Integrating Geopolymer Pervious Concrete Pavement for Sustainable Stormwater Management: A Case Study in the UAE

Ahmed Wagih [1], Mohamed Hamouda [1], Hilal El-Hassan [1]

[1] Department of Civil and Environmental Engineering, UAE University, Al Ain, 15551, United Arab Emirates

Keywords: Stormwater Management, SUDS, Pervious Concrete Pavement, GIS, Hydrological Modeling.

Abstract

Stormwater management poses a significant challenge in urbanized regions, particularly in areas prone to flash flooding. This study evaluates the potential of geopolymer pervious concrete pavement (PCP) as an innovative sustainable drainage system (SUDS) to mitigate stormwater impacts. With its highly permeable structure, geopolymer PCP enhances infiltration, reduces runoff intensity, and minimizes flooding risks, making it a promising solution for urban flood management. The research integrates laboratory testing with real-world analysis, utilizing advanced geographic information system (GIS) tools and hydrological modeling techniques. A case study was conducted at the UAE University Campus, covering an area of approximately 1.26 km². This analysis focused on an extreme rainfall event that occurred from April 15th and 16th, 2024, which recorded a total of 168 mm of precipitation. The study simulated rainfall-runoff dynamics under baseline conditions and compared them to scenarios incorporating geopolymer PCP in urban infrastructure elements, such as sidewalks, parking lots, and road shoulders, to evaluate the effectiveness of the lab-tested PCP.

Hydrological modeling, conducted using PCSWMM, demonstrated significant benefits of geopolymer PCP. Results showed a 20% reduction in peak flow at the outlet compared to baseline conditions, preventing stormwater pipes from reaching full capacity and enabling the optimization of stormwater infrastructure, including the use of smaller pipe diameters. Additionally, spatial analyses revealed substantial reductions in flooded areas, reinforcing the viability of PCP as an effective solution for managing urban stormwater. This innovative approach bridges the gap between laboratory research and practical applications, showcasing the transformative potential of geopolymer PCP in addressing urban flooding challenges.

1. Introduction

Urban environments face growing flood risks due to the dual pressures of climate change and the widespread presence of impervious surfaces, which hinder natural water infiltration and increase surface runoff. As urbanization expands, the rise in impermeable areas contributes to more intense stormwater runoff, urban flooding, and water quality deterioration. Traditional stormwater management strategies, which primarily depend on drainage infrastructure, are often insufficient during extreme weather events. In contrast, Sustainable Urban Drainage Systems (SUDS) provide a nature-based solution that replicates natural hydrological processes to manage stormwater more effectively (Chen et al., 2016; Seyedashraf et al., 2021). These systems aim to minimize runoff, promote infiltration, and enhance overall water quality. Among these alternatives, Pervious Concrete Pavement (PCP) stands out as a viable option for flood mitigation in arid regions. Beyond facilitating water infiltration and aquifer recharge, PCP also contributes to reduced tire-pavement noise, lower energy use, improved skid resistance, and better water quality (Yang et al., 2021; Wang et al., 2024).

Unlike vegetative-based SUDS, PCP does not rely on a continuous water supply to maintain its functionality or appearance. This makes it particularly well-suited for stormwater management in arid and semi-arid regions such as the United Arab Emirates (UAE), where water conservation is critical (Kamali et al., 2016). Notably, the UAE has experienced increasingly extreme rainfall events in recent years, including the intense hailstorm that struck Al Ain in February 2024 and the unprecedented storm in April 2024, which delivered over 250 mm of rainfall within just two days. These events have placed immense pressure on conventional drainage infrastructure, revealing its limitations in effectively handling excess surface runoff. In this context, PCP offers a resilient, low-maintenance solution that enhances infiltration and reduces reliance on overburdened drainage systems.

Previous studies have demonstrated the effectiveness of permeable pavement and other SUDS in reducing urban flooding. For instance, Hoghooghi et al. (2018) converted parking lots and driveways into permeable pavements, leading to a 3% reduction in surface runoff and a 6% increase in infiltration. Similarly, Kaykhosravi et al. (2022) evaluated rain gardens, infiltration trenches, and porous pavements using PCSWMM, observing reductions in runoff volume of 8.9–11.3% and peak runoff reductions of 1.3–19.9%. Another study showed that this ratio can reach be higher (11-38%), depending on the pavement's design and coverage area (Pachaly et al., 2023). Permeable pavements effectively filter out total suspended solids (TSS) and total phosphorus (TP), improving the quality of stormwater before it reaches local water bodies (Bateni et al., 2023). These studies highlight the potential of permeable solutions, such as geopolymer PCP, to effectively enhance stormwater management.

To accurately simulate the complex interactions of surface runoff, infiltration, evapotranspiration, and related physical and biological processes, it is essential to utilize an integrated rainfall-runoff and hydraulic routing model. One widely used tool for this purpose is the Storm Water Management Model (SWMM), developed by the U.S. Environmental Protection Agency (EPA), is a widely used hydrologic-hydraulic simulation engine capable of modeling both the quantity and quality of urban runoff over single events or continuous periods (USEPA, 2017). PCP is modeled in SWMM using a multi-layer conceptual approach, including surface, pavement, soil, storage, and underdrain components, with real-time water balance calculations for each layer (Rossman, 2015). SWMM has been widely used in examining SUDS performance in stormwater management (Kong et al., 2017; Seyedashraf et al., 2021; Chuang et al., 2023) and enhancing stormwater quality (Ghodsi et al., 2016; Kaykhosravi et al., 2022; Janbehsarayi et al., 2023).

This research assesses the performance of geopolymer PCP in an arid environment, utilizing the United Arab Emirates (UAE) as a case study. The study integrates laboratory tests with geospatial and hydrological modeling to assess its impact on runoff reduction and infiltration enhancement during an extreme rainfall event in April 2024.

2. Methodology[AWM1]

The overall framework of the study is presented in Figure 1.

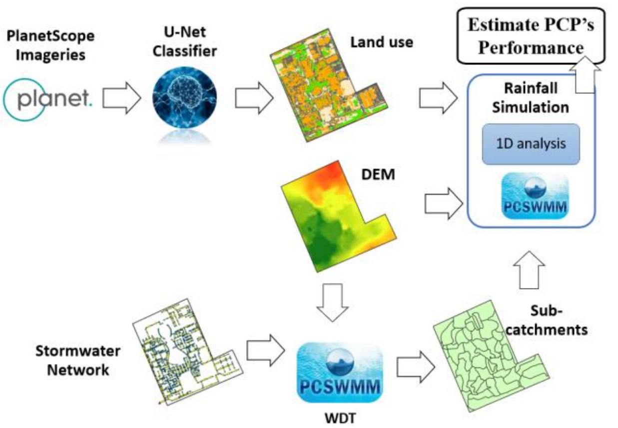

Figure 1: The overall workflow of the PCP simulation process.

While PCP offers numerous advantages, its production, involving cement and aggregates, is not entirely environmentally friendly since it consumes a significant amount of energy and natural resources, in addition to the resulting high carbon dioxide emissions (Afkhami et al., 2016). Geopolymer PCP, a permeable and environmentally sustainable material, is selected for this study due to its promising properties and low carbon emissions. The material key parameters for SWMM, such as thickness, void ratio, surface slope, surface roughness, permeability, and clogging factor, are presented in Table 1 (Anwar et al., 2024).

Layer	Parameter	Value
Surface	Surface Slope %	1.5
	Surface Roughness	0.1
Pavement	Void Ratio %	0.188
	Thickness mm	60
	Clogging Factor	590
	Permeability cm/h	1450

Table 1: Geopolymer PCP properties used to develop the model.

2.1 Study area

The study area considered is the UAE University (UAEU) campus, located in Al Ain City, Abu Dhabi, United Arab Emirates, which spans an area of approximately 1.26 km² (Figure 2). The campus has five main types of Land use: buildings, green areas, undeveloped areas, water bodies, and roads (including parking lots, pedestrian paths, and pavement), making it a representative site for evaluating the potential of geopolymer PCP in stormwater management. Al Ain city experienced an extreme rainfall event from April 15th and 17th, 2024, resulting in a total precipitation of 168 mm, which led to significant surface runoff and localized flooding.

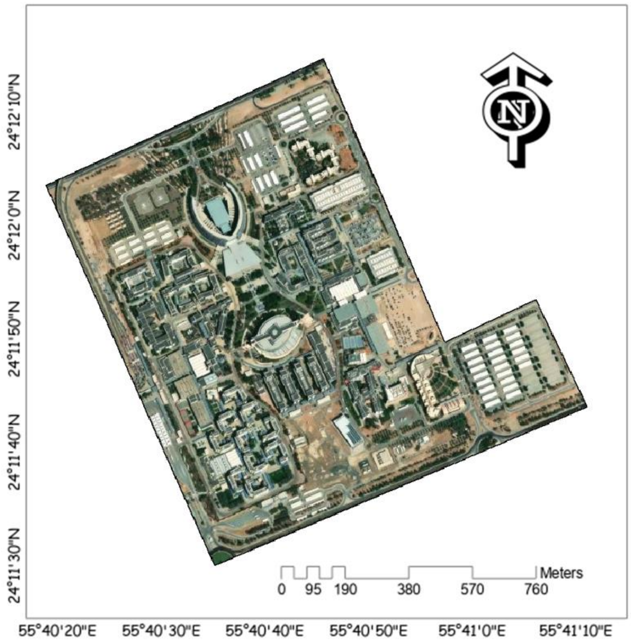

Figure 2: Google Earth Image of UAEU Campus.

2.2 Hydrological Modeling

To simulate the rainfall runoff process, the PCSWMM (CHI, 2024) (Personal Computer Storm Water Management Model), a GIS-integrated modeling software for stormwater and watershed systems, is used. It is built on the SWMM engine, enhancing its capabilities with advanced tools for analysis, data management, and visualization. CSWMM requires a variety of spatial and non-spatial data inputs to effectively simulate hydrologic and hydraulic processes within a watershed or urban stormwater system. Key spatial data include a Digital Elevation Model (DEM) for terrain analysis and watershed delineation, Land use maps to estimate runoff characteristics and imperviousness, and soil maps for infiltration modeling. These datasets help define catchment areas, flow paths, and surface characteristics essential for accurate hydrologic modeling. PCSWMM requires detailed information on the stormwater and sewer network infrastructure, such as manholes, pipes, inlets, outfalls, and storage facilities. In addition to spatial data, time-series data such as precipitation records are also used.

To obtain a DEM for the study area, junction (manholes and rain-gutters) cover elevations from the stormwater network are interpolated (Figure 3). A U-Net deep learning classifier using

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1501-2025

ArcGIS Pro software (Esri, 2024) is employed to generate high-resolution land-use maps from 3-m resolution PlanetScope imagery (Figure 4). PlanetScope satellites are small Earth observation satellites operated by Planet Labs (Planet Labs PBC, 2024), equipped with multispectral sensors that collect data across eight spectral bands as presented in Table 2. The Land use maps are used to distinguish between two pervious classes (green and undeveloped areas) and impervious areas (roads, buildings, and water). The Watershed Delineation Tool (DWT) in PCSWMM is used to divide the study area into subcatchments based on the surface slope and stormwater network (locations of manholes and rain gutters). For each subcatchment, the runoff is simulated to flow in a rectangular open channel using the nonlinear reservoir model (Chen & Shubinski, 1971) from the impervious surface towards the pervious surface, and then it flows out of the subcatchment to the specified outlet node or subcatchment.

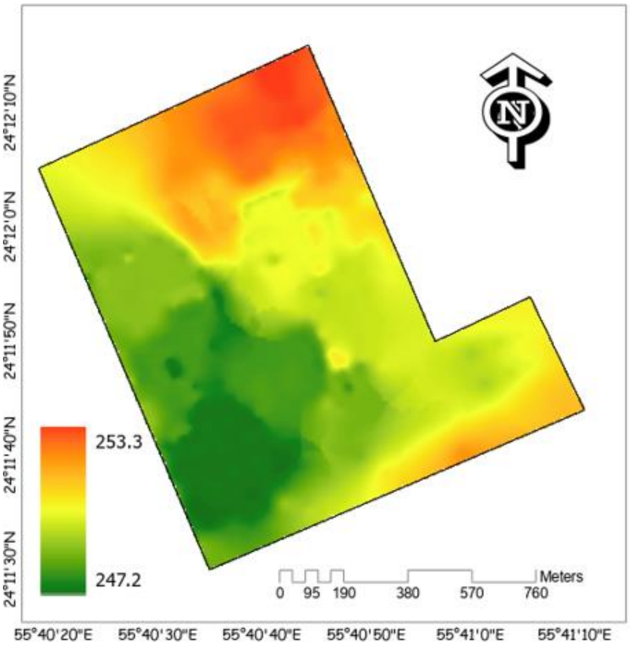

Figure 3: DEM of the UAEU Campus interpolated from junctions cover elevation.

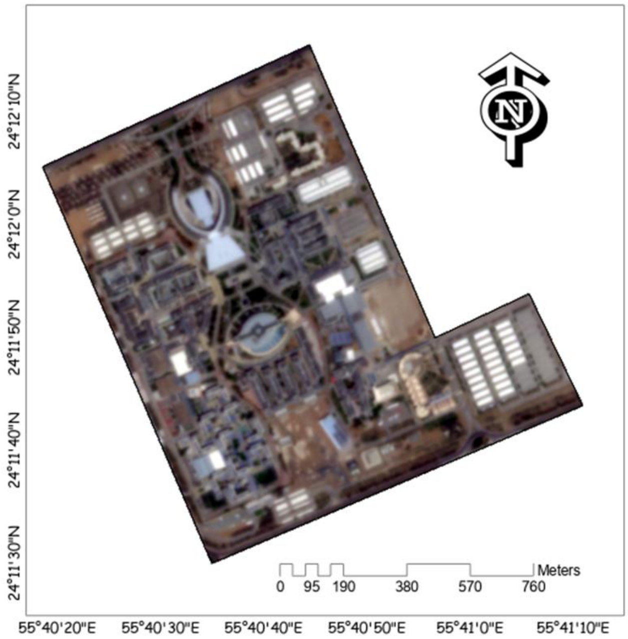

Figure 4: 3-m resolution PlanetScope imagery of the UAEU Campus on 5th April 2024.

Band	Spectrum Region	Wavelength (nm)	Spatial Resolution
Band_1	Coastal Blue	431 - 452 nm	3 meters
Band_2	Blue	465 – 515 nm	
Band_3	Green I	513 - 549 nm	
Band_4	Green	547 – 583 nm	
Band_5	Yellow	600 - 620 nm	
Band_6	Red	650 – 680 nm	
Band_7	RedEdge	697 – 713 nm	
Band_8	NIR	845 – 885 nm	

Table 2: Spectral bands of PlanetScope satellite.

Two distinct scenarios have been simulated to analyze their impacts on urban infrastructure and runoff management. The first of these is the baseline scenario, which reflects the current state of the existing urban infrastructure characterized by traditional impervious surfaces, such as concrete and asphalt, that prevent water absorption and can lead to increased runoff. The second scenario, referred to as the PCP scenario, involves the innovative implementation of geopolymer Permeable Concrete Pavement (PCP) on approximately half of the campus road surfaces, which together account for about 15% of the total campus area. By utilizing this advanced material, we aim to enhance rainwater infiltration, thereby reducing the volume of surface runoff. To evaluate these scenarios effectively, rainfall-runoff simulations have been conducted using recorded rainfall data from a significant rainfall event that occurred in April 2024, which serves as a critical benchmark for understanding the effects of both scenarios in real-world conditions.

3. Results and discussion

3.1 Land use Classification and WDT results

Land-use classification derived from U-Net deep learning pixel-based models revealed the distribution of surface types across

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1501-2025

the study area, as presented in Figure 5. Buildings account for 40% of the campus, roads and parking lots comprise 28%, green areas cover 14%, and the remaining 18% consists of undeveloped and water surfaces. These findings highlight the prevalence of impervious surfaces, which account for more than two-thirds of the total area and substantially contribute to surface runoff during rainfall events.

In the results of the watershed delineation process using PCSWMM’s watershed delineation tool, the study area was divided into multiple hydrologically meaningful subcatchments. These subcatchments were delineated based on topographic gradients derived from the DEM and the spatial layout of the stormwater infrastructure, including manholes and rain gutters. The tool automatically generated flow paths and subcatchment boundaries, ensuring hydrologic connectivity to the stormwater network. Following the delineation of subcatchments, hydrologic parameters were assigned to each unit based on land use and slope characteristics following Lee et al. (2018). These parameters included slope, percentage of impervious area, depression storage, infiltration parameters considering the Green-Ampt method, and Manning’s roughness coefficients for both impervious and pervious surfaces. Land use was spatially overlaid within each subcatchment to derive spatially distributed values. This enabled a more accurate representation of runoff generation and flow routing under varying land use and surface conditions. For the development of the model, PCSWMM version 7.7.3895 from Computational Hydraulics International (CHI) was used.

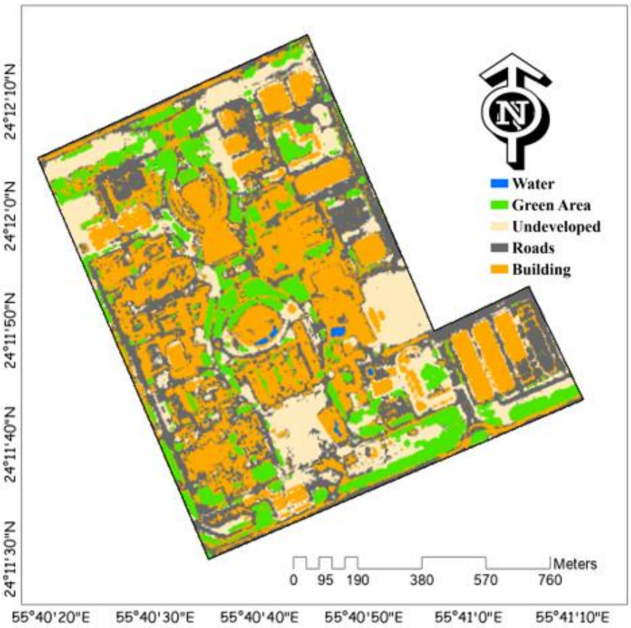

Figure 5: land-use map developed by the U-Net deep learning classifier from the PlanetScope imagery.

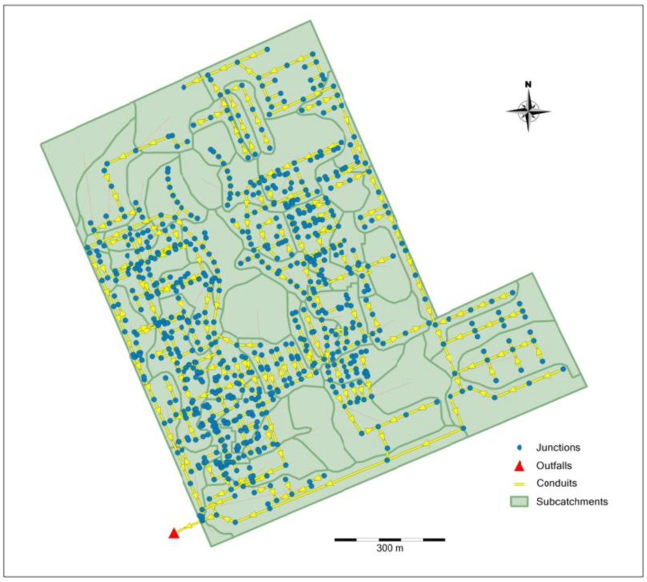

Figure 6: land-use map developed by the U-Net deep learning classifier from the PlanetScope imagery.

3.2 PCP simulation

The rainfall event recorded over April 15–16, 2024, exhibits three distinct phases of varying intensity. The first phase occurred on the evening of April 15th, with a gradual increase in intensity peaking at 14 mm/hr around 20:00, followed by moderate rain until midnight. The second phase, early on April 16th (06:00–08:00), was characterized by short but intense rainfall reaching 18 mm/hr. The third and most severe phase took place in the afternoon of April 16th (15:00–17:00), culminating in a peak intensity of 35 mm/hr at 16:00. This multi-peak pattern, totalling approximately 168 mm of rainfall.

The runoff results presented in Figure 7 highlight the improved permeability of the PCP scenario compared to the baseline. During the early hours of the event (17:00 to 18:30), runoff rates are negligible for both scenarios due to low rainfall intensity. However, as rainfall intensifies, significant differences emerge. At 20:00, runoff in the baseline scenario peaks at approximately 2.05 m^3/s, compared to 1.33 m^3/s in the PCP scenario, representing a 35% reduction.
This trend continues throughout the event, with the PCP scenario consistently showing lower runoff rates than the baseline. Even during periods of declining rainfall intensity (e.g., after 23:00), the PCP scenario maintains a notable reduction in runoff volumes. For instance, at 23:30, runoff in the baseline scenario is 0.93 m^3/s, while the PCP scenario achieves a reduced rate of 0.94 m^3/s.

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1501-2025 |

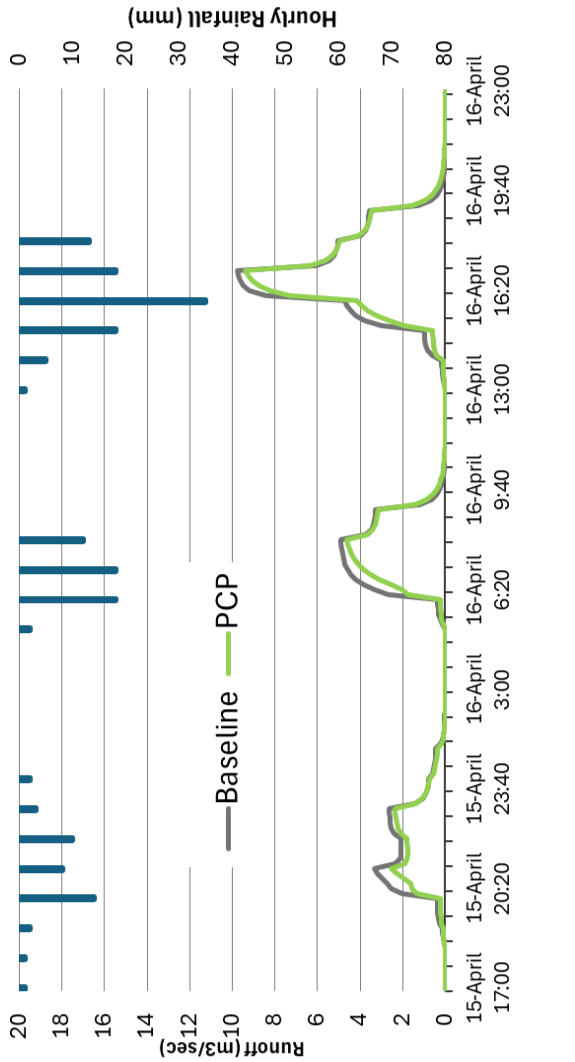

Figure 7: Surface runoff for the baseline scenario and PCP implemented scenario during the rainfall.

Figure 8 provides further evidence of the effectiveness of PCP in mitigating stormwater impacts by increasing infiltration. Initially, infiltration increases for the same scenarios with precipitation until the soil becomes saturated; however, the PCP scenario exhibits a higher infiltration rate due to the increased pervious surface area. For most of the recorded period, the infiltration rate in the PCP scenario is consistently double that of the baseline. For example, from 17:00 to 18:30 on April 15, 2024, the infiltration rate in the baseline remained constant at approximately 15.3 mm/hr., while the PCP scenario exhibited a rate of about 30.5 mm/hr. This trend persists until peak rainfall intensity is observed at 20:00, when the infiltration rate reaches 138.4 mm/hr in the baseline and 275.9 mm/hr in the PCP scenario.

The PCP scenario continuously maintains a greater infiltration rate than the baseline, but after the peak, infiltration rates progressively decline as rainfall decreases. This illustrates how geopolymer PCP has a greater ability to encourage water percolation into the subsurface, lowering surface runoff and increasing the effectiveness of stormwater control.

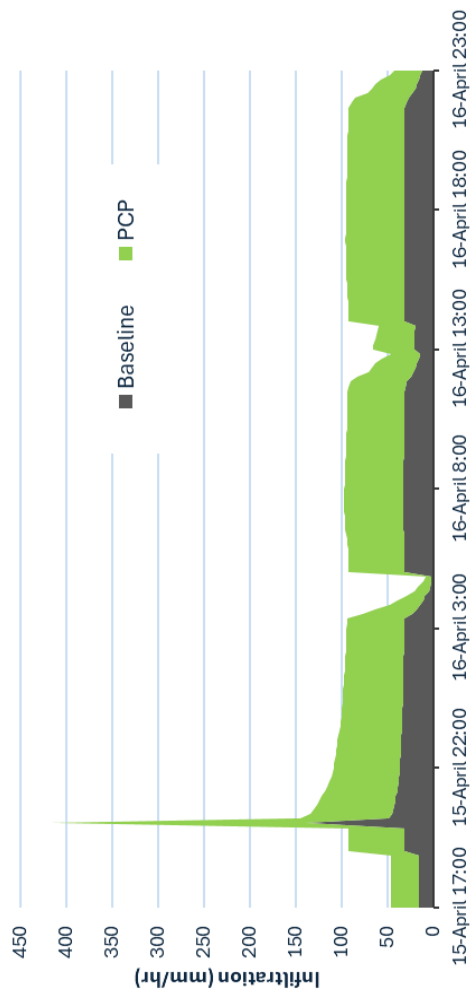

Figure 8: Infiltration rate of the watershed for the baseline scenario and PCP scenario.

4. Conclusion

This study highlights the potential of geopolymer PCP as an effective sustainable drainage solution for mitigating stormwater impacts in urban environments, particularly within arid regions like the United Arab Emirates. Conducted on the UAEU campus, where PCP was simulated on approximately 15% of the total area, specifically covering half of the campus road network, the research integrates geospatial modeling, deep learning classification, and hydrological simulations to evaluate performance under a severe rainfall event recorded in April 2024.

This extreme event featured multiple high-intensity rainfall phases, with the most intense peak reaching 35 mm/hr in the afternoon of April 16th. The total recorded rainfall over the event was 166 mm, with three distinct peaks contributing to rapid surface runoff. Under these conditions, the simulation results showed that geopolymer PCP reduced peak runoff by 35% compared to the baseline scenario. Additionally, infiltration rates in the PCP scenario were consistently double those of traditional impervious surfaces, achieving a peak infiltration rate of 275.9 mm/hr during the highest rainfall intensity. These findings underscore PCP’s high permeability and its potential to reduce pressure on urban stormwater infrastructure during short-duration, high-volume rainfall events.

Building on the promising results of this study, future work should focus on the long-term performance and durability of geopolymer PCP under real-world conditions, particularly in arid climates with extreme temperature variations. Field-based pilot implementations on selected road sections within the similar urban settings would enable validation of simulation outputs and provide insights into maintenance needs and hydraulic performance over time. Additionally, conducting a comprehensive life cycle cost analysis that considers construction, maintenance, and water-saving benefits would help evaluate the economic feasibility of large-scale adoption. Future research could also explore the integration of this practice with other green infrastructure practices (e.g., bioswales, rain gardens) and assess the combined effect on urban flood mitigation, groundwater recharge, and urban heat reduction. Moreover, incorporating climate change projections into hydrologic simulations would enhance understanding of PCP's resilience under future rainfall extremes.

Acknowledgment

The authors would like to express their sincere gratitude to CHI (Computational Hydraulics International) for providing an educational license of PCSWMM, which was instrumental in conducting the hydrologic and hydraulic modeling for this study. We also extend our appreciation to Planet Labs for granting access to PlanetScope imagery, which significantly supported the land use analysis and spatial assessment components of the research.

References

Anwar, F. H., El-Hassan, H., Hamouda, M., El-Mir, A., & Mo, K. H. (2024). Performance evaluation of pervious geopolymer concrete incorporating recycled concrete aggregate. *International Journal of Sustainable Engineering*, *17*(1), 149–166. https://doi.org/10.1080/19397038.2024.2417003

Bateni, N., Najib, L. M., Roslan, K., Seng, M. Y., Othman, I., Maseri, H., & Mannan, M. D. (2023). Environmental performance of the Stormpav permeable pavement using the Stormwater Management Model (SWMM). International Journal of Integrated Engineering, 15(6). https://doi.org/10.30880/ijie.2023.15.06.006

CHI PCSWMM

Computational Hydraulics International (CHI). (2024). PCSWMM (Version 7.x) [Computer software]. https://www.chiwater.com/Software/PCSWMM/

Chuang, W. K., Lin, Z. E., Lin, T. C., Lo, S. L., Chang, C. L., & Chiueh, P. T. (2023). Spatial allocation of LID practices with a water footprint approach. Science of the Total Environment, p. 859, 160201. https://doi.org/10.1016/j.scitotenv.2022.160201

Chen, C.W. & Shubinski, R.P. (1971). "Computer Simulation of Urban Storm Water Runoff", *J. Hydraul. Div., Proc. ASCE*, 97(HY2):289-301.

Chen, Y., Samuelson, H.W., Tong, Z. (2016). Integrated design workflow and a new tool for urban rainwater management. J. Environ. Manag. 180, 45–51. https://doi.org/10.1016/j.jenvman.2016.04.059

Esri. (2024). *ArcGIS Pro (Version 3.x)* [Computer software]. Environmental Systems Research Institute. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Ghodsi, S. H., Kerachian, R., & Zahmatkesh, Z. (2016). A multi-stakeholder framework for urban runoff quality management: Application of social choice and bargaining techniques. Science of the Total Environment, 550, 574–585. https://doi.org/10.1016/j.scitotenv.2016.01.052

Hoghooghi, N., Golden, H. E., Bledsoe, B. P., Barnhart, B. L., Brookes, A. F., Djang, K. S., Halama, J. J., McKane, R. B., Nietch, C. T., & Pettus, P. P. (2018). Cumulative effects of Low Impact Development on watershed hydrology in a mixed land-cover system. Water (Switzerland), 10(8). https://doi.org/10.3390/w10080991

Kamali, M., Delkash, M., & Tajrishy, M. (2016). Evaluation of permeable pavement responses to urban surface runoff. Journal of Environmental Management, 187, 43–53. https://doi.org/10.1016/j.jenvman.2016.11.027

Kaykhosravi, S., Khan, U. T., & Jadidi, M. A. (2022). A simplified geospatial model to rank LID solutions for urban runoff management. *The Science of the Total Environment*, *831*, 154937. https://doi.org/10.1016/j.scitotenv.2022.154937

Kaykhosravi, S., Khan, U. T., & Jadidi, M. A. (2022). A simplified geospatial model to rank LID solutions for urban runoff management. Science of the Total Environment, 831(March), 154937. https://doi.org/10.1016/j.scitotenv.2022.154937

Kong, F., Ban, Y., Yin, H., James, P., & Dronova, I. (2017). Modeling stormwater management at the city district level in response to changes in land use and low impact development. Environmental Modelling & Software, pp. 95, 132–142. https://doi.org/10.1016/j.envsoft.2017.06.021

Lee, J. G., Nietch, C. T., & Panguluri, S. (2018). Drainage area characterization for evaluating green infrastructure using the Storm Water Management Model. Hydrology and Earth System Sciences, 22(5), 2615–2635. https://doi.org/10.5194/hess-22-2615-2018

Mousavi Janbehsarayi, S. F., Niksokhan, M. H., Hassani, M. R., & Ardestani, M. (2023). Multi-objective decision-making based on theories of cooperative game and social choice to incentivize implementation of low-impact development practices. Journal of Environmental Management, p. 330, 117243. https://doi.org/10.1016/j.jenvman.2023.117243

Pachaly, R. L., Biessan, D. G. V., Vasconcelos, J. G., O'Donnell, F. C., & Bowers, B. F. (2023). Continuous Hydrologic Modeling of a Parking Lot and Related Best Management Practices with PCSWMM. Journal of Contemporary Water Research & Education, 177(1), 72–82. https://doi.org/10.1111/j.1936-704x.2022.3382.x

Planet Labs PBC. (2024). PlanetScope imagery [Satellite data]. https://www.planet.com/products/planet-imagery/

Rossman LA (2017). Stormwater management model reference manual - hydraulics. US EPA Office of Research and Development, Washington, DC.

Seyedashraf, O., Bottacin-Busolin, A., & Harou, J. J. (2021). Many-Objective Optimization of Sustainable Drainage Systems in Urban Areas with Different Surface Slopes. Water Resources Management, 35(8), 2449–2464. https://doi.org/10.1007/s11269-021-02840-4

United States Environmental Protection Agency (USEPA) (2017). Green Infrastructure in Parks: þA Guide to Collaboration, Funding, and Community Engagement (Technical Report). United States Environmental Protection Agency, Washington, DC.

Wang, X., Liu, S., Ruan, B., Luo, Y., & Wu, L. (2024). A spatial optimal allocation method considering multiattribute decision making and multiple BMPs random combination in sub-watersheds. Journal of Environmental Management, 350, 119655. https://doi.org/10.1016/j.jenvman.2023.119655

Yang, L., Pang, S., Wang, X., Du, Y., Huang, J., & Melching, C. S. (2021). Optimal allocation of best management practices based on receiving water capacity constraints. Agricultural Water Management, 258, 107179. https://doi.org/10.1016/j.agwat.2021.107179