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Performance Evaluation of Bioretention Systems in Selected Residential Area

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Abstract

Managing stormwater runoff in urban areas is becoming increasingly challenging, resulting in strain on drainage systems, flooding, and environmental degradation. This research examines the effectiveness of bioretention systems in mitigating stormwater runoff in the residential area of Eco Majestic, Semenyih. The EPA SWMM 5.1 model was used to simulate stormwater scenarios both with and without bioretention systems to assess their impact. The findings show that bioretention systems reduce runoff volume by 92.63%, which significantly lowers surface runoff and lowers the risk of floods, while also increasing infiltration rates to ease the strain on conventional drainage infrastructure. Furthermore, a cost-benefit analysis indicates savings from reduced flood damage and other environmental benefits, proving the systems' economic viability. Beyond its effects on hydrology, bioretention systems improve community well-being, biodiversity and urban aesthetics, all of which support sustainable urban development. This study emphasizes the significance of incorporating bioretention systems into urban development to manage stormwater issues and build environmental resilience. Future research should investigate field monitoring, long-term performance in various climates, and the broader ecological and socioeconomic benefits to enhance the use of bioretention systems in urban areas.

1 Introduction

The rapid infrastructural development and expansion of built-up areas in Malaysia over the past few decades have led to an unprecedented increase in impervious surfaces, including pavements, buildings, and highways, which inhibit natural water absorption and overwhelm existing drainage systems, thereby causing flooding in residential areas. Efficient stormwater management methods, including wetlands, detention basins, gross pollutant traps, and bioretention systems, are essential for mitigating these issues. Historically, Malaysia has depended on open channel drainage; however, contemporary methodologies prioritise sustainable methods. Research conducted by Nor et al. [1] indicates that bioretention systems, a prevalent Low Impact Development (LID) technique reliant on infiltration, significantly reduce stormwater runoff and peak flow rates. Multiple studies in Malaysia advocate for the implementation of sustainable stormwater practices in residential zones, such as rain gardens, green roofs, and pervious pavements, which have demonstrated favourable outcomes regarding runoff reduction and enhanced water management [1].

The U.S. EPA Stormwater Management Model (SWMM), specifically SWMM-5 and its specialised Low Impact Development (LID) modules, is extensively utilised to simulate the hydrology and hydraulics of both urban and rural settings. This model enables engineers and planners to evaluate the efficacy of various green infrastructure methods in managing runoff and reducing pollution [2], [3]. SWMM is capable of simulating both individual storm occurrences and prolonged continuous scenarios. This makes it an effective tool for monitoring the quantity and quality of stormwater runoff, thereby providing extensive information on the effectiveness of stormwater management systems over time [3]. The bioretention system refers to the practice of mitigating runoff by temporarily storing water in a storage area until it is discharged through the soil layers into the urban drainage system. Mah et al. [4] explained that a bio-retention system is considered to perform adequately in managing surface water runoff, as verified by extensive studies conducted under both laboratory and field conditions. They can retain substantial runoff and contaminants on-site, enhance surface water quality, reduce specific pollutants in the water, and promote biodiversity [5]. Nor et al. [1] assert that any open space can integrate green infrastructure with bio-retention to mitigate stormwater runoff by facilitating natural processes. Bioretention is a method for mitigating stormwater runoff volume. Nevertheless, there are extensive debates over the advantages and disadvantages of bio-retention development, as noted by MSMA [6].

Numerous research studies indicate that sustainable stormwater practices, such as rain gardens, bioretention systems, green roofs, and pervious pavements, have to be implemented in residential areas. Surfaces that are impermeable to water are more prevalent in rapidly expanding residential zones, exacerbating stormwater runoff issues and increasing the risk of flooding [7]. The designated study location for this research is Eco Majestic in Semenyih, a residential locality with a history of flooding. Residential areas require an efficient and sustainable stormwater management system. The rising demand for sustainable solutions necessitates a comprehensive understanding of how the installation of bioretention systems affects stormwater runoff, enabling the development of effective flood prevention measures. This study aims to model and simulate the design of a bioretention system using the Environmental Protection Agency's Storm Water Management Model (EPA-SWMM) to ensure an accurate representation of hydraulic and hydrologic dynamics in the designated area.

This study aims to evaluate the efficiency of bioretention systems in reducing stormwater runoff volume and peak flow in residential areas. It compares hydrological outcomes with and without bioretention systems, quantifies potential flood risk mitigation, and conducts a cost-benefit analysis to assess economic feasibility and long-term sustainability. This establishes a comprehensive approach for designing sustainable urban drainage systems. Researchers have determined that the objectives of the system significantly influence the expenses associated with designing, implementing, and maintaining bioretention systems [8]. This study will illustrate that, despite differing initial building expenses, bioretention systems offer long-term economic sustainability with reduced operational and maintenance costs compared to conventional infrastructure.

2 Methodology

The research technique for LID and hydrological modelling will employ a systematic approach—defining the problem, establishing objectives, and delineating the scope—with an emphasis on LID methods, cost-benefit analyses, and hydrological effects. This involves an examination of pertinent literature and the Malaysian Urban Stormwater Management Manual (MSWM) to compare contemporary methods with local regulations. Rainfall data from the Department of Irrigation and Drainage (DID) is collected, cleaned, verified, and prepared for use in hydrological modelling. The modelling software has been used as an input to simulate urban runoff, infiltration losses, and other processes. The EPA-SWMM Version 5.1 simulation is then used to model and simulate scenarios involving stormwater runoff, considering various variables such as the presence or absence of bioretention systems and varying rainfall amounts. Graphs serve to illustrate model outputs, including infiltration loss, runoff quantities, and flood hazards. A cost-benefit analysis will substantiate a comparative study of scenarios with and without LID interventions to assess economic viability. The findings will ultimately be analysed, synthesised, and compiled into a report with actionable recommendations for enhancing stormwater management.

2.1 Study Area

The research focused on the Eco Majestic residential area in Semenyih, exploring specific elements of the community. Nestled within the green surroundings of Semenyih, Eco Majestic offers a unique residential environment that blends contemporary living with environmentally conscious design principles. This residential complex provided a distinctive setting for investigating various aspects of the project. Fig. 1 displays a map of the study area.

The study area consists of 121 residential houses. It covers approximately 83,378.43 m^2, equivalent to 8.337843 hectares, with coordinates of 2.911470 N, 101.840108 E. According to DID [6], bioretention systems are typically the best option for collecting and managing runoff from small catchments with less than 1.0 hectare of impermeable area.

Fig. 1 *Study area from Google Maps*

2.2 Rainfall Data

This study primarily uses rainfall data, specifically daily rainfall measurements. The data spans from April 2023 to December 2023, which is considered the peak period for rainfall in the study area. This timeframe was chosen because it represents the months when the location typically receives the highest amount of rainfall, providing a comprehensive overview of the area's precipitation patterns. Analysing data from this peak period allows for a more accurate assessment of the effectiveness of bioretention systems in managing stormwater runoff. By focusing on daily rainfall data, the study can capture detailed fluctuations and trends in precipitation, which are crucial for understanding the performance of stormwater management practices. This detailed data helps in evaluating the capacity of bioretention systems to handle varying volumes of runoff, ensuring their reliability and efficiency during periods of intense rainfall.

2.3 Model Development

This research employed the SWMM 5.1 hydrology model to quantify runoff volumes and identify the factors contributing to runoff in the designated catchment area. To determine the effectiveness of bioretention systems in achieving the proposed goals, further research was conducted on the changes that occurred when rainfall of varying intensities was simulated. Fig. 2 illustrates a diagram of the research area for SWMM 5.1 modelling. The region is partitioned into eight smaller sub-catchments, each connected to its respective junction and outfall. This information, derived from the EPA-SWMM tutorial, was employed to determine the parameters required for simulation. The EPA-SWMM modelling software must then integrate with the research area to accurately depict it. This phase facilitates the accurate representation of sub-catchments and the precise positioning of rain gauges, contingent upon the exact location of the research area. To ensure the simulation operates effectively, it is essential to include connectors, conduits, and outfalls within the study area. The meticulous configuration of these elements facilitates a comprehensive simulation that accurately reflects the hydrological dynamics of the area, hence permitting a more precise evaluation of the bioretention system's efficacy.

Moreover, the integration of these aspects facilitates the creation of a functional model that can simulate many stormwater scenarios, yielding significant insights for enhancing stormwater management. Table 1 below presents a comprehensive list of each sub-catchment together with its corresponding connection to a junction or directly to the outfall.

Upon finalising the design in the modelling program, the data for each element is subsequently entered according to values derived from prior research, Google Earth measurements, and SWMM's suggested values. This rigorous method ensures the precise depiction of all elements within the model. The proper organisation and positioning of these parts enable the simulation of hydrological processes and the assessment of interactions between the bioretention system and the larger drainage network. Precise data entry and organisation provide a comprehensive simulation, permitting an exhaustive assessment of the bioretention system's efficacy and its influence on stormwater management in the research region.

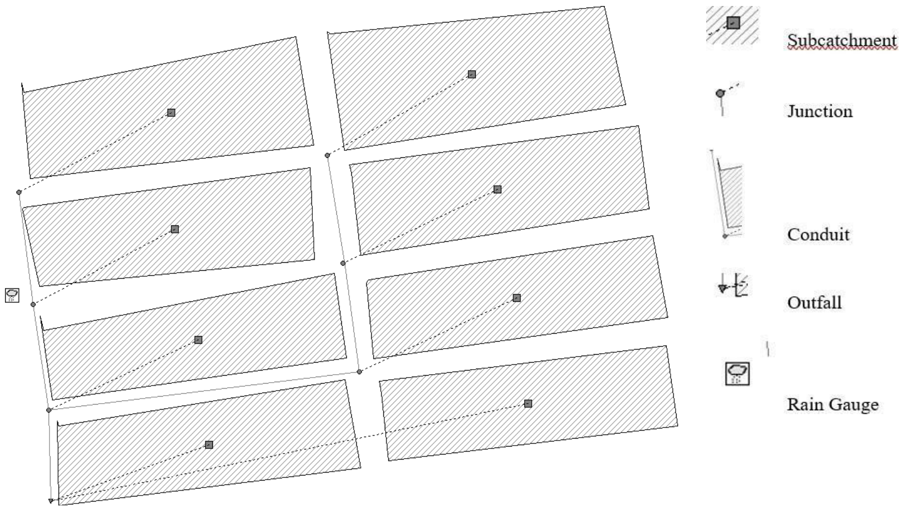


Fig. 2 *Drawing of the catchment area*

Table 1 *Sub catchments with their junction, conduits and outfall*

Sub catchment	Junctions	Conduits	Outfall
S1	J4	C3	Out2
S2	J5	C3	
S3	J6	C4	
S4	-	-	
S5	-	-	
S6	J3	C5	
S7	J2	C2	
S8	J1	C1	

2.4 LID: Bioretention System

For the bioretention system simulation in SWMM to accurately reflect real-life conditions, it is necessary to provide certain important details. It is essential to collect accurate geometric data regarding the bioretention area, including its surface area, form, dimensions, and arrangement. This information is essential for assessing the stormwater runoff capacity and processing efficiency of the system. Secondly, the characteristics of the designed soil media in the bioretention basin must be determined, emphasising aspects such as porosity, infiltration rates, and hydraulic conductivity. These attributes affect the system's capacity to filter pollutants, enhance infiltration and evapotranspiration, and regulate water movement through the soil. Table 2 below presents the parameters of the bioretention system.

Based on the requirements outlined in MSMA, previous research, such as Nor et al. [1], is utilised to describe the bioretention system's features, along with suggestions from the SWMM 5.1 software. A berm height of 300mm is chosen, aligning with the MSMA's recommended range of 150mm to 300mm for effective stormwater management. Each property input is important because it has a direct impact on the bioretention system's ability to control surface runoff by regulating flow rates and enhancing infiltration. In many meteorological circumstances and urban environments, the system's efficacy depends on carefully analysed elements, such as plant selection, soil characteristics, and hydraulic conductivity. According to MSMA recommendations, a bioretention system should have a minimum width of 4 meters and an optimal length-to-width ratio of 2:1. The optimal location for the bioretention system is adjacent to the impermeable surfaces bordering the roadway.

Table 2 *Bioretention system's parameter values*

Parameter	Value
Berm Height (mm)	300
Vegetation Volume Fraction	0.1
Surface Roughness (Manning)	0.08
Soil Thickness (mm)	600
Porosity (volume fraction)	0.5
Conductivity (mm/h)	10
Storage Thickness (mm)	300

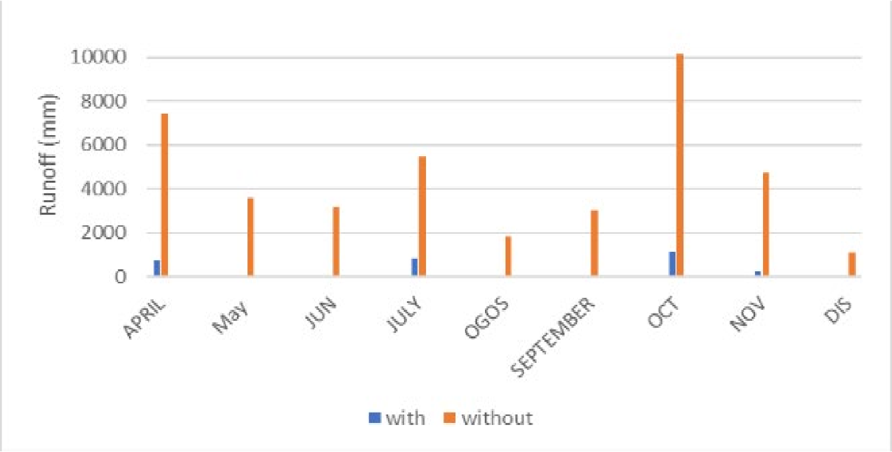
3 Results and Discussion

A comparative analysis is conducted by contrasting results between different scenarios: with and without a bioretention system. This approach enables the determination of the bioretention system's effectiveness by calculating the percentage reduction in surface runoff, flood losses, and infiltration depletion. To calculate the percentage reduction in volume, according to Yang & Chui [9], the reduction in the runoff volume was determined using the equation below:

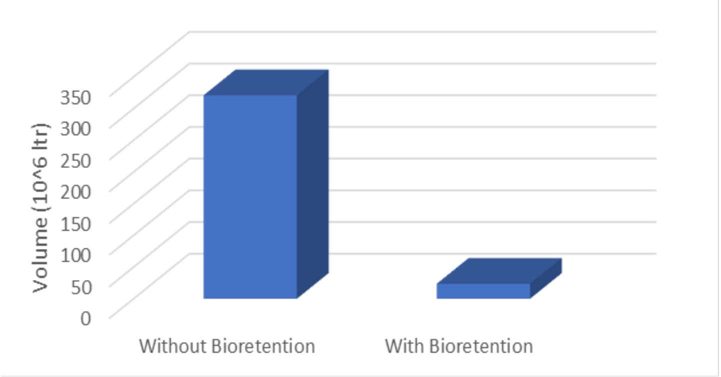
$$R_{vt} = \frac{v_o - v_b}{v_o} x100 \qquad (1)$$

3.1 Surface Runoff and Flooding Loss

The simulation results show that installing a bioretention system in the area significantly reduces surface runoff compared to what would happen if the system weren't present. According to Shafique [7], numerous research studies have consistently demonstrated that bioretention systems are an effective means of managing stormwater runoff in cities. Surface runoff is significantly greater in the absence of the bioretention system than in its presence, with the most pronounced disparities recorded in April 2023 and October 2023. This trend continues across all months, underscoring the significant potential of bioretention systems in mitigating surface runoff. Furthermore, a notable disparity exists between flooding losses with and without the bioretention system. Flooding loss, as described in SWMM, refers to the volume of water that exceeds the capacity of the drainage system and escapes from the model network, signifying potential surface flooding in the study area. The evident disparity arises from the bioretention system's ability to manage rainwater efficiently, diminishing runoff and enhancing infiltration. Bioretention systems mitigate immediate surface runoff by catching and storing excess rainfall, thereby promoting slow soil infiltration or evaporation. Zhang & Shibata [10] assert that this systematic strategy mitigates pressure on drainage systems during heavy rains, thereby reducing the risk and effects of flooding in metropolitan areas. Fig. 3 presents a comparison of surface runoff between the two scenarios across several months, as well as the flooding losses associated with each scenario and the monthly percentage reductions in both runoff and flooding losses.



(a)



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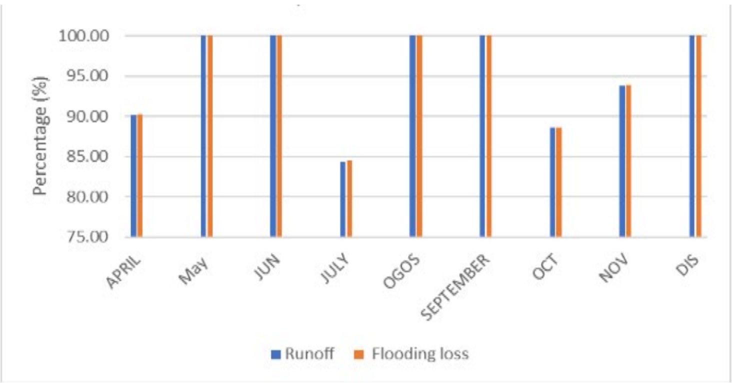


(c)

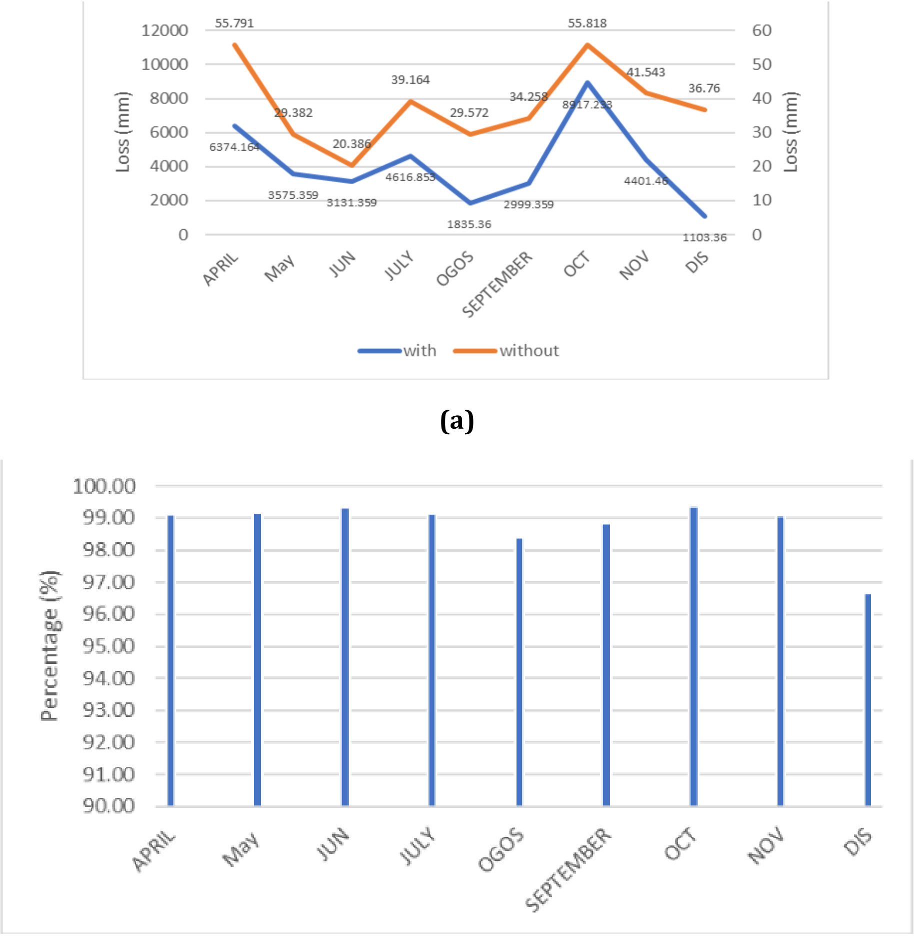
Fig. 3 *(a) Comparison of surface runoff; (b) Comparison of the flooding loss, and (c) Percentage reduction of runoff and flooding loss by months*

The analysis indicates a notable reduction in runoff volume percentage, measured at 92.63%. This significant decrease highlights the bioretention system's efficacy as an exceptionally effective approach to stormwater management. Significantly, the most substantial decreases in floods and runoffs, approaching 100%, occur between May and September. Throughout this period, the bioretention system demonstrates exceptional efficacy, presumably due to advantageous operational conditions. Conversely, July exhibits a lesser decrease, notably in flooding losses, suggesting possible constraints under harsh weather conditions or heightened precipitation. According to a recent study by Wicaksono et al. [11] in East Java, Indonesia, a bioretention system was demonstrated in the field, showing an average reduction of up to 83% in runoff. Similarly, Nazarpour et al. [12] highlighted that the bioretention system could achieve volume reduction rates that range from 50% to 98% in the study field. The results from these studies align with the outcome of the current study, where a 92.63% reduction in runoff volume was observed.

3.2 Infiltration Loss

The simulation findings indicate a considerable difference that emphasises the efficiency of bioretention devices for improving penetration rates. According to Bhuiyan et al. [5], this illustrates the system's potential to promote natural rainwater infiltration into the native soil, a crucial process for mitigating runoff. Bioretention systems use specialised soil mixtures and vegetation to improve water absorption, effectively mimicking natural hydrological processes. This method creates favourable conditions for groundwater recharge, which explains the observed increase in infiltration rates in the bioretention model. It is essential that infiltration rates remain sufficiently high to avert floods and possible ponding problems, as emphasised by Vijayaraghavan et al. [8]. Fig. 5 shows a comparison of the infiltration losses in the two scenarios over several months, along with the percentage decrease in infiltration loss each month.

It can be observed that the bioretention system exhibits high efficiency from April to November, consistently attaining depletion rates of nearly 99%. This signifies that infiltration loss was effectively managed during this period. In December, there is a significant decline, with the rate falling just above 90%. Seasonal fluctuations, possibly influenced by changes in precipitation or lower temperatures affecting infiltration processes, may contribute to the decline in system performance. The system functions efficiently for most of the year; nevertheless, the diminished efficacy in December suggests a need for further examination or adjustments to ensure continuous optimal performance throughout all seasons. However, the importance of considering snow management practices in cold regions is further emphasised in research by Gougeon et al. [13], which models bioretention cell performance during snowmelt. Unlike in tropical conditions, where rainfall intensity and soil permeability dominate system efficiency [14], bioretention systems in colder climates must be evaluated based on their ability to handle slow infiltration processes induced by snowmelt. This differentiation highlights the need for region-specific engineering strategies when optimising bioretention performance.



(a)

(b)

Fig. 4 *(a) Comparison of infiltration loss; and (b) Percentage depletion of infiltration loss by months*

3.3 Cost-Benefit Analysis

The costs of planning, installing, and maintaining bioretention systems vary significantly depending on their intended use [8]. Bioretention systems are cost-effective relative to other Best management Practices (BMPs), as stated by DID [6]. The cost of these systems is influenced by multiple factors, including the composition of the soil medium and the choice of plants. Table 3 presents the cost analysis for the initial building and maintenance of the bioretention system for this study.

A landscape design measuring 74.32 m^2 was projected to cost approximately US$2,399.55 [1]. The annual maintenance expenses, generally ranging from 5% to 7% of the construction cost, as indicated by the US Environmental Protection Agency (USEPA) in 1999, were determined to be US $51.66 for the bioretention system in this study. The total anticipated building expenses amounted to US $1033.28. Although these statistics represent initial expenditures, a properly maintained bioretention system, which can last up to 20 years according to MSMA criteria, can reduce labour and maintenance costs [1]. Bhuiyan et al. [15] indicated that the primary expenses associated with direct flash flood damage are incurred in residential zones, potentially amounting to RM 2 million. The elevated expense is attributable to the costly road upkeep and necessary home building repairs. Establishing a bioretention system can help mitigate maintenance expenses, thereby alleviating the financial strain on both the government and its citizens. In addition to economic factors, bioretention systems offer advantages from both social and environmental perspectives

Table 3 *Estimated initial cost of bioretention system*

Bioretention system cost [1]	US \$2399.55 for 74.32 m^2
Bioretention system of 32 m^2	32.29/m^2 x 32 m^2 = US \$1033.28
Maintenance [1]	5% x US \$1033.28 = US \$51.66

Table 4 *Benefit analysis from a social and environmental point of view*

Benefit Category	Social Benefits	Environmental Benefits
Flood control	A bioretention system can effectively help reduce the flood risk [12].	Mitigates peak stormwater flows.
Aesthetic value	Enhance urban aesthetics and community well–being [7].	Increases biodiversity by providing habitat.
Property value	Enhances property values through improved surroundings.	Enhances the overall appeal of the neighbourhood.
Water quality	Minimises potential health risks from pollutants.	Enables some suspended particles to settle, promoting the removal of pollutants [10].

Table 4 above illustrates the advantages of implementing bioretention systems in residential zones. The table highlights the social and environmental benefits of bioretention systems across four categories: flood control, aesthetic value, property value, and water quality. For flood control, bioretention systems offer significant social benefits by reducing flood risks in urban areas. This enhances community safety, minimises property damage, and improves overall resilience, as noted by Nazarpour et al. [12] and Khadir et al. [16]. In terms of the environment, these systems lower the highest levels of stormwater runoff during heavy rain. This reduces the stress on urban drainage systems and prevents soil erosion, which is beneficial for aquatic ecosystems. In terms of aesthetic value, bioretention systems contribute to urban beautification, enhancing the community’s quality of life and promoting mental well-being. Shafique,M. [7] highlight how green infrastructure fosters a sense of community pride and encourages outdoor activities. From an environmental perspective, these systems increase biodiversity by providing habitats for various species, contributing to ecological balance and sustainability in urban settings. When considering property value, the social benefits are evident in how bioretention systems improve neighbourhood surroundings, boosting property desirability and value. This encourages investment in community development and enhances residents' socioeconomic status. Environmentally, these systems improve the visual and ecological appeal of neighbourhoods by aligning with greener real estate practices and promoting sustainable urban development. Finally, regarding water quality, bioretention systems play a vital role in minimising health risks by reducing pollutants in stormwater and ensuring access to cleaner, safer water for the community. This improvement in public health has a significant benefit for urban populations. Environmentally, these systems act as natural filters, allowing suspended particles to settle and removing pollutants from the runoff. As highlighted by Zhang & Shibata [10], this process improves downstream water quality, benefiting aquatic ecosystems and reducing the environmental impact of urban runoff. This comprehensive approach demonstrates how bioretention systems address both social and environmental challenges, promoting sustainability and community well-being in urban areas. This demonstrates that the effectiveness of bioretention systems aligns with sustainability goals by enhancing biodiversity, reducing urban heat, and mitigating air pollution, thereby supporting cities in adapting to the impacts of climate change [7], [8].

4 Conclusion

In summary, this study carefully examined the use and effectiveness of the bioretention system in reducing stormwater runoff in the Eco Majestic, Semenyih residential neighbourhood. By developing and evaluating bioretention systems, the research effectively met its objectives through thorough modelling and simulation with EPA-SWMM. Through a comparison of scenarios with and without bioretention systems, the study determined the effectiveness of these systems in reducing the risk of flooding and revealed considerable reductions in surface runoff. The findings indicate that infiltration loss was effectively managed, with depletion rates reaching nearly 99% from April to November. However, a decline to just above 90% in December highlights the need for further evaluation to maintain year-round efficiency. This indicated a significant rise in infiltration rates, which lessened the burden on traditional urban drainage systems during periods of excessive precipitation. Furthermore, the bioretention system demonstrated its effectiveness in stormwater management by successfully controlling surface runoff, resulting in a significant 92.63% reduction. The economic feasibility of the bioretention systems was emphasised by the cost-benefit analysis, which also highlighted the systems' potential savings from reduced flood damage and enhanced environmental benefits. In addition, the study considered qualitative aspects such as ecological benefits and community acceptability, demonstrating how bioretention systems improve biodiversity, urban aesthetics, and community well-being. All things considered, these results are consistent with the study's goals, which were to model, simulate, compare, and assess the viability and efficacy of bioretention systems in urban settings as sustainable stormwater management options. Several suggestions have been proposed for future studies to enhance future research outcomes. Future studies should undertake extensive field monitoring and data collection to effectively assess how bioretention systems manage stormwater runoff and mitigate flood risks throughout different phases of Eco Majestic's development. Additionally, research should explore the broader ecological and socioeconomic benefits, alongside the hydrological effects, to provide a comprehensive understanding of the role of bioretention systems in resilient planning and sustainable urban development. Long-term monitoring across various climatic conditions and seasons is also recommended to evaluate the sustained effectiveness of bioretention systems in urban environments.

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Conflict of Interests

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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