Effectiveness of bioretention system and vegetated swale for reducing urban flood risk in equatorial region: a case study in Kuching, Malaysia

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Abstract

One of the main causes of urban inundation is the rise of impermeable surfaces brought on by increasing urbanization. Low impact development (LID) practices have been employed in previous studies to mitigate urban flooding. However, the effectiveness of LID practices in reducing runoff peaks and improving water quality is unknown, especially in the equatorial region. This study explored nine alternative scenarios to evaluate the effectiveness of the bioretention system and vegetated swale using the Storm Water Management Model (SWMM). Using precipitation data of December 2021, the Swinburne University of Technology Sarawak Campus has been chosen as the case study. The findings demonstrated that these two LID practices could significantly lessen urban flooding. Under scenario 7, the combination of 28.4% bioretention system and 11.3% vegetated swale reduced the maximum runoff peaks by 22.98% at Peak A, 24.71% at Peak B, and 24.09% at Peak C. In the meantime, under scenario 7, the implemented LID practice has removed 20.09% of TSS, 19.75% of TP, and 12.26% of TN. It was discovered that runoff peak reduction increases as the area covered by vegetated swale and bioretention system increases. The outcomes showed that bioretention system performed better than the vegetated swale in reducing peak runoff and enhancing water quality. Local authorities can use the findings of this study to offer recommendations for reducing disaster risk, controlling urban flooding, and revitalizing urban areas.

Keywords Storm water management model (SWMM) · Low impact development (LID) · Pollutant removal · Bioretention system · Vegetated swale

Introduction

The urbanization rate in Malaysia has increased rapidly in the past 30 years. In 1950, only 20% of the country's population lived in towns and cities, and 80% lived in rural settlements (Siong, 2008). In 2020, those percentages were almost reversed completely, where 75.1% lived in urban areas, while only 24.8% lived in rural settlements (Trisha 2022; Bernama 2022). Due to increasing urbanization, the landscape of human settlement is changing with significant implications for living conditions, the environment and development. Urban areas are dominated by impervious road pavement and a mass of concrete, and only small green areas are available (Bilgili and Gökyer 2012).

As more impervious surfaces replace natural ones due to rapid urbanization, stormwater management is becoming more vital in urban areas (Vijayaraghavan et al., 2021). Urbanization has modified the ground surface condition, including the amount of vegetation, type of soil, and land use (Bhuiyan et al. 2018). Construction of road pavements, concrete structures, and roofs had increased impervious surfaces, significantly reducing the infiltration rate and capacity. As a result, most of the rainwater was transformed into an excessive surface runoff, which led to flash floods in urban cities, in addition to extreme precipitation and low

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standards for urban drainage infrastructure (Beckers et al. 2013; Zahmatkesh et al. 2015; Islam et al. 2021).

There are a few measures to improve stormwater management in urban areas, and one of them is Low Impact Development (LID). LID is an innovative approach to land planning and design that aims to preserve a site's predevelopment ecological and hydrological function by preserving, enhancing, or mimicking natural processes. LID is able to reduce the impacts of impervious surfaces by storing the excessive rainfall temporarily within the system, hence reducing the discharges and peak flows significantly (Kim and Kim 2021). LID practitioners ensure that the critical functions and advantages that the natural landscape offers are balanced with active human activities through sustainable planning and design (Abduljaleel and Demissie 2021). By thoroughly analyzing the site's hydrology, terrain, soils, vegetation, and water characteristics, the planner or designer can better place buildings and site elements to minimize potential effects by balancing environmental function and human benefits. LID practices have been widely adopted in Europe, the United States of America, and other developed countries since the 1990s (Zeng et al. 2020; Liu et al. 2021).

LID controls including permeable pavement, green roof, bioretention system, vegetated swale, infiltration well/trench, infiltrating wetland, and rain barrel, can be designed to fit its site characteristics (Li et al. 2019; Bae and Lee 2020). Bioretention system and vegetated swale consist of vegetation at the uppermost layer, which will improve and raise the aesthetic, recreational, and real estate values. Besides, bioretention system and vegetated swale have a high potential to improve surface runoff quality (Vijayaraghavan et al., 2021).

Bioretention system consists of four layers: surface layer, soil layer, storage layer, and underdrain layer. The surface layer consists of vegetation, which aids in reducing runoff volume through evapotranspiration and removes pollutants by absorbing them through its roots (Li et al. 2021). The soil layer supplies optimal conditions for plants and microbes, apart from treating accumulated runoff (Zhang et al. 2021). The storage layer stores and may filter the infiltrated runoff, which will flow out of the bioretention system through the underdrain layer. Meanwhile, vegetated swale is a shallow channel covered with vegetation built along the sides of roadways with a flat bottom for passing through the runoff (Leroy et al. 2016). Vegetated swale is popular in managing stormwater runoff as they can be constructed within limited spaces with low construction and maintenance costs (Ekka et al. 2021).

The hydrological effectiveness of bioretention system and vegetated swale have been researched through field and laboratory studies. The previous studies revealed that bioretention system and vegetated swale helped lower runoff,

peak flows, and discharge volumes (Qin et al. 2013; Zhang et al. 2016; Ahiablame and Shakya 2016). Shafique (2016) summarised the results of research conducted by various scientists on the performance of bioretention system applications for sustainable stormwater management in urban areas, including the hydrologic and water quality performances, and concluded that bioretention system could help to mitigate flash flooding and enhance an area's environment. Leroy et al. (2016) also found that vegetated swale's low flow velocity features improved infiltration rates, allowed for the removal of pollutants, and thus improved water quality.

Bioretention system and vegetated swale have been adopted in Malaysia. However, the effectiveness of bioretention system and vegetated swale in improving stormwater management, such as mitigating flash floods, improving stormwater quality, and maintaining the water cycles without enlarging and deepening the existing drainage systems, are still unavailable. Currently, LID controls are designed in accordance with the Urban Stormwater Management Manual 2nd Edition (MSMA2). Unfortunately, MSMA2 does not cover East Malaysia. The checklist released by the Department of Irrigation and Drainage (DID) Sarawak, Urban Stormwater Management (SUStoM) does not provide any detailed calculation for LID controls, especially for bioretention system and vegetated swale. Moreover, when designing the bioretention system and vegetated swale, engineers or developers tend to focus more on selecting vegetation based on aesthetic purposes to improve the surrounding environment rather than accounting for its impact on the LID system.

This study's objective is to assess the effectiveness of bioretention system and vegetated swale in reducing urban flooding in a case study of an urban university. The particular goal is to create a hydrodynamic model utilizing the open-source and free hydrological software Storm Water Management Model (SWMM) to assess the efficacy of vegetated swale and bioretention system under various scenarios. This project intends to enrich LID inundation mitigation research and serve as a guide in managing stormwater runoff and inundation mitigation for watersheds located in equatorial regions.

Study area

The selected study area is the Swinburne University of Technology Sarawak Campus (SUTS), located at the Latitude of 1° 31' 32.99" N and Longitude of 110° 21' 14.99" E, as shown in Fig. 1. SUTS was established in the year 2000, and it is a foreign branch campus located in Kuching, Sarawak, Malaysia. The campus is situated in an urban area nestled

Fig. 1 Selected study area

within commercial and residential areas, 15 min from Kuching city center. The total study area is approximately 6.5 ha (16.5 acres), comprising three main institutional buildings, which include a cafeteria and lecture halls. Apart from that, the campus has a lecture theatre, multi-storey car park, a multipurpose hall, and two blocks of four-storey hostels. The percentage of impervious surfaces within the study area is about 90%.

Kuching is the biggest city on Borneo Island and enjoys the tropical rainforest climate. The temperature in Kuching ranges from 19 to 36 °C, with the average temperature of 23 °C in the early hours of the morning and rising to around 33 °C in the afternoon. Rain may fall nonstop for hours or even days during the Northeast Monsoon between November and March (Kuok et al. 2013). Storms are frequently present together with the rain. Kuching is Malaysia's wettest city and receives much rain all year long (Kuok et al. 2019). In 2022, Kuching experienced total annual rainfall of 4200 mm.

To study the performance of bioretention system and vegetated swale in storing the excess runoff and improving the stormwater quality, the rainfall data of Station 1,403,001, located at Kuching International Airport, was obtained from the Department of Irrigation and Drainage (DID) Sarawak. Since December 2021 received the highest rainfall throughout the year, rainfall data for that month, as depicted in Fig. 2, is employed in this study's modeling.

Methodology

This study examines the effect of bioretention system and vegetated swale on the reduction of surface runoff and infiltration rate using the Storm Water Management Model (SWMM) version 5.1. SWMM is an open-source hydrological modeling program developed by the United States Environmental Protection Agency (US EPA) (Rong et al. 2021). It is widely used for simulations of hydrologic and water quality performances (Wu et al. 2013; Rossman 2015). In 2010, LID functions such as bioretention system and vegetated swale were included in SWMM to investigate the water storage capacity and quality improvement, especially after heavy rainfall (Lisenbee et al. 2021).

Figure 3 presents the flow chart of the methodology for this research project. The topographical map is used as the backdrop in SWMM to accurately locate the catchment, subcatchments, junction nodes, outfall nodes and stormwater conduits, to model the drainage system in SWMM. The project layout of the SWMM model is presented in Fig. 4. After going through a series of trial and error processes, the optimal parameters of surface, soil, storage, and drain layers were obtained for both bioretention system and vegetated swale, as tabulated in Table 1.

Considering the feasibility and representativeness of LID practices for urban inundation mitigation, bioretention system and vegetated swale were selected to simulate and investigate their effectiveness for urban inundation mitigation. Table 1 presents the parameters for bioretention
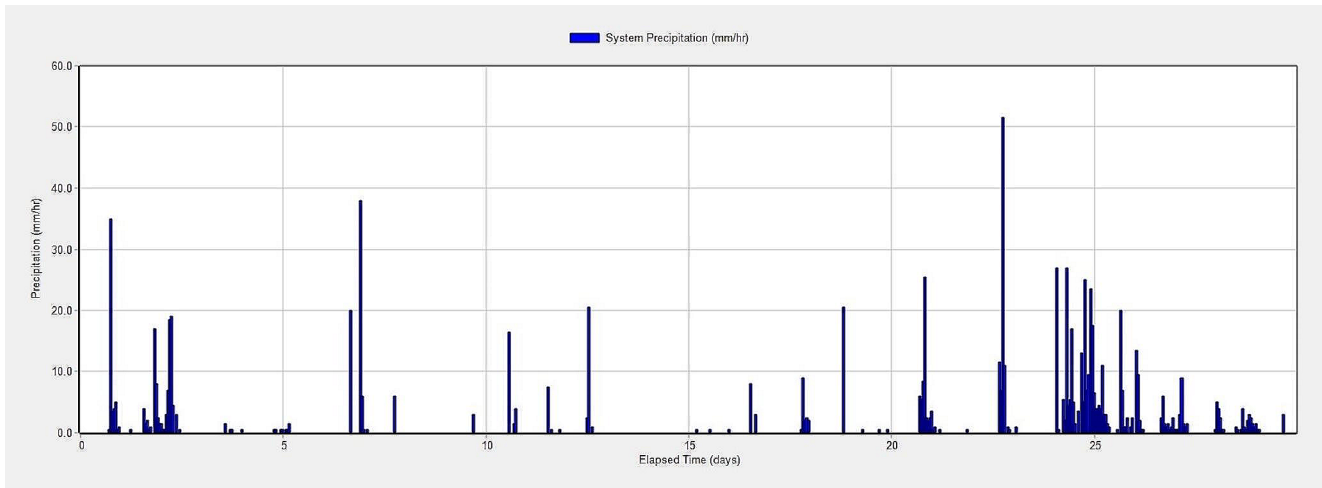
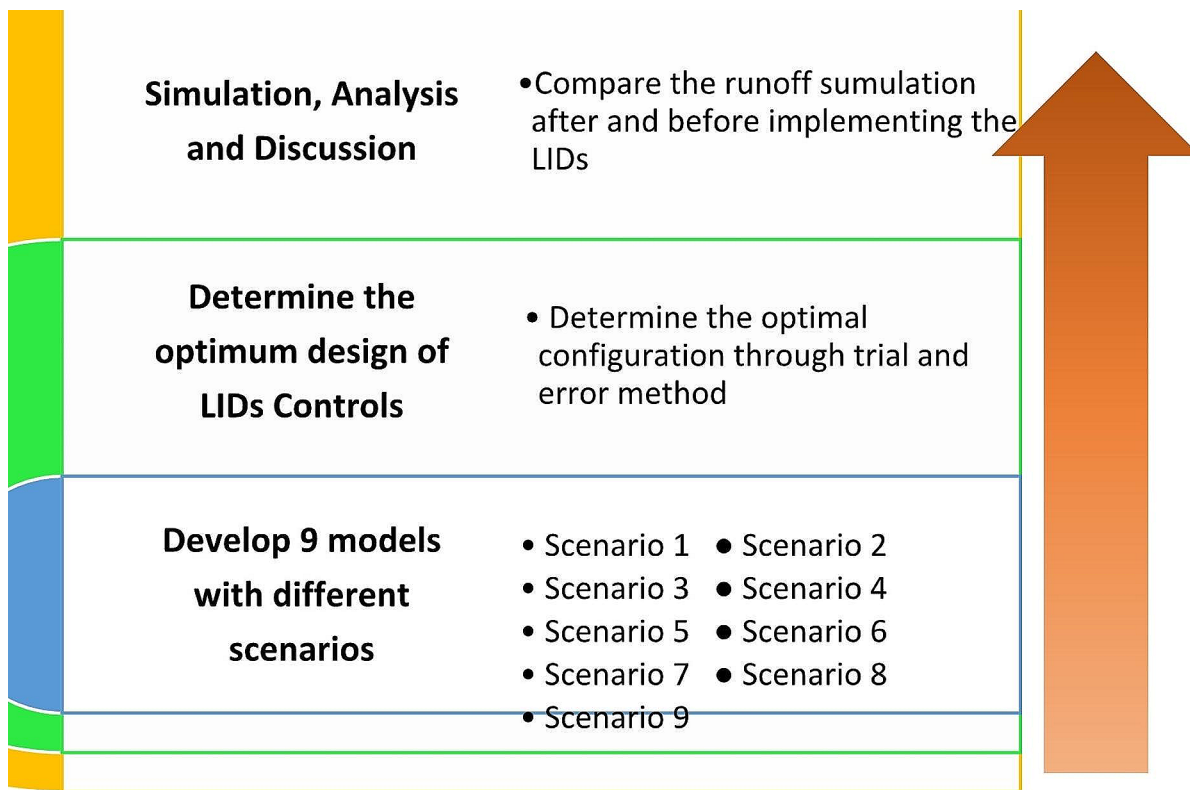Fig. 2 The daily precipitation in December 2021 (Kuok and Chiu 2022)

Fig. 3 Flow chart of methodology

system and vegetated swale, which were designed based on SWMM and LID requirements (Chui et al. 2016; Kong et al. 2017). The total area of available unoccupied spaces within the campus compound that can be converted into bioretention system is 28.4%. Meanwhile, the drain covers 11.3% of the entire surface and can be placed with a vegetated swale.

Figures 5 and 6 present the probable locations for installing the bioretention system and vegetated swale within the campus area.

Hence, a series of proportions for bioretention system and vegetated swale were devised to test their efficacy in lowering the runoff peak. The following eight scenarios
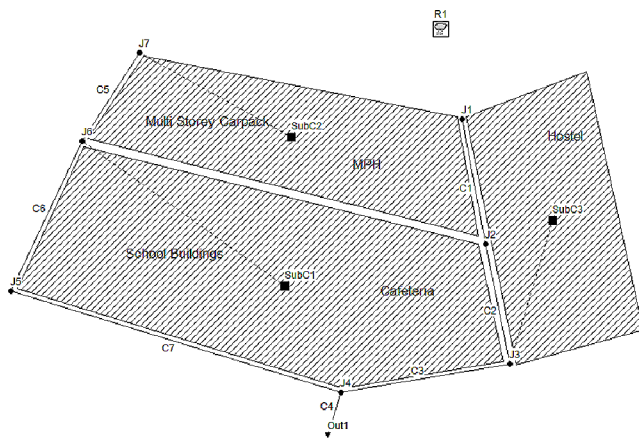
Fig. 4 Model of the study area using SWMM

Table 1 Optimal parameters values

Layer	Parameter	Unit	Bioretention Cell	Vegetated Swale
Surface	Berm Height	mm	300	200
	Vegetation Volume Fraction	-	0.2	0.2
	Surface Roughness (Manning's n)	-	0.05	0.05
	Surface Slope	%	1	0.5
	Swale Side Slope	run/rise	-	2
Soil	Thickness	mm	300	-
	Porosity	volume fraction	0.5	-
	Field capacity	volume fraction	0.2	-
	Wilting point	volume fraction	0.1	-
	Conductivity	mm/hr	6.6	-
	Suction head	mm/hr	170	-
Storage	Thickness	mm	500	-
	Void Ration	-	0.4	-
Drain	Flow Coefficient	-	0	-
	Flow Exponent	-	0.5	-
	Offset	mm	6	-

with bioretention system and vegetated swale combination were developed.

- Scenario 1 (S1): No LID.
- Scenario 2 (S2): 5% bioretention system + 5% vegetated swale.
- Scenario 3 (S3): 10% bioretention system + 10% vegetated swale.
- Scenario 4 (S4): 15% bioretention system + 10% vegetated swale.
- Scenario 5 (S5): 20% bioretention system + 10% vegetated swale.
- Scenario 6 (S 6): 25% bioretention system + 10% vegetated swale.
- Scenario 7 (S7): 28.4% bioretention system + 11.3% vegetated swale.
- Scenario 8 (S8): 28.4% bioretention system.
- Scenario 9 (S9): 11.3% vegetated swale.

Scenario S1 will be used as a benchmark to determine peak runoff and water quality when no LID control was adopted. The results obtained will be compared with scenarios S2 to S9, to analyze the impact of bioretention system and vegetated swale on the surface runoff generation and water quality improvement.

Besides, this study also evaluates the performance of bioretention system and vegetated swale in improving the water quality. The pollutants considered for this study are total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). Table 2 presents the Event Mean Concentration (EMC) values of pollutants based on land use obtained from MSMA2 (2012). The pollutant values that input into the developed model to evaluate the effectiveness of bioretention system and vegetated swale in treating the pollutants are under Urban land use with 85 mg/l of TSS, 1.20 mg/l of TN, and 0.13 mg/l of TP.

Results and discussion

The rainfall input data used in this study is 30 h of continuous rain that occurred on the 25th and 26th of December 2021. The outflow hydrographs were generated at the interval of every 15-minute time step. Figure 7 presents the generated hydrograph comprising three peaks corresponding to the storm event. Results revealed that both LIDs are able to reduce the runoff peaks by storing the excess water temporarily. It was observed that the bioretention system is more significant in providing better urban inundation mitigation than vegetated swale. This can be seen in Fig. 7, where the peak runoff generated under scenario 8 with a bioretention system is significantly lower than the peak runoff generated by scenario 9 with a vegetated swale.

Nine scenarios were investigated to better identify the effectiveness of the bioretention system and vegetated swale in mitigating the flood. Results demonstrated that under the S2 scenario with a combination of 5% bioretention system and 5% vegetated swale, the runoff peaks, as indicated in the red line referring to Fig. 7, were significantly reduced compared to scenario S1, which is referred to as benchmark without any LID control. The runoff peaks are further reduced as the percentage of bioretention system increased from 5 to 28.4%, and vegetated swale increased from 5 to 11.3%. The runoff peak reduced to the lowest level under scenario S7 with the combination of 28.4% bioretention system and 11.3% vegetated swale.
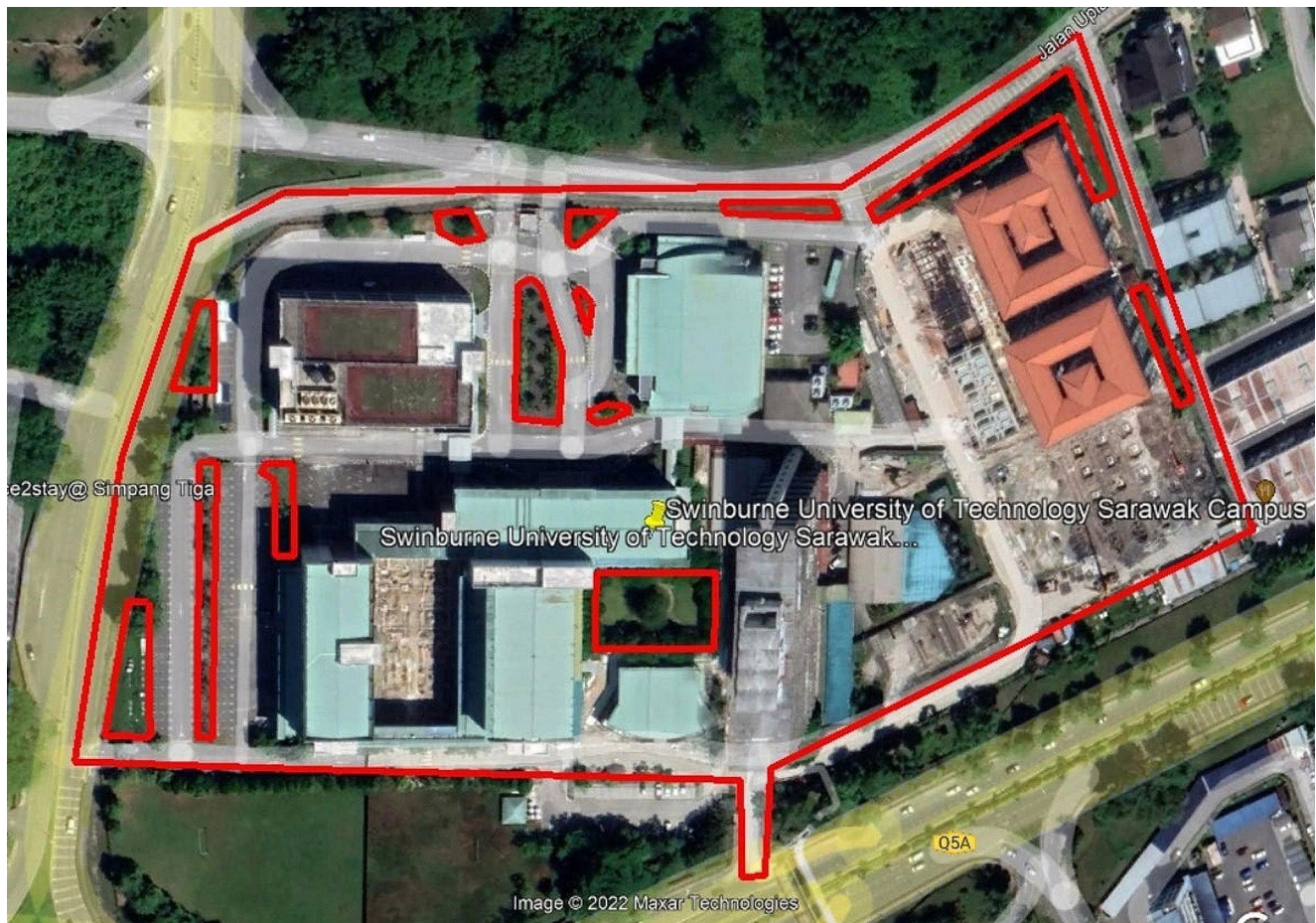
Fig. 5 Red-lined polygons showing the probable location of the bioretention system within the campus area

Meanwhile, the percentage of peak reduction with different scenarios was calculated using Eq. (1). Table 3 presents the peak discharge values for different scenarios.

$$Percentage\ of\ reduction\ (\%) = \\ \frac{Peak\ Run\ off - Reduced\ Peak\ Runoff}{Peak\ Runoff}\ X\ (100) \qquad (1)$$

The simulated runoff consists of three peaks, namely Peak A, Peak B, and Peak C. Without LID, the peaks were yielded to 1.97m³/s, 2.10m³/s, and 1.32m³/s at Points A, B and C, respectively. The peaks were reduced for 5.04%, 4.96%, and 4.81% at Points A, B, and C, respectively, after introducing 5% of bioretention system and 5% of the vegetated swale under scenario S2. As the bioretention system and vegetated swale increased to 10% as indicated in scenario S3, the runoff peaks were further reduced to 7.83%, 8.56%, and 8.42% for Peaks A, B, and C, respectively. The runoff peaks were further reduced to 11.84% at Peak A, 12.91% at Peak B, and 12.67% at Peak C under scenario S4, which consists of 15% of Bioretention system and 10% of vegetated swale.

The peaks at Points A, B, and C, respectively, were lowered by 15.91%, 17.26%, and 16.91% after installing a 20% bioretention system and a 10% vegetated swale under scenario S5. The runoff peaks A, B, and C were further decreased to 22.98%, 24.71%, 24.09%, respectively, as the bioretention system grew to 25% and vegetated swale grew to 10% under scenario S6. With 28.4% of bioretention system and 11.3% of vegetated swale as indicated in scenario S7, the runoff peaks were further lowered to 24.51% at Peak A, 25.55% at Peak B, and 24.98% at Peak C.

Under scenario S8, which only consists of 28.4% of bioretention system, the runoff peak at A was reduced to 20.17%. Meanwhile, the peaks at B and C are also lowered to 21.77% and 21.27%, respectively. Results revealed that the vegetable swale is ineffective in reducing the runoff peak. These were proven with only 3.12%, 1.84%, and 1.56% reduction for Peaks A, B, and C, respectively, with the adoption of 11.3% of vegetated swale under scenario S9.

The performance of bioretention system and vegetated swale in pollutant removal was investigated in this study. Only three scenarios were chosen for evaluation: scenario S7 with 28.4% bioretention + 11.3% vegetated swale;
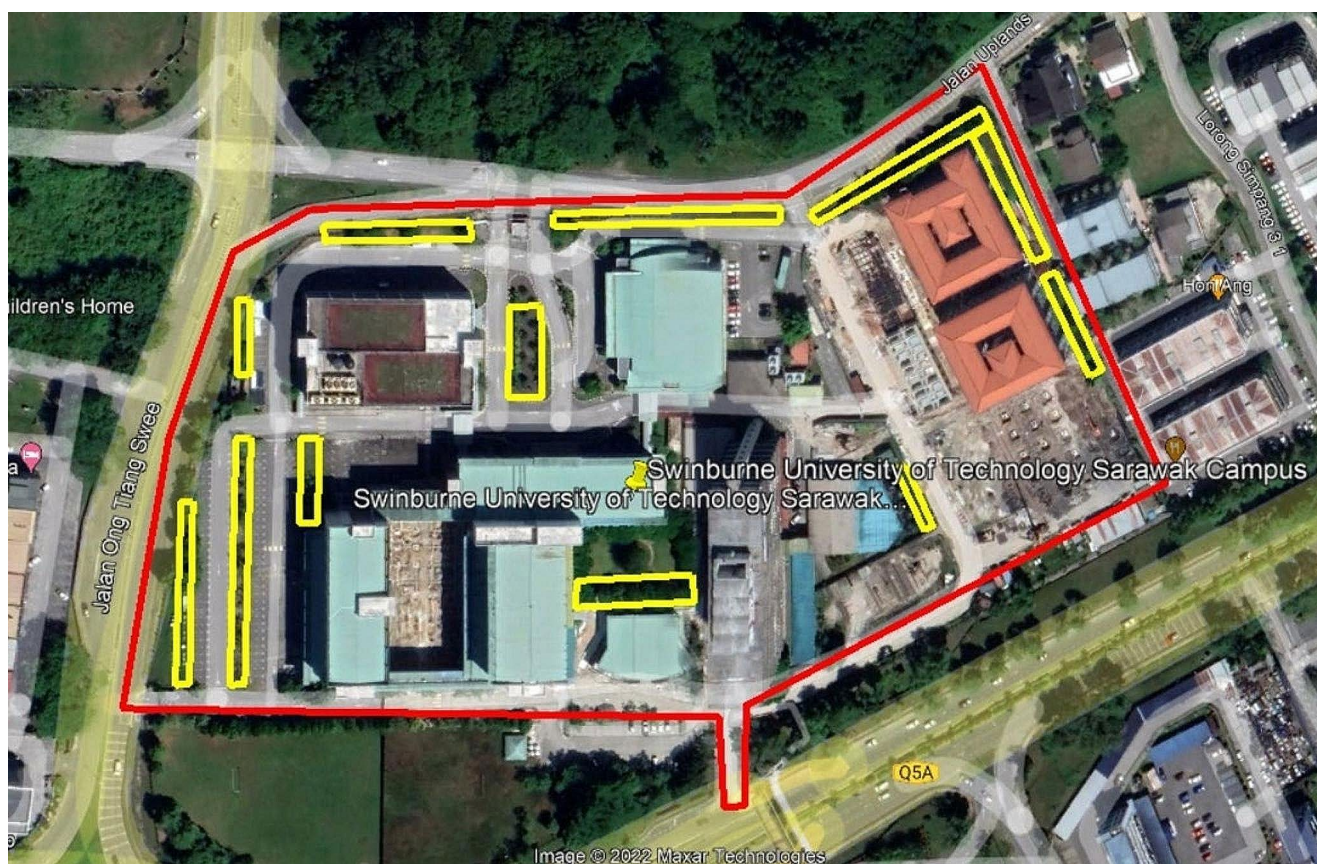
Fig. 6 Yellow-lined polygons show the probable location of vegetated swale within the campus area

Table 2 Summary of pollutants and land uses used (MSMA2, 2012)

Land Use	TSS (mg/l)	TN (mg/l)	TP (mg/l)
Residential	128	4.21	0.34
Commercial	122	4.84	0.32
Urban	85	1.20	0.13
Road	80	2.25	0.16

scenario S8 with 28.4% bioretention and scenario S9 with 11.3% vegetated swale. The pollutants analyzed were total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The performance was evaluated by comparing the TSS, TN, and TP values before and after treatment using LIDs. Table 4 shows the TSS, TP, and TN values before and after treatment.

The result revealed that the TSS values were lowered by 20.09%, 16.02%, and 12.24% for scenarios S7, S8, and S9, respectively, as presented in Fig. 8. TN values, the results also demonstrated that the implementation of LIDs also removed the pollutant by 20.00%, 15.83%, and 12.50% for scenarios S7, S8, and S9, respectively. Meanwhile, the results also showed that the combination of bioretention system and vegetated swale under scenario S7 had successfully lowered the TP by 23.08%. S8 with bioretention system and

scenario S9 with vegetated swale were also able to reduce the TP by 15.38% and 15.38%, respectively.

The scenario with the highest pollutant removal percentage is S7, followed by S8 and S9. Based on the water quality simulation result, vegetated swale performs better than bioretention system in terms of pollutant removal.

Conclusion

This study constructed a hydrological model using SWMM incorporated with bioretention system and vegetated swale LIDs controls. The model was used to examine the effectiveness of LID controls in reducing runoff peaks and mitigating flooding issues in urban areas under different scenarios. It was discovered that the LID controls are able to lower the peak runoff and enhance the water quality. The outcomes demonstrated that bioretention system outperformed vegetated swale in lowering peak runoff and improving water quality. Additionally, it was discovered that runoff peak reduction increases as the area covered by vegetated swale and bioretention system increases. Through infiltration, the LID practices used in this study can store part of the excess rainfall. This would avoid constructing a more extensive
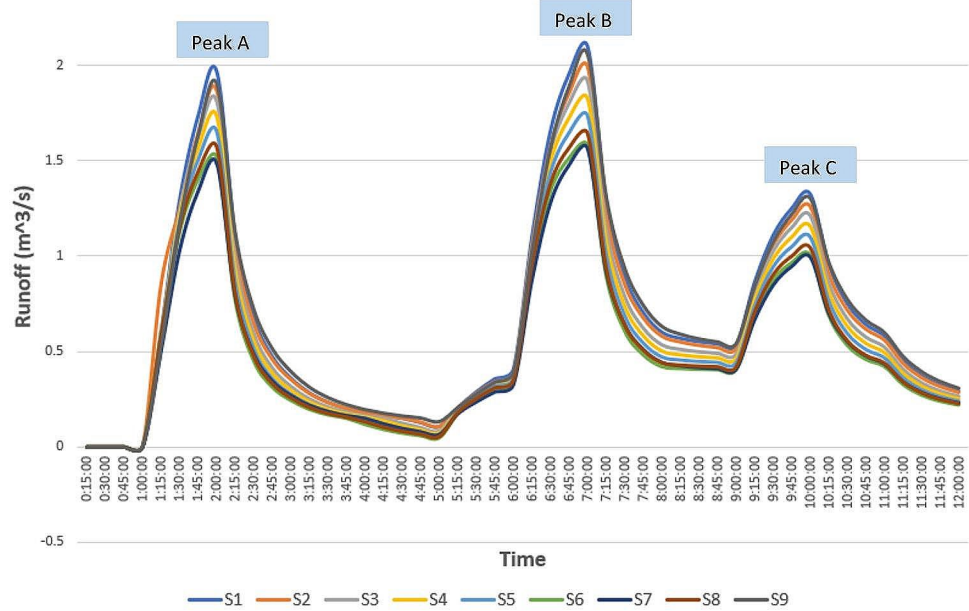
Fig. 7 Simulated runoff for different scenarios

Table 3 Peaks values reduction for scenarios S2, S3, S4, S5, S6, S7, S8 and S9 compared to S1

	S2	S3	S4	S5	S6	S7	S8	S9
Peak A (%)	5.04	7.83	11.84	15.91	22.98	24.51	20.17	3.12
Peak B (%)	4.96	8.56	12.91	17.26	24.71	25.55	21.77	1.84
Peak C (%)	4.81	8.42	12.67	16.91	24.09	24.98	21.27	1.56

Table 4 Pollutants values before and after being treated by LIDs

	Without Treatment	S7	S8	S9
TSS (mg/l)	85.00	67.92	71.38	74.60
TN (mg/l)	1.20	0.96	1.01	1.05
TP (mg/l)	0.13	0.10	0.11	0.11
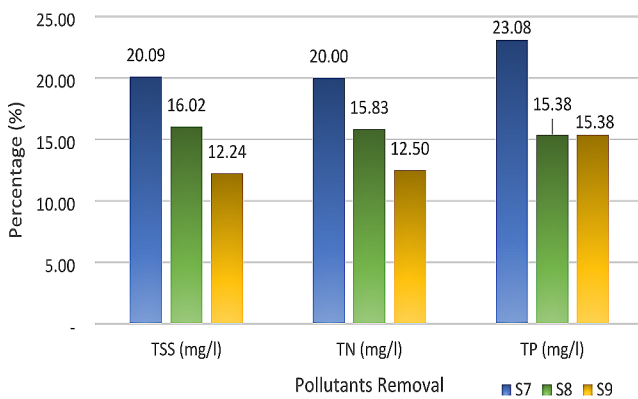
Fig. 8 Percentage of pollutant removal for TSS, TN, and TP

drainage system and is very cost-effective in reducing the flood risk within the study area. If the study area has significant flooding in the future, additional mitigating measures must be implemented. This conclusion may not hold in other areas, but policymakers can apply it locally.

Declarations

We here submitted the manuscript entitled "Effectiveness of Bioretention System and Vegetated Swale for Reducing Urban Flood Risk in Equatorial Region: A Case Study in Kuching, Malaysia" to be considered for publication. We declare that this is our original research work.

Conflict of interest There is no conflict of interest between authors.

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