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Evaluation of low impact development and best management practices on peak flow reduction using SWMM

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Abstract. Rapid urbanisation has caused an increased in peak discharge that conventional drainage systems cannot adequately handle. Low Impact Development (LID) practices are becoming a new approach in helping to better mimic the pre-development discharges. This study aims to evaluate the effectiveness of LID and Best Management Practices (BMP) under different rainfall conditions. Vegetative swale and detention pond were selected to represent LID and BMP. Simulations of four main scenarios namely, base case, LID, BMP, and combined LID-BMP were performed using Stormwater Management Model (SWMM). Results show that among the scenarios simulated, the combined LID-BMP is most effective with average peak flow reduction of 54%. This is followed by BMP that achieved 37% in average peak flow reduction as compared to 27% peak flow reduction by LID. The findings indicate the need for integrated strategy when dealing with stormwater management measures.

1. Introduction

Urban drainage systems are designed to dispose of surface runoff from the developed areas as quickly as possible to avoid flooding. However, rapid urbanization coupled with climate change effects have resulted in increasing runoff quantity that normal urban stormwater management systems cannot adequately handle [1]. This includes increased peak flows and runoff volume, and shorter time to peak. As such, a different approach to urban stormwater management is needed.

In recent years, Low Impact Development (LID) practices have become a new approach in managing stormwater runoff. LID practices aim to mimic the natural hydrological flow characteristics like that in the pre-development conditions [2], [3]. This includes characteristics such as infiltration, runoff reduction and extending lag time [1]. Previous study conducted found that Best Management Practices (BMPs) such as conventional detention ponds are still more effective than LID for flood control [6].



This implies that LID will not be able to completely substitute urban drainage systems for stormwater runoff control. As such, integrated urban drainage systems using different approaches would be a better strategy for stormwater management, to cover a larger spectrum of storm events. However, little research has been done in combined approaches for urban drainage system. In this case, the effectiveness of integrating LID and BMP into the design of urban drainage system.

This study aims to evaluate the effectiveness of LID and BMP and the combined LID-BMP for stormwater management under different rainfall conditions. The work scope involved application of stormwater model simulation to evaluate the impacts of LID and BMP on hydrographs and peak flows generated from a range of design storm events.

2. Methodology

2.1. Stormwater model

This study used the U.S. Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) to simulate the rainfall-runoff processes. The study area is an arbitrary catchment area, extracted from the tutorial in the SWMM manual [8]. The reason for using an arbitrary catchment area is the improved understanding of the effectiveness of LID and BMP practices. In this case, maintaining a simpler catchment setup will direct the focus towards implementation of LID and BMP for stormwater management, and not distracted by various catchment characteristics, properties, and parameters, which, all are not the focus of this study. This simple model setup provides a basis for better understanding the effectiveness of LID and BMP.

Figure 1 shows the schematic diagram of the stormwater model setup for this study. The setup comprises two sub-catchments, five conduits (C1, C2, C3, C4, C5) and four junctions (J1, J2, J3, J4). Sub-catchment 1 is located at the upstream while Sub-catchment 2 is located at the downstream. The sub-catchments' runoffs are directed through storm sewer conduits to the outlet.

Table 1 shows the values of parameters for both sub-catchments under pre-development and post-development conditions. Table 2 shows the invert levels for the nodes. Other settings include selection of Green-Ampt method for infiltration and the dynamic wave routing for hydraulic modelling.

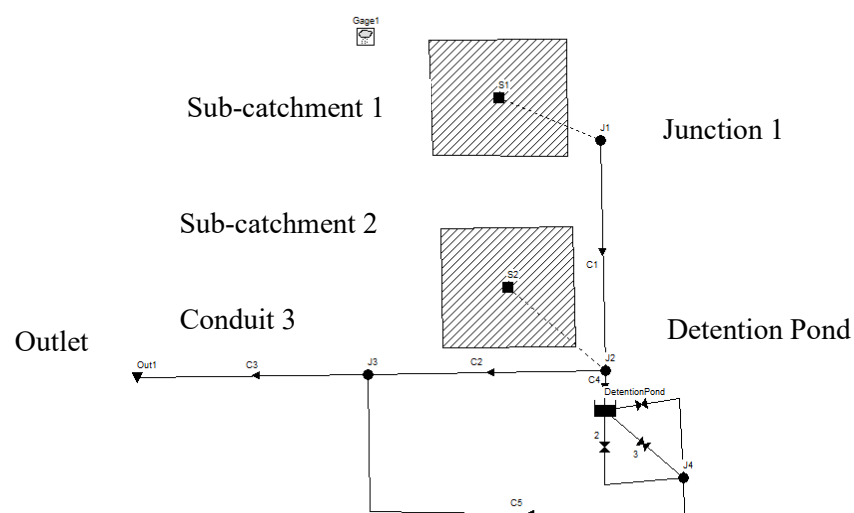


Figure 1. SWMM Rainfall-Runoff Simulation Model for LID-BMP Scenario.

Table 1. Values of parameters for sub-catchments.

	Pre-development		Post-development	
	Sub-catchment		Sub-catchment	
	1	2	1	2
Area (ha)	1.6	1.6	1.6	1.6
Slope (%)	0.05	0.05	0.05	0.05
Impervious area (%)	0	0	50	50
Manning's roughness coefficient-impervious	0.015	0.015	0.015	0.015
Manning's roughness coefficient pervious	0.045	0.045	0.045	0.045
Depression storage depth on impervious area (mm)	1.27	1.27	1.27	1.27
Depression storage depth on pervious area (mm)	1.27	1.27	1.27	1.27

Table 2. Invert levels of nodes.

Nodes	J1	J2	J3	J4	Detention Pond	Outlet
Invert level (m)	29	28	26	27	27	24

2.2. Design rainfall

Rainfall data is among the most important input for stormwater simulation. In this study, calculations for design rainfall and rainfall temporal patterns were carried out in accordance to Urban Stormwater Management Manual for Malaysia (MSMA) [4], using the coefficients for Kuala Lumpur.

Three design rainfalls of 30 minutes duration and 20, 50, and 100 years average recurrence intervals (ARI) were calculated. Design rainfall temporal patterns were applied to the design storms. These temporal patterns are standardised to allow for the adoption of standard design procedures in flow calculation (MSMA) [4], and hence, remove the elements of subjectivity due to rainfall when comparisons simulated results between scenarios. Table 3 shows the rainfall depth calculated for 20, 50, and 100 years ARI. Table 4 shows the fractions of the rainfall temporal pattern used for the 30 minutes rainfall. Each time period has time intervals of five minutes.

Table 3. Rainfall depths for each return period.

Return Periods, ARI	Rainfall Depth (mm)
20	118
50	130
100	141

Table 4. Rainfall fraction at each time period from temporal pattern.

Time period	1	2	3	4	5	6
Fraction of rainfall	0.160	0.250	0.330	0.090	0.110	0.06

In addition to the design rainfall ARI, two sets of rainfall conditions namely, Group I and II were simulated. In Group I rainfall input, the design rainfall is input as single event. In Group II, the values of rainfall are the same as those in Group I, but the rainfall event occur two times in each simulation, with a 12 hours interval between the two events. These Group II simulations aim to model continuous events. The 12 hours interval between the events will provide enough time for the runoff to be discharged from the sub-catchment areas and conduits before the next event.

2.3. Design scenario

Four design scenarios were simulated namely, (i) base case scenario; (ii) LID scenario; (iii) BMP scenario; and (iv) combined LID-BMP scenario. The base case scenarios represent post-development conditions using conventional urban drainage system without stormwater management measure. For this scenario, 50% of the sub-catchment area is considered impervious surface that represents urban development.

There are two sub-scenarios for the LID conditions. In the first sub-scenario, the vegetative swale is placed at the upstream (Sub-catchment 1) whereas in the second scenario it is located at the downstream (Sub-catchment 2). These arrangements aim to analyse as to what effect the LID placement will have on peak flow. In these LID scenarios, the vegetative swales are arranged in a sub-catchment along with the base case scenario drainage system. These swales will have an area coverage of 50% of the sub-catchment area and will treat the runoff generated from 50% of the pervious and impervious area of the sub-catchment's non-LID area. The outflow from the vegetative swale will be routed to the sub-catchment's outlet. Table 5 shows the values of parameters for the vegetative swale. These values are taken from the Urban Stormwater Management Manual for Malaysia (MSMA) [4].

Table 5. Values of parameters for vegetative swale [4].

Layer	Parameter	Swale
Surface	Berm Height (mm)	300
	Vegetation Volume Fraction	0.0
	Surface Roughness (Manning's n)	0.003
	Surface Slope (%)	0.5
	Swale Side Slope (run/rise)	5

In the BMP scenario, a storage unit was used to represent the detention pond for storing runoff from both sub-catchments. The values of sub-catchment parameters for the base case scenario are used for this BMP scenario. A portion of the runoff generated from both sub-catchments will pass through Conduit 4 into the detention pond and will be gradually released over time. The detention pond was designed in accordance to MSMA [4]. The Rational Hydrograph Method (RHM) was used in estimating the required pond volume. The detention pond has an invert level of 27 m, depth of 2 m and a storage capacity of 1092 m³. In the model, the combined LID-BMP scenario implements both LID (vegetative swale) and BMP (detention pond) scenarios. Table 6 shows the experimental design with different scenarios for model simulations. Simulations were performed for each scenario using three different design rainfall ARI, for both Group I and II rainfall conditions, with a total of 36 simulations.

Table 6. Experimental design for post-development stormwater model simulation.

Simulation number	Simulation Scenario	LID (Vegetative Swale)		BMP (Detention Pond)
		Sub-catchment 1	Sub-catchment 2	
1	Base case	No	No	No
2	LID1	Yes	No	No
3	LID2	No	Yes	No
4	BMP	No	No	Yes
5	LID1-BMP	Yes	No	Yes
6	LID2-BMP	No	Yes	Yes

2.4. Data analysis

The simulated results from Conduit 3, where runoff from both Sub-catchment 1 and 2 will flow through were extracted for analysis. This is because runoff from all scenarios including the BMP scenarios with detention pond are connected to Conduit 3. As such, the simulated results from Conduit 3 will provide the data for evaluation of effectiveness of various stormwater management measures.

3. Results and discussion

3.1. Effects of LID placement on peak flows

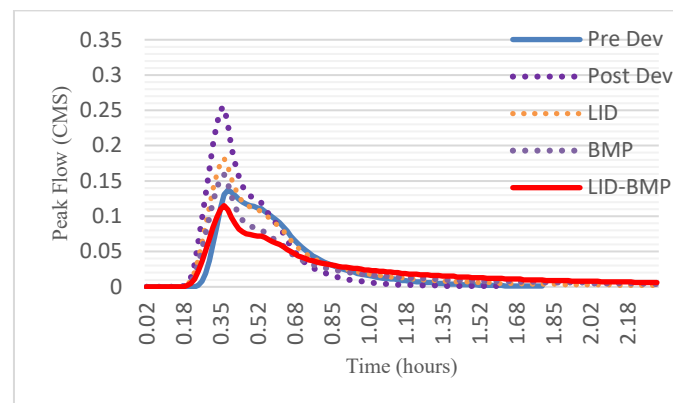
The first step in the simulation was to evaluate the impacts of LID placements in different sub-catchments, namely the upstream Sub-catchment 1 (LID1) and the downstream Sub-catchment 2 (LID2) on peak flow. Table 7 shows the simulated peak flows for these scenarios. From the table, it can be seen that the time to peak flow of 22 minutes is the same for all the scenarios and design rainfalls. This is because only one design rainfall temporal pattern was used for all scenarios, which results in only one rainfall pattern, and hence, the same time to peak flow. On peak flows, even though both LID1 and LID2 scenarios have similar hydrograph patterns, the peak flows for LID1 scenarios (LID1 and LID1-BMP) are consistently lower, and hence, deemed more effective than the LID2 scenarios. However, the differences are considered negligible, where these differences range between 1.6% to 1.9% for LID1 and LID2, and between 2.1% to 3.1% for LID1-BMP and LID2-BMP.

Table 7. Peak flows for different scenarios (post-development).

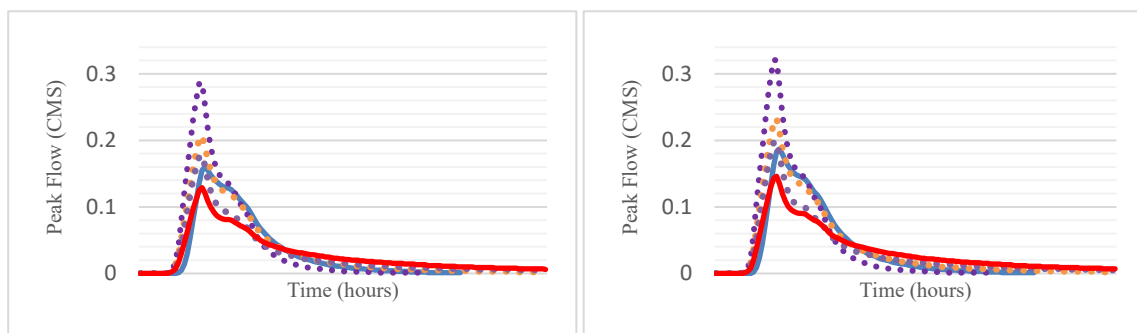
ARI (Years)	Time to Peak Discharge (minutes)	Peak Discharge, Q (m ³ /s)					
		Base case	LID1	LID2	BMP	LID1- BMP	LID2- BMP
20	22	0.255	0.182	0.185	0.159	0.115	0.118
50	22	0.287	0.207	0.211	0.178	0.129	0.133
100	22	0.320	0.233	0.237	0.199	0.146	0.149

3.2. Effects of LID and BMP on peak flows

Stormwater model simulation were carried out to evaluate the impacts of LID and BMP on peak flows. The simulation cases were adopted from the experimental design as illustrated in Table 7 above. However, only the LID1 and LID1-BMP scenarios were presented as they are found more effective than the LID2 and LID2-BMP scenarios. As such, four scenarios namely base case, LID1, BMP, and LID1-BMP from Table 7 are presented. In addition, the pre-development condition is added as it is the basis for comparison. This made a total of five scenarios. Figures 2(a) to (c) show the simulated hydrographs for these five scenarios for 20, 50, and 100 years return period.



(a)



(b)

(c)

Figure 2. Hydrographs for five scenarios for three design rainfalls: (a) 20 years, (b) 50 years, and (c) 100 years ARI.

The peak flow generated by the base case scenario is significantly higher than the pre-development condition for all three design rainfalls. In addition, the hydrograph for base case scenario rises more rapidly than the pre-development condition. This is expected as there is increased in impervious area in the base case (post-development) condition.

For the LID and BMP scenarios, the peak discharges generated are significantly lower than the base case scenario, but their magnitudes are not reduced to the level of the pre-development condition. However, the hydrographs for both the LID and BMP scenarios show a better match with the hydrographs for pre-development condition in terms of the rise and fall of hydrographs. This trend is seen in all three design rainfalls.

The reduction in peak discharges is most significant in the combined scenario compare to other scenarios. In addition, this reduction in peak discharge also results in a gradual fall of the hydrograph that sustains a much longer flow compare to the other scenarios. This shows that incorporating both BMP and LID practices can help relieving urban drainage systems from the more rapid, higher magnitude runoff discharge due to development.

The simulated results show that similar to the base case scenario, the peak discharges generated by both LID and BMP scenarios are greater than the pre-development condition. This indicates that both LID and BMP are insufficient to handle the quantity of increased stormwater due to development. In this case, only the combined LID1-BMP is able to provide sufficient protection for stormwater management, to bring down the peak discharge to a level of lower than pre-development. This finding is in line with the suggestion to combine LID and BMP into the design of urban drainage systems [2].

3.3. Effects of rainfall depth on peak discharges

Table 8 shows the reduction of peak discharges for all the three scenarios in comparison to the base case for three design rainfall ARI with different rainfall depth. From table 8, the simulated results show a decreasing trend in peak reduction in the LID scenario. In this case, the effectiveness of LID practice decreases as the rainfall depth increases. This may be due to the reduced infiltration capacity where the vegetative swale may be saturated with increased rainfall depth. The results are in line with [2] which indicates that LID practices are more effective for more frequent, smaller, less intense events.

Table 8. Percentage reduction in peak discharge for all scenarios in comparison to base case.

Rainfall		Reduction of Peak Discharge (%)		
ARI (years)	Depth (mm)	LID	BMP	LID-BMP
20	118	28.6	37.6	54.9
50	130	27.9	38.0	55.1
100	141	27.2	37.8	54.4

On the other hand, there is absent of trend for the BMP scenario, where in general, the effectiveness of BMP remains the same for all design storms, with constantly higher peak discharge reduction than the LID scenarios. In this case, BMP is able to maintain a more stable performance where the detention pond is able to handle stormwater runoff from 20-year to 100-year design rainfall.

Among the three scenarios, the LID-BMP combined scenario provides the highest percentage in peak discharge reduction for all design storms. In addition, although LID is unable to provide the same peak discharge reduction as BMP for the storm events, the LID with its vegetative properties is able to mimic the pre-development hydrograph in terms of time to peak that matches the pre-development conditions. In this case, combining the benefits of peak flow reduction and extending the time to peak by incorporating both LID and BMP using vegetative swale and detention pond for urban drainage design can significantly reduce the post-development base case peak discharge by more than half, and hence, contributed to better stormwater management. This finding is in line with the outcome from previous studies that mentioned that the best option for achieving stormwater control objectives will often be combining LID and BMP [2], [5].

3.4. Effects of continuous rainfall events

Figures 3 show the model simulated hydrographs for five scenarios under the second rainfall event. These figures show that there is similar pattern between these hydrographs and those for the first rainfall event. The main difference, however, is the shorter time to peak discharge for all scenarios as compared to that of the first rainfall event. The reason for the more rapid time to peak is the difference in initial conditions for the sub-catchments. In this case, the sub-catchments have been wetted by the first rainfall event, leading to a more rapid conversion of rainwater from the second rainfall event to surface runoff and hence, a shorter time to peak.

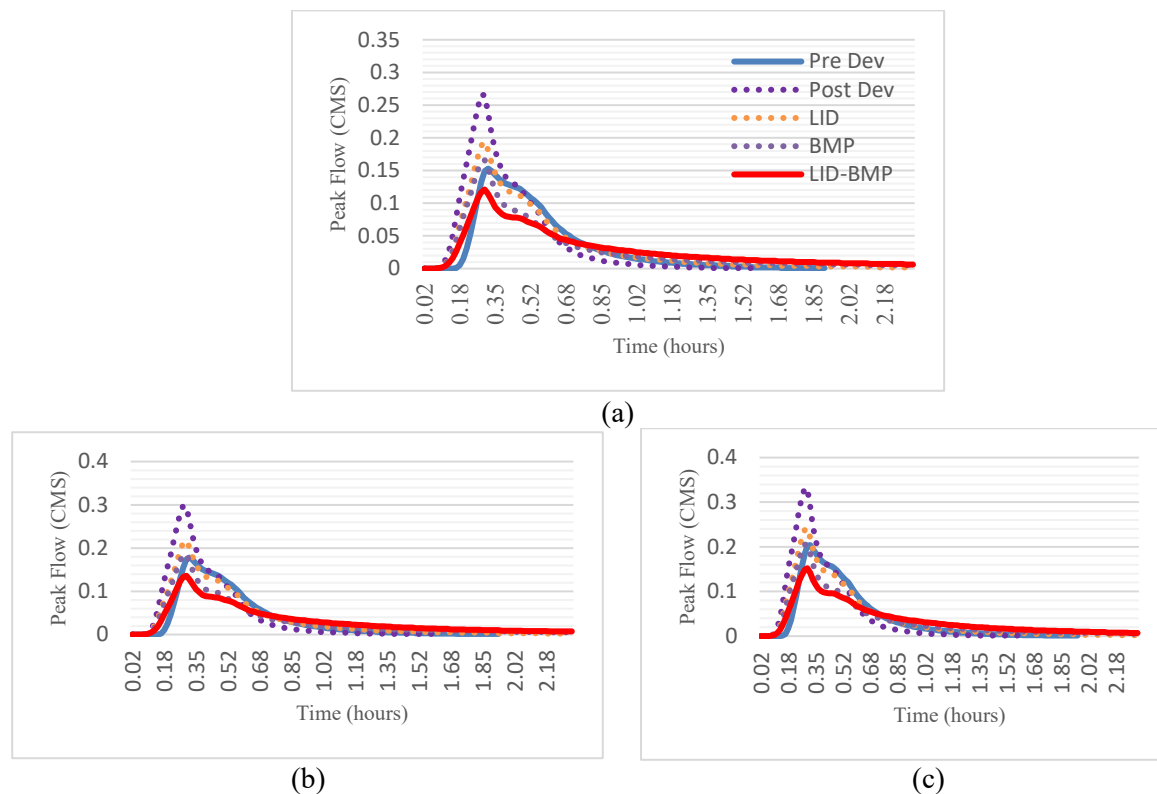


Figure 3. Hydrographs for second rainfall event for three design rainfalls: (a) 20 years, (b) 50 years, and (c) 100 years ARI.

Table 9. Increase in peak discharge for all scenarios for second rainfall event in comparison to the first rainfall event.

ARI (years)	Increase in peak flow (%) for Second Rainfall Event in Comparison to First Rainfall Event						
	Pre-development	Base case	LID1	LID2	BMP	LID1-BMP	LID2-BMP
20	11.7	4.3	6.6	5.9	4.4	5.2	5.1
50	11.3	3.8	4.8	4.3	4.5	5.4	3.8
100	9.1	3.8	3.9	3.8	3.0	4.1	3.7

Table 9 shows the percentage increase in peak discharge for the second rainfall event in comparison to the first event, where the simulated results show an increase in peak flow during the second rainfall event for all scenarios. From the table, it is shown that the changes between 20 years and 50 years ARI are greater as compared to those between 50 years and 100 years ARI. This is in line with the greater increase in rainfall depth of 10.2% from 20 years (118 mm) to 50 years ARI (130 mm) as compared to only 8.5% increase in rainfall depth from 50 years to 100 years ARI (141 mm).

Also, there are some interesting outcomes from the simulations. First, the base case scenario shows the lowest increase among all cases. This could be due to the high peak flow for both first and second rainfalls where without stormwater management measure, most rains have been converted to runoff and hence, there's minimum increase from the previous rainfall event. Secondly, there is major increase in peak flow from the pre-development condition which could be due to the well saturated pervious areas after the first rainfall event. In this case, the infiltration and depression storage capacity have both been

filled. As such, rainwater from the second rainfall event will not be able to infiltrate into the ground, resulting in increased net rainfall and surface runoff that will ultimately results in higher peak discharges.

The BMP scenario on the other hand is not affected by these reductions in infiltration and depression storage capacities, and hence, it is able to maintain a more stable performance during the second rainfall event.

For the combined LID-BMP, in addition to providing the most reduction in peak discharge, the LID-BMP is the only measure that is able to reduce the peak discharge to a level lower than those of the pre-development conditions, for all design rainfall ARI and rainfall conditions. This indicates that although there is increased in peak flow for the LID scenarios, there is still contribution from the vegetative swales. In this case, the vegetative swales help to delay the time to peak for the combined LID-BMP scenario while the detention pond assist in storing the additional runoff to maintain a lower peak flow. This finding agrees well with the results of previous study, which stated that LID strategies with other flood control measures will significantly help mitigate and reduce flood risks during longer and heavier storms [7].

4. Conclusion

This study simulated six scenarios to evaluate the effectiveness of LID and BMP i.e. vegetative swales and detention pond on stormwater management. A total of 36 simulations have been performed for 20, 50, and 100 years design rainfalls, with two different rainfall conditions.

The simulated results indicate that although both the LID and BMP are able to reduce the peak discharge, the combined LID-BMP measure shows better performance and effectiveness in peak flow reduction. In this case, the combined LID-BMP is the only stormwater measure that is able to keep the peak flow below the pre-development conditions, under different rainfall design ARI, for both the first and second rainfall events. These findings indicate the need for an integrated strategy when dealing with stormwater management rather than designing different measures separately.

This study applied LID and BMP to a hypothetical study area. For improved understanding, other stormwater management measures can be included for evaluation of the effectiveness of different measures. Also, simulations can be performed using real catchments to allow for evaluation of the impacts of catchment characteristics on stormwater management, and the interactions between these catchment characteristics and stormwater management measures. Then, cost-benefit studies on different measures can be performed to investigate the feasibility of LID or BMP implementation.

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