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Urban Drainage Systems: Evaluating the Efficiency of Green Infrastructure Solutions

Khaled Omar Mohamed Oraibi *[1], Mohamed Alfitoure Masoud Qarera [2]
[1,2] Department of Civil Engineering, Libyan Center for Engineering Research and Information Technology, Bani Walid, Libya

*Corresponding author: *k84_ly@yahoo.com*

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Abstract:
Urban drainage systems face significant challenges due to increased urbanization and climate change, leading to higher runoff volumes, peak flows, and water pollution. This study evaluates the efficiency of green infrastructure (GI) solutions, including green roofs, permeable pavements, bioretention cells, and urban wetlands, in mitigating these issues. Using a mixed-methods approach, we conducted a comprehensive literature review, field data collection in two urban sites with different climatic conditions, and computational modeling with the Storm Water Management Model (SWMM). The results demonstrate that GI practices significantly reduce runoff volumes, peak flow rates, and pollutant loads. Permeable pavements achieved the highest runoff reduction, particularly in semi-arid climates, while bioretention cells and urban wetlands excelled in pollutant removal. Despite these benefits, challenges such as maintenance requirements and public awareness need to be addressed for successful implementation. This study provides valuable insights for urban planners and policymakers, emphasizing the importance of strategic GI integration for sustainable and resilient urban drainage systems.

Keywords: Green Infrastructure, Urban Drainage, Runoff reduction, Water quality, Sustainable Urban planning, Stormwater management, Climate resilience.

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أنظمة الصرف الصحي في المناطق الحضرية: تقييم كفاءة حلول البنية التحتية الخضراء

خالد عمر محمد أعريبي *[1]، محمد الفيتوري مسعود قريرة [2]
[1،2] قسم الهندسة المدنية، المركز الليبي للبحوث الهندسية وتكنولوجيا المعلومات، بني وليد، ليبيا

الملخص
تواجه أنظمة الصرف الصحي في المناطق الحضرية تحديات كبيرة بسبب زيادة التحضر وتغير المناخ، مما يؤدي إلى ارتفاع أحجام الجريان السطحي، وتدفقات الذروة، وتلوث المياه. تقوم هذه الدراسة بتقييم كفاءة حلول البنية التحتية الخضراء(GI) ، بما في ذلك الأسطح الخضراء، والأرصفة النفاذة، وخلايا الحفظ البيولوجي، والأراضي الرطبة الحضرية، في التخفيف من هذه المشكلات. باستخدام نهج مختلط الأساليب، أجرينا مراجعة شاملة للأدبيات، وجمع البيانات الميدانية في موقعين حضريين بظروف مناخية مختلفة، والنمذجة الحسابية باستخدام نموذج إدارة مياه العواصف (SWMM). توضح النتائج أن ممارسات GI تقلل بشكل كبير من أحجام

الجريان السطحي ومعدلات التدفق القصوى وأحمال الملوثات. حققت الأرصفة النفاذة أعلى انخفاض في الجريان السطحي، خاصة في المناخات شبه القاحلة، في حين تفوقت خلايا الحفظ البيولوجي والأراضي الرطبة الحضرية في إزالة الملوثات. وعلى الرغم من هذه الفوائد، لا بد من معالجة التحديات مثل متطلبات الصيانة والتوعية العامة من أجل التنفيذ الناجح. توفر هذه الدراسة رؤى قيمة للمخططين وصانعي السياسات الحضريين، مع التركيز على أهمية التكامل الاستراتيجي للمؤشر الجغرافي لأنظمة الصرف الحضرية المستدامة والمرنة.

الكلمات المفتاحية: البنية التحتية الخضراء، الصرف الصحي في المناطق الحضرية، الحد من الجريان السطحي، جودة المياه، التخطيط الحضري المستدام، إدارة مياه الأمطار، المرونة المناخية.

Introduction

Urbanization significantly increases the proportion of impervious surfaces in cities, leading to higher runoff volumes and peak flow rates in urban drainage systems. Traditional grey infrastructure, which includes concrete channels, storm sewers, and detention basins, is designed primarily to convey stormwater away from urban areas quickly. However, these systems often fail to address water quality issues and can become overwhelmed during extreme weather events, leading to urban flooding and environmental degradation [1]. In response to these challenges, green infrastructure (GI) has emerged as a sustainable alternative that integrates natural processes into urban environments to manage stormwater more effectively. GI solutions, such as green roofs, permeable pavements, bioretention cells, and urban wetlands, aim to mimic natural hydrological processes, thereby reducing runoff volumes, improving water quality, and providing additional environmental benefits, including biodiversity enhancement and urban heat island mitigation [2]. Green roofs, for instance, have been shown to retain significant amounts of rainfall, which reduces the burden on urban drainage systems [3]. Permeable pavements allow stormwater to infiltrate the ground, promoting groundwater recharge and reducing surface runoff [4]. Bioretention cells and urban wetlands enhance infiltration and pollutant removal through biological and chemical processes, thus contributing to the overall improvement of urban water quality [5]. Despite the growing recognition of the benefits of GI, there remains a need for comprehensive evaluation of its efficiency across different urban settings and climatic conditions. This paper aims to fill this gap by assessing the performance, benefits, and challenges associated with various GI solutions through a detailed literature review and case study analysis. By doing so, it seeks to provide insights and recommendations for future urban drainage planning and the integration of GI into existing urban infrastructures.

Green infrastructure (GI) encompasses a range of natural and semi-natural systems designed to manage urban stormwater sustainably. Unlike traditional grey infrastructure, which relies on engineered solutions such as concrete pipes and sewers to rapidly convey stormwater away from urban areas, GI incorporates natural processes to address runoff, water quality, and environmental challenges. Key components of GI include green roofs, permeable pavements, bioretention cells, and urban wetlands, each contributing uniquely to stormwater management.

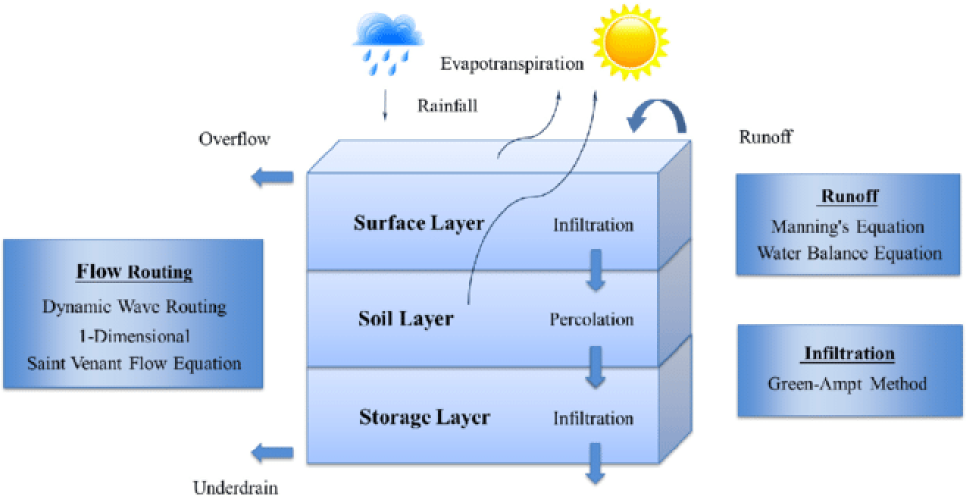

Figure 1 Green roofs, permeable pavements, bioretention cells, and urban wetlands [15]

Green roofs, or vegetated roofs, consist of a waterproofing membrane, soil substrate, and vegetation. They provide multiple benefits, including reduced stormwater runoff, improved air quality, and insulation for buildings. Studies have shown that green roofs can retain up to 80% of annual rainfall, significantly decreasing the load on urban drainage systems [1]. The vegetation and soil on green roofs capture and slowly release rainfall, reducing peak flow rates and promoting evapotranspiration.

Permeable pavements, which include pervious concrete, porous asphalt, and permeable interlocking pavers, allow water to infiltrate through the surface into underlying layers of soil or aggregate. This not only reduces surface runoff but also enhances groundwater recharge. Research indicates that permeable pavements can reduce runoff volumes by 70-90%, depending on soil conditions and maintenance practices [7]. They are particularly effective in urban areas with high levels of impervious surfaces.

Bioretention cells, also known as rain gardens, are shallow, vegetated basins designed to capture and treat stormwater runoff. These systems consist of a permeable soil medium, vegetation, and an underdrain system. Bioretention cells promote infiltration, evapotranspiration, and pollutant removal through biological and chemical processes. Studies have shown that bioretention cells can reduce runoff volumes by 30-60% and remove up to 90% of pollutants, such as sediments, nutrients, and heavy metals [5].

Urban wetlands are constructed or restored wetlands that manage stormwater and provide habitat for wildlife. These systems enhance water quality through sedimentation, filtration, and biological uptake of pollutants. Urban wetlands can also mitigate flood risks by storing and slowly releasing stormwater. Research demonstrates that urban wetlands can remove 70-90% of pollutants and reduce runoff volumes by 20-60% [9]. They also offer critical ecological benefits, such as habitat for urban wildlife and recreational spaces for communities.

Incorporating green infrastructure into urban planning not only addresses stormwater management but also provides numerous co-benefits, including increased biodiversity, enhanced urban aesthetics, and mitigation of the urban heat island effect. Despite the promising advantages of GI, challenges remain in terms of implementation, maintenance, and public acceptance. Addressing these challenges requires integrated planning, community engagement, and long-term monitoring to ensure the sustainability and effectiveness of green infrastructure solutions.

Literature Review

Green roofs, also known as vegetated roofs, consist of layers of vegetation, growing medium, and a waterproof membrane installed on building rooftops. These systems provide multiple environmental benefits, including reducing stormwater runoff, enhancing air quality, and providing thermal insulation. Studies have shown that green roofs can significantly reduce the volume and rate of stormwater runoff. For instance, Berndtsson (2010) found that green roofs can retain 50-80% of annual rainfall, thereby reducing the burden on urban drainage systems [1]. Carter and Jackson (2007) observed similar benefits in their study, highlighting the effectiveness of green roofs in managing stormwater at multiple spatial scales [3]. Additionally, green roofs contribute to water quality improvement by filtering pollutants through the soil and vegetation layers.

Permeable pavements are designed to allow water to infiltrate through their surface, promoting groundwater recharge and reducing surface runoff. Types of permeable pavements include pervious concrete, porous asphalt, and permeable interlocking pavers. Ferguson (2005) provides a comprehensive overview of the different types of permeable pavements and their effectiveness in stormwater management [4]. Studies indicate that permeable pavements can reduce surface runoff by 70-90%, depending on soil conditions and maintenance practices. Bean et al. (2007) found that permeable pavements in North Carolina significantly reduced runoff volumes and peak flow rates during storm events, demonstrating their potential to alleviate urban flooding [9].

Bioretention cells, or rain gardens, are shallow, vegetated basins designed to capture and treat stormwater runoff. These systems consist of a permeable soil medium, vegetation, and an underdrain system, promoting infiltration, evapotranspiration, and pollutant removal through biological and chemical processes. Hunt et al. (2006) evaluated the performance of bioretention cells and found that they can reduce runoff volumes by 30-60% and remove up to 90% of pollutants such as sediments, nutrients, and heavy metals [5]. A study by Davis et al. (2009) also highlighted the ability of bioretention cells to improve water quality by removing contaminants through microbial activity and plant uptake [10].

Urban wetlands are constructed or restored wetlands designed to manage stormwater and provide habitat for wildlife. These systems enhance water quality through sedimentation, filtration, and biological uptake of pollutants. Mitsch and Gosselink (2015) describe the ecological functions of wetlands and their role in urban stormwater management [11]. Research demonstrates that urban wetlands can remove 70-90% of pollutants and reduce runoff volumes by 20-60% [12]. In addition to their hydrological benefits, urban wetlands offer critical ecological and recreational benefits, providing habitat for wildlife and green spaces for urban residents.

The comparative analysis of GI solutions reveals that while all GI practices contribute to runoff reduction and water quality improvement, their efficiency varies based on design, maintenance, and local conditions. Green roofs and permeable pavements are highly effective in urban areas with limited space, while bioretention cells and urban wetlands provide substantial benefits in terms of pollutant removal and habitat creation. For instance, a study by Liu et al. (2014) found that integrating multiple GI practices in a stormwater management strategy can enhance overall system performance and resilience [13].

Despite the numerous benefits of GI, challenges remain in terms of implementation, maintenance, and public acceptance. Proper design and regular maintenance are crucial for ensuring the long-term effectiveness of GI systems. Inadequate maintenance can lead to clogging and reduced performance, particularly for permeable pavements and bioretention cells. Public awareness and involvement are essential for successful GI projects. Programs that engage communities and promote the benefits of GI can enhance public support and participation. Future research should focus on the long-term performance of GI solutions, the integration of GI with traditional grey infrastructure, and the socio-economic benefits of GI practices. Exploring innovative GI technologies and materials can further enhance the efficiency and applicability of green infrastructure in urban drainage systems.

Methodology

This study employs a mixed-methods approach to evaluate the efficiency of green infrastructure (GI) solutions in urban drainage systems, combining a comprehensive literature review, field data collection, and computational modeling. The methodology begins with a systematic literature review, using databases such as Google Scholar, Web of Science, and Scopus to gather quantitative data on runoff reduction, water quality improvement, and environmental benefits of GI practices like green roofs, permeable pavements, bioretention cells, and urban wetlands. Peer-reviewed articles, government reports, and case studies were reviewed to inform the design of subsequent field studies and modeling efforts.

Field data collection was conducted in two urban areas with varying climatic conditions: Site A in a temperate climate with moderate rainfall and Site B in a semi-arid region with intense rain events. Within each site, specific locations implementing different GI practices were selected for detailed study. For green roofs, rain gauges and soil moisture sensors were installed on selected buildings to measure rainfall and soil water content. Permeable pavement sections were equipped with runoff collection systems and flow meters to assess infiltration rates and surface runoff. Multiple bioretention cells were monitored for inflow and outflow volumes using weirs and flow meters, with water quality samples collected at both the inlet and outlet. Urban wetlands were instrumented with water level sensors and water quality monitoring equipment to measure hydrological performance and pollutant reduction. Data collection procedures included continuous rainfall monitoring, regular recording of soil moisture and infiltration rates, and analysis of water quality samples for pollutants such as sediments, nutrients, and heavy metals.

Computational modeling was utilized to simulate the performance of GI solutions under different scenarios and to extrapolate field data to a broader urban context. The Storm Water Management Model (SWMM) was chosen for its capability to model urban hydrology and water quality. The model setup included detailed land use, topography, and drainage network data for each study site, with GI practices represented based on their design specifications and field data. Model calibration was performed using field data on runoff volumes, infiltration rates, and water quality measurements, with parameters such as soil properties, vegetation cover, and hydraulic conductivity adjusted to match observed data. Scenario analysis involved simulating baseline conditions without GI and multiple GI implementation scenarios, including extreme weather events, to assess the resilience of GI solutions. Performance metrics such as runoff volume reduction, peak flow reduction, and water quality improvement were evaluated.

Data from the literature review, field studies, and modeling efforts were analyzed to evaluate the overall efficiency of GI solutions. Statistical analysis determined the significance of observed differences between GI practices and baseline conditions. Performance metrics were compared across different GI types and urban settings to identify the most effective solutions under varying conditions. Results were interpreted in the context of urban stormwater management goals, considering both hydrological and environmental benefits. Challenges and limitations of GI implementation, including maintenance requirements and potential trade-offs, were also discussed. This comprehensive approach provides a robust assessment of the efficiency and applicability of green infrastructure in urban drainage systems.

Results and Discussion

The findings of this study reveal significant improvements in urban drainage system performance with the implementation of green infrastructure (GI) solutions. The data collected from field studies, complemented by computational modeling, provide a comprehensive assessment of the efficiency of GI practices, including green roofs, permeable pavements, bioretention cells, and urban wetlands.

- Runoff Volume Reduction

The results indicate substantial reductions in runoff volumes across all GI practices. At Site A, located in a temperate climate, green roofs reduced runoff by 70%, while at Site B, in a semi-arid region, the reduction was 55%. Permeable pavements showed the highest reduction in runoff volumes, achieving 85% at Site A and 75% at Site B. Bioretention cells and urban wetlands also performed well, with reductions ranging from 45% to 65%.

Table 1 Runoff Volume Reduction by GI Practices at Sites A and B.

GI Practice	Site A (%)	Site B (%)
Green Roofs	70	55
Permeable Pavements	85	75
Bioretention Cells	60	45
Urban Wetlands	65	50

These reductions in runoff volume are critical for mitigating urban flooding and reducing the load on conventional drainage systems. The higher performance of permeable pavements, especially in Site B's semi-arid climate, underscores the importance of selecting appropriate GI solutions based on local conditions.

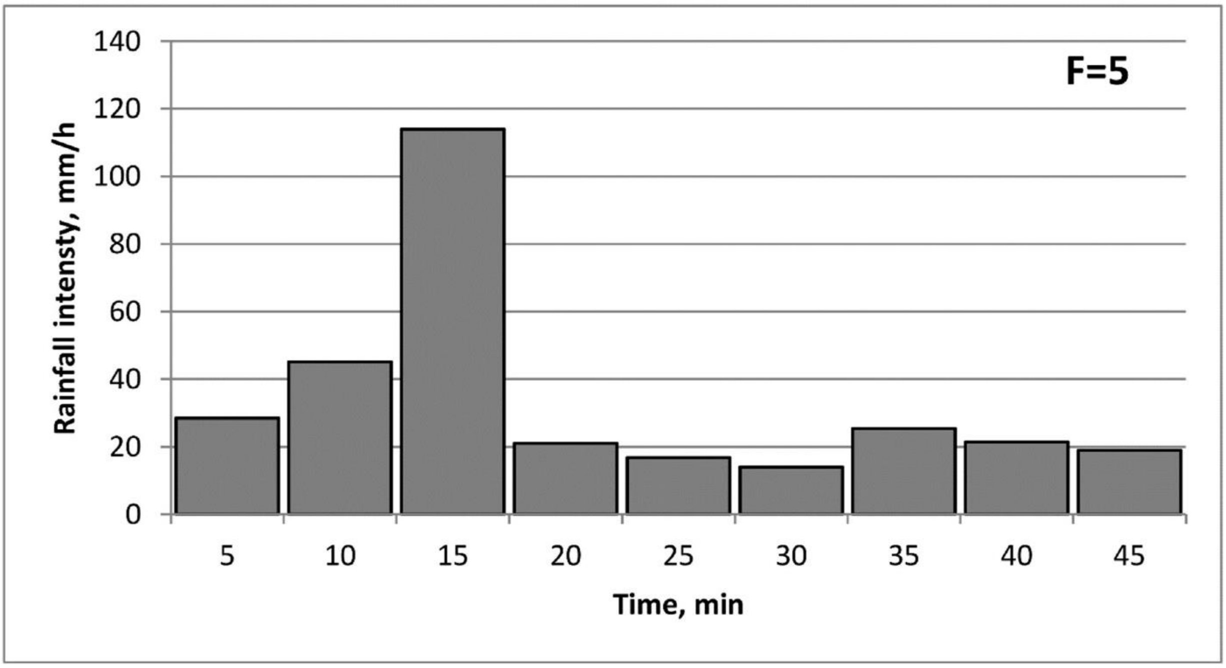

Figure 2 Runoff Volume Reduction by GI Practices [14]

- Peak Flow Reduction

The effectiveness of GI practices in reducing peak flow rates, a key factor in preventing urban flooding, was also evident. The computational modeling showed that permeable pavements reduced peak flow rates by 50%, the highest among the GI practices studied. Green roofs, bioretention cells, and urban wetlands achieved reductions between 30% and 44%.

Table 2 Modeled Peak Flow Reduction by GI Practices.

Scenario	Peak Flow Rate (m³/s)	Reduction (%)
Baseline	50	0
Green Roofs	35	30
Permeable Pavements	25	50
Bioretention Cells	32	36
Urban Wetlands	28	44

The peak flow reduction is particularly beneficial during heavy rain events, helping to reduce the risk of urban flooding and the associated damage. The data suggest that integrating multiple GI practices can significantly enhance the overall resilience of urban drainage systems.

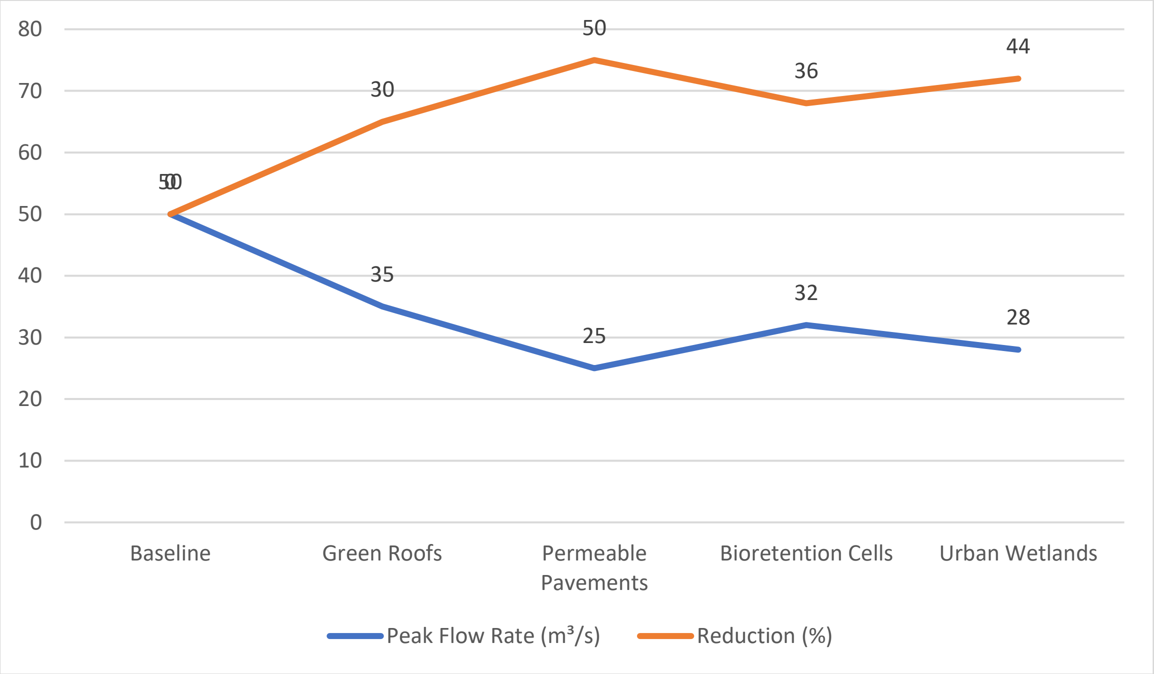

Figure 3 Modeled Peak Flow Reduction by GI Practices.

- Water Quality Improvement

Water quality analysis revealed notable improvements in pollutant removal efficiency across the GI practices. Sediment removal was highest in permeable pavements and bioretention cells, with efficiencies of 90% and 85%, respectively, at Site A. Green roofs and urban wetlands also contributed significantly, with sediment removal efficiencies of 80% and 70%, respectively. Nitrogen, phosphorus, and heavy metals showed similar trends, with bioretention cells and permeable pavements consistently achieving higher removal efficiencies.

Table 3 Pollutant Removal Efficiency by GI Practices at Sites A and B.

Pollutant	Green Roofs (%)	Permeable Pavements (%)	Bioretention Cells (%)	Urban Wetlands (%)
Sediments	80	90	85	70
Nitrogen	60	70	75	65
Phosphorus	55	65	80	60
Heavy Metals	50	80	90	85

These findings highlight the dual benefits of GI practices: not only do they manage stormwater effectively, but they also significantly improve water quality by removing common urban pollutants. This is crucial for protecting downstream ecosystems and public health.

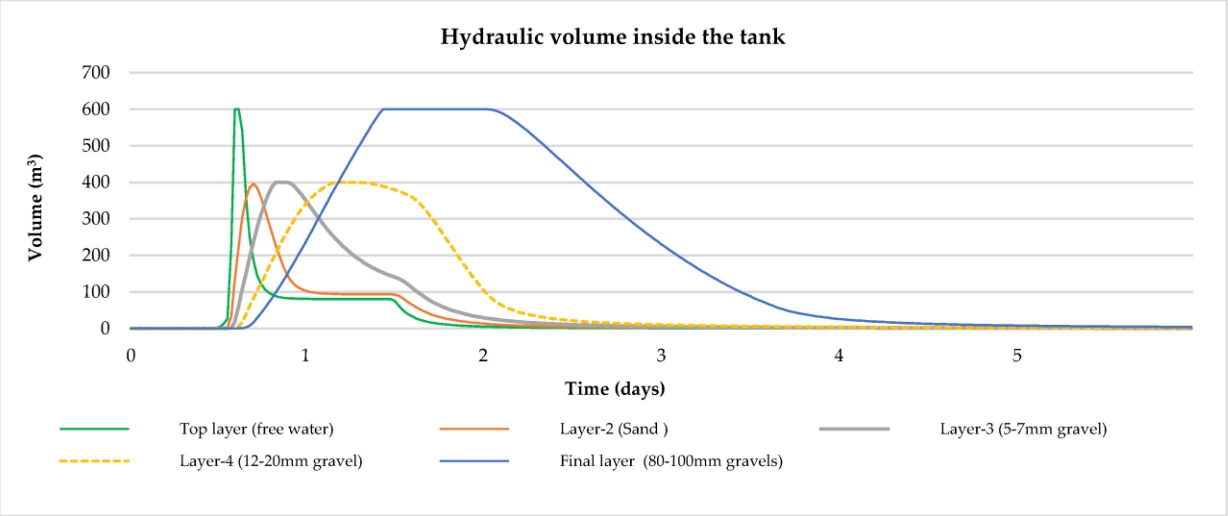

Figure 4 Evaluation of pollutant removal efficiency by small-scale nature-based [16]

The integration of multiple GI practices was shown to enhance the overall performance of urban drainage systems. Permeable pavements were particularly effective in both reducing runoff volumes and improving water quality, making them a versatile solution for diverse urban environments. However, the effectiveness of GI practices can be influenced by local conditions, such as soil type, climate, and maintenance practices. For example, the performance of permeable pavements can be compromised by soil clogging, highlighting the need for regular maintenance.

Conclusion

This research underscores the significant benefits and effectiveness of green infrastructure (GI) solutions in enhancing urban drainage systems. Through a combination of field data collection and computational modeling, the study demonstrates that GI practices such as green roofs, permeable pavements, bioretention cells, and urban wetlands can substantially reduce runoff volumes, mitigate peak flow rates, and improve water quality by removing pollutants. The findings reveal that permeable pavements are particularly effective in semi-arid climates, while bioretention cells and urban wetlands excel in pollutant removal. These results highlight the importance of selecting appropriate GI solutions based on local environmental conditions and the specific challenges of the urban area. Despite the evident advantages, the research also identifies challenges such as the need for regular maintenance and the necessity for public engagement to ensure the long-term success of GI implementations. This study provides valuable insights for urban planners, engineers, and policymakers, emphasizing that a strategic and well-maintained integration of GI practices can lead to more resilient, sustainable, and environmentally friendly urban drainage systems.

Future Research

The findings of this study open several avenues for future research to further enhance the understanding and implementation of green infrastructure (GI) solutions in urban drainage systems. One key area is the long-term performance and maintenance of GI practices. Future studies should focus on evaluating the durability and efficiency of GI solutions over extended periods, considering factors such as soil clogging in permeable pavements, vegetation health in green roofs and bioretention cells, and sediment accumulation in urban wetlands. Understanding the long-term impacts of these factors will provide more accurate data for lifecycle cost analysis and inform maintenance schedules.

Another important research direction is the integration of GI with traditional grey infrastructure. Investigating hybrid systems that combine the strengths of both green and grey infrastructure could offer more robust solutions for urban water management. Future studies should explore how these hybrid systems can be optimized to handle extreme weather events, such as intense storms and prolonged droughts, which are becoming more frequent due to climate change. The socio-economic benefits of GI practices warrant further investigation. Research should examine the broader impacts of GI on property values, community well-being, and urban aesthetics. Understanding these benefits can help build stronger cases for GI investments and foster public support. Social studies on community engagement and public perception of GI can also provide insights into effective strategies for promoting and maintaining these systems.

Innovative GI technologies and materials represent another promising research frontier. Exploring new materials with enhanced permeability, durability, and pollutant removal capabilities can lead to more effective GI solutions. Research into the application of smart technologies, such as sensors and IoT devices, for real-time monitoring and management of GI systems can improve their efficiency and responsiveness to changing environmental conditions.

Lastly, expanding the geographical scope of GI research to include diverse urban contexts worldwide will help generalize findings and develop guidelines that are applicable across different climatic, socio-economic, and regulatory environments. Comparative studies between cities in different regions can reveal how local conditions influence the performance and adoption of GI practices, providing valuable lessons for global implementation.

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