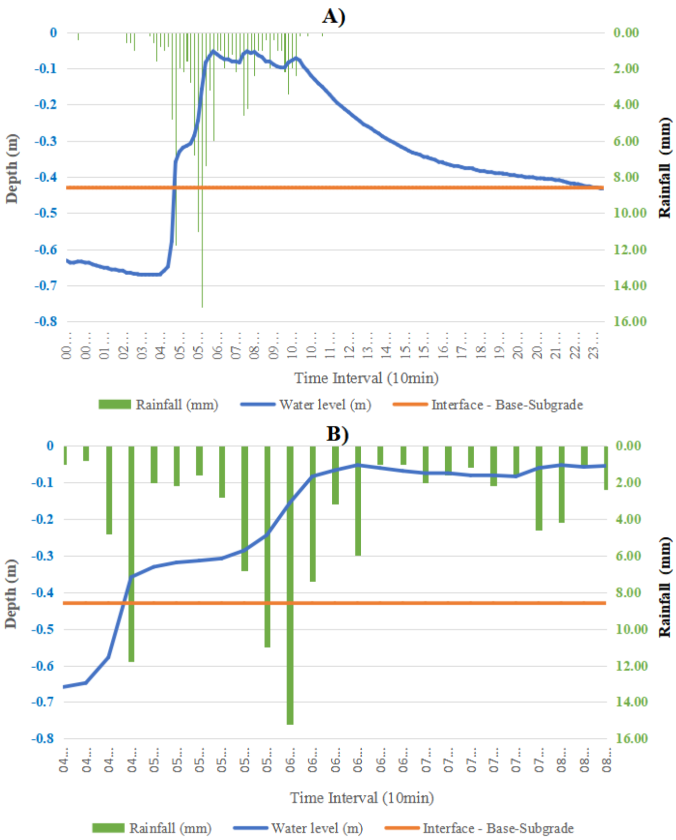

Figure 9 – Water level in the permeable pavement system × precipitation — 05/24/2023. (A) 05/24/2023. (B) 05/24/2023 – 4-h critical interval (04:20–08:20).

The results from the monitored period indicate that the implemented NbS managed, through infiltration and without surface water accumulation, successive and intense rainfall events such as those recorded on May 24, 2023 (122.8 mm), and June 15, 2024 (137.6 mm). Therefore, the 840 m² of permeable pavement constructed on the university campus serves as a practical example of how an area can be adapted to promote sustainable urban drainage, emphasizing on-site stormwater retention and efficient stormwater management through an NbS approach.

Conclusion

This study evaluated the use of a permeable pavement as a Nature-Based Solution (NbS) typology for the sustainable management of stormwater in urban areas, demonstrating its potential to reduce the impacts of urban flooding. The assessment of the hydraulic performance of the pavement constructed at the POLI-UPE revealed satisfactory system behavior, with a good capacity for stormwater infiltration and retention, which contributes to the reduction of surface runoff and, consequently, to the mitigation of flood magnitude.

The geotechnical tests indicated that the subgrade soil exhibits suitable infiltration capacity. The permeable pavement presented permeability coefficients consistent with the requirements established in NBR 16416 (ABNT, 2015), indicating adequate infiltration performance. The analysis of rainfall and water-level data revealed that the permeable pavement was capable of meeting stormwater retention demands, even during intense rainfall events, throughout the monitoring period. The pavement exhibited a cyclical behavior of rising and receding water levels and satisfactorily managed large precipitation volumes.

This study highlights that the use of permeable pavements, as an NbS typology, can be an effective solution for promoting more sustainable urban drainage, particularly in regions prone to intense rainfall and flooding, such as the city of Recife. The adoption of solutions such as permeable pavement contributes to urban planning aimed at developing more resilient cities with respect to stormwater management and may serve as a successful example for other areas of Recife and for urbanized cities throughout Brazil. Thus, the NbS highlighted in this work may help address the challenges posed by growing and unplanned urbanization, as well as the impacts of climate change.

For future studies, it is recommended to evaluate the impact of permeable pavement at the sub-basin scale, determining the percentage reduction in total surface runoff, as well as the relationship between a given intense rainfall event and the time required for the water level within the permeable pavement to exceed its storage capacity and generate surface runoff.

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Authors' Contributions

Menezes, L.A.A.: conceptualization, formal analysis, investigation, methodology, validation, writing – original draft, writing – revision and editing.
Cabral, J.J.S.P.: formal analysis, methodology, supervision, visualization, writing – revision and editing. **Santos**, S.M.: formal analysis, supervision, validation, visualization, writing – revision and editing.

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