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Evaluating the Peak Flow and Runoff Coefficient Reductions of Bioretention, Infiltration Trench, and Permeable Pavement LID Using Stormwater Management Model

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Rapid urbanization and climate change have brought hydrological changes in urban catchments, prompting new research on the application of more sustainable, climate-resilient, and cost-effective systems for stormwater management. Low impact development (LID), a new research topic about sustainable stormwater systems, is currently being studied as the new approach to managing untreated runoff. Studies have proven that LIDs have many benefits that can range from alleviating floods, treating runoff pollutants, and enhancing stormwater infiltration, making it a practical structure in developed locations. The objective of this study was to assess the peak flow and runoff coefficient reductions of LID controls using Stormwater Management Model (SWMM). Using three different LID controls (bioretentions, infiltration trenches, and permeable pavements) and four rainfall scenarios (80th, 90th, 95th, and 99th rainfall percentile), evident reductions in the peak flow and runoff coefficient have been observed. Larger reductions were observed in the 80th percentile than the other higher percentiles from the simulations. These reductions can reach up to 32 % in the peak flow and a 0.29 decrease in the runoff coefficient, where the high reduction values were found in the multiple LID scenarios. The widespread use of LID can help in mitigating these major stormwater impacts.

1. Introduction

The spread of impervious surfaces due to rapid development and urbanization have disrupted natural hydrological processes, causing irreversible effects on fluvial systems and the community in general. Hydrological, geomorphological, and ecological issues have challenged urban channels, leading to an increase in flood frequency, bank erosion, and channel enlargement (Chin et al., 2022). The degradation of water quality also becomes an issue when it comes to stream health, as urbanized regions were observed to have higher dissolved oxygen and temperature as opposed to non-urban catchments (Sheldon et al., 2019). Together with climate change, intensified rainfall and more frequent ‘rare’ floods will occur more often (Wasko et al., 2021) as well. In mitigating the negative impacts of these issues, several approaches have been proposed, including increasing the amount of vegetation, physically altering used building materials, and expanding strategically planned green infrastructures (Emilsson, 2021).
The research for newer and more sustainable stormwater systems escalated over the years to resolve the prevalent problems brought upon by rapid urbanization and climate change. Low impact development (LID) is one of these emerging studies regarding nature-based stormwater approaches, whose aim is to restore the hydrological balance of a catchment (York and Jacob, 2020). By mimicking the predeveloped conditions, these LID structures could effectively reduce runoff volumes, decrease runoff pollutant loads, and improve infiltration conditions (Newman, 2020) in their application. Several countries have already adopted LID structures (Amoruso et al., 2020), however, there is a lack of studies about LIDs in the Philippines. Continuous development has urbanized the Philippine landscape these past few decades due to the increasing urban population (WorldBank, 2018) and the push for economic growth (Licuanan et al., 2019). This has resulted in extensive hydrological changes in various locations in the country, where studies have reported an increase in flooding issues (Lagmya et al., 2017), alongside increased runoff and streamflow with reduced baseflow

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(Boongaling et al., 2018) to name a few. The objective of this study was to assess the peak flow and runoff coefficient reductions of LID controls in the site area using Stormwater Management Model (SWMM).

2. Materials and methods

2.1 Study area

The selected study site is a residential park located in Bacoor, Cavite, Philippines (14°27′6.3432″, 120°56′48.264”), as shown in Figure 1. The park is predominantly impervious, with 61.3 % of its total area converted into impervious cover. The rest of the green spaces located in the area was in the form of a lawn area and some greeneries. As this was the only portion of the land with sufficient spaces for LID application, it was used in the following assessments.

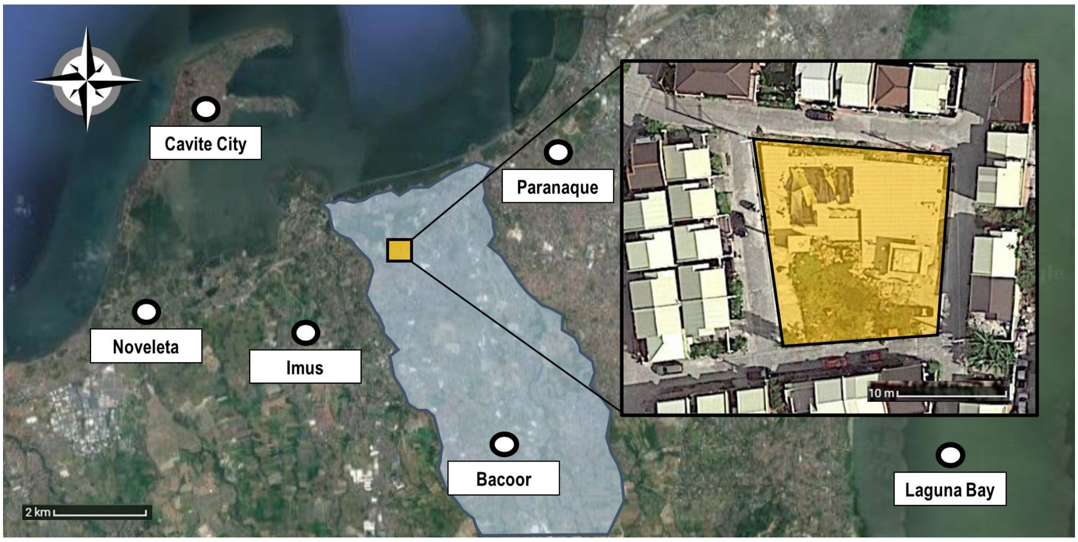

Figure 1: The geographical location of the study site

2.2 Rainfall scenarios

This study used the 80th, 90th, 95th, and 99th rainfall percentiles of the historical rainfall data from the nearest rain gauge in the vicinity. The collected data is composed of the 40-year rainfall from 1975 to 2019, with some years omitted due to missing values. These rainfall percentiles represent the initial part of runoff to capture, and these have been used in several LID-related studies (Frias and Maniquiz-Redillas, 2021) to compare the results of varying rainfall amounts.

2.3 Hydrological model

The US EPA SWMM was used as the hydrological model in the study. SWMM is a dynamic rainfall-runoff model for stormwater simulation, which can model both single and long-term events and produce runoff and pollutant loads (Rossman, 2015). The bioretention (BR), infiltration trench (IT), and permeable pavement (PP) controls have been selected from the SWMM LID module for application. Both bioretentions and infiltration galleries have been used in the study of He et al. (2022) in reducing flows and runoff coefficients, while Ben-Daoud et al. (2022) utilized permeable pavements in exploring their effects on surface runoff, suggesting their effectiveness in water quantity problems. Table 1 shows the LID scenarios formed from these three controls for this study.

Table 1: LID scenarios used in the modeling process

Scenario name	LID controls included	Capture area (%)
BR	Bioretention	43.8
IT	Infiltration Trench	42.2
PP	Permeable Pavement	14.0
BR+IT	Bioretention & Infiltration Trench	86.0
BR+PP	Bioretention & Permeable Pavement	57.8
IT+PP	Infiltration Trench & Permeable Pavement	56.2
BR+IT+PP	Bioretention, & Infiltration Trench, & Permeable Pavement	100

The BR had the largest capture area on the site, closely followed by the IT. The joint use of all controls in this study would indicate that all the rainfall collected at the site would be treated by the LIDs. An additional no LID scenario was also simulated for comparison with these LID scenarios. Due to site limitations, the varying surface areas of the selected LIDs were kept at smaller sizes in the modeling process.

2.4 Weibull Plotting Position

The use of probability distribution functions has been adopted in hydrology to fit distributions of continuous random variables (Ewemoje and Ewemooje, 2011). The Weibull Plotting Position is an approach used in estimating the probability of exceedance in rainfall simulations and this was used in the estimation of rainfall percentiles in this study, as performed by Frias and Maniquiz-Redillas (2021). Eq(1) shows the formula for the Weibull Plotting Position.

$$P = \frac{m}{n+1} \tag{1}$$

where P is the probability of exceedance of the mth observation, m is the rank number, and n is the number of observations.

3. Results and discussion

3.1 Rainfall analysis

Shown in Figure 2 are the average and cumulative frequency of the processed 40-year rainfall data. The average precipitation recorded by the rain gauge was 2,100.1 mm. The lowest maximum monthly rainfall was observed during March, with 105.8 mm at a standard deviation of 24.664 mm, while the largest maximum monthly rainfall was observed in July, with 1,596.7 mm at a standard deviation of 267.85 mm. These results were expected given that the province of Cavite has a Type I Climate, whose wet season typically occurs from May to October (Villarin et al., 2016). Cumulative rainfall results have also shown that August is the month where rainfall accumulates the most, at around 650 mm on average.

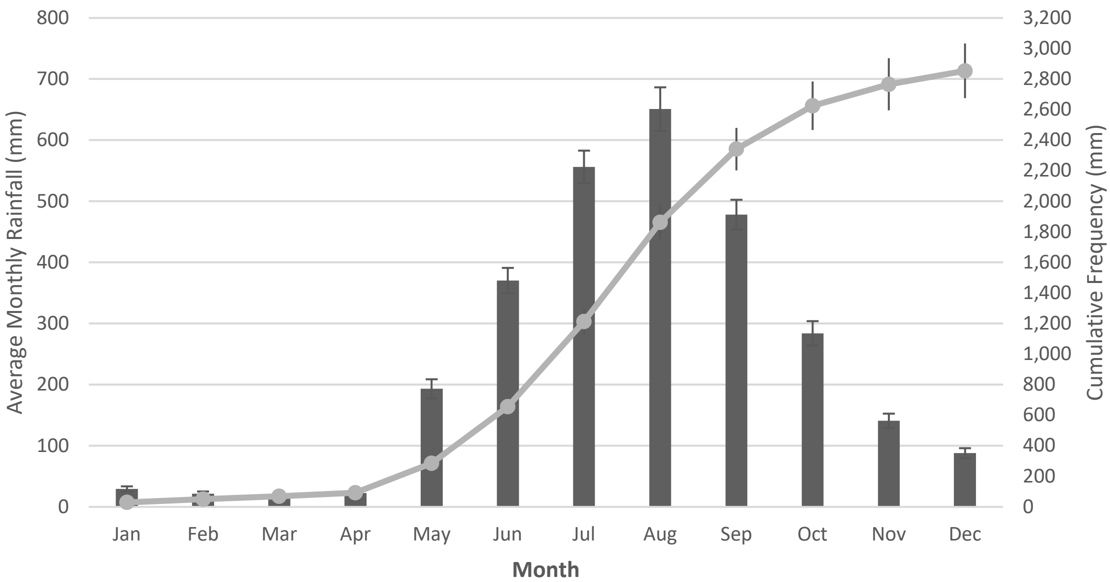

Figure 2: Average and cumulative frequency of the 40-year rainfall data

The collected rainfall was then ranked using the Weibull Plotting Position for each year, where its corresponding percentile amounts (80th, 90th, 95th, 99th) were averaged through interpolation. The result of the cumulative plotting position of the 40-year rainfall data is shown in Figure 3. Using this methodology, the calculated rainfall amount used in the study for each percentile is shown as follows: 4.517mm for the 80th percentile, 16.64mm for the 90th percentile, 35.44mm for the 95th percentile, and 99.44mm for the 99th percentile. These were then distributed over a 24-hour duration for input in the SWMM model.

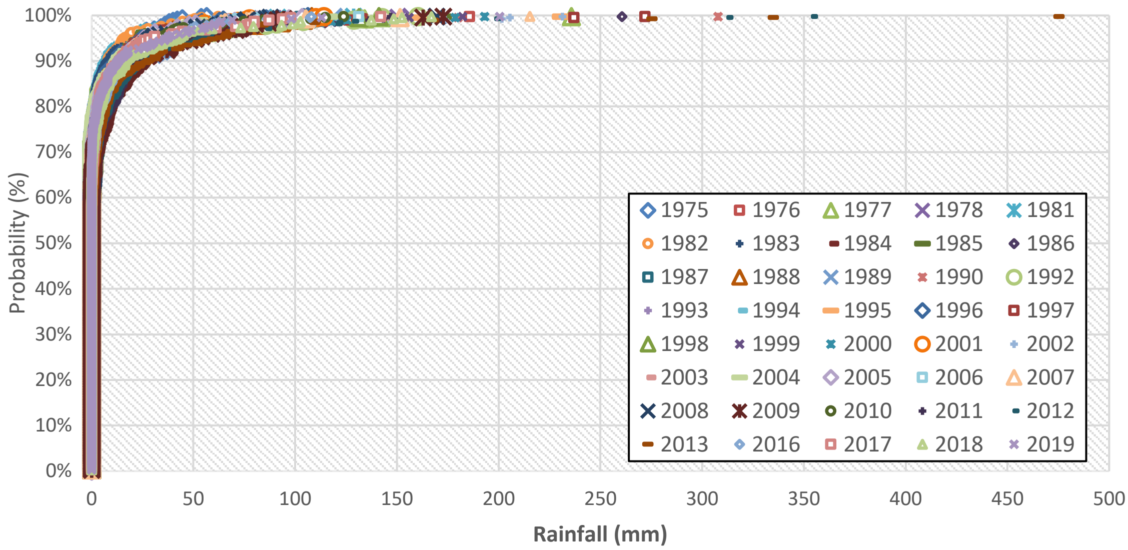

Figure 3: Weibull Plotting Position of the rainfall data for the years 1975 to 2019

3.2 Peak flow reduction

The comparison of the peak flow of the no LID scenario and LID scenarios is shown in Figure 4. The trend of all LID scenarios was observed to be visually lower than the no LID scenario, which suggests that all LID scenarios applied can be effective in reducing the peak flow of the receiving pipe. The single LID scenarios, which consisted of the BR, IT, and PP scenarios, generated peak flow reductions varying from 1 to 16 %, with the IT scenario taking the largest reductions in most rainfall percentiles due to its large capture area. The multiple LID scenarios, on the other hand, had reductions ranging from 22 to 32 % in the 80th percentile, 11 to 15 % for the 90th percentile, 4 to 18 % for the 95th percentile, and 6 to 18 % for the 99th percentile. The best scenarios from this assessment mostly included the BR+IT and BR+IT+PP scenarios, which indicates that these were the best LID combinations in the site concerning peak flow reduction only. Furthermore, results have shown that higher peak flow reductions were observed in lower rainfall percentiles, as opposed to higher rainfall amounts. This was due to the small LID sizes distributed in the study site, whereas larger sizes could produce better reductions. Multiple LID scenarios have also been noted by some studies as the most effective arrangements for runoff (Yang et al., 2020) and peak flow reduction (Wang et al., 2021), although the rising costs could become an issue in further constructions (Yang et al., 2020).

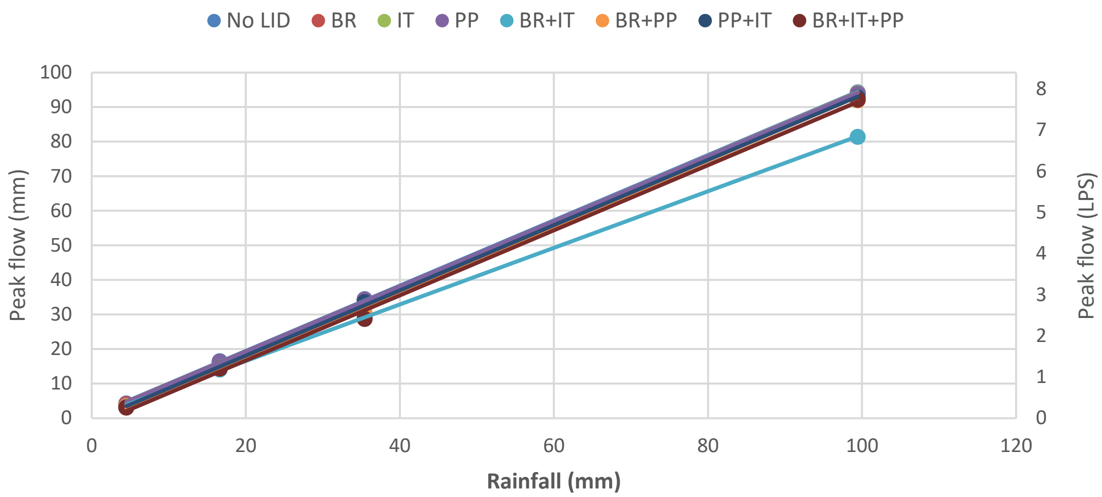

Figure 4: Peak flow reduction of all simulated scenarios

3.3 Runoff coefficient reduction

The comparison of the runoff coefficient for all single LID scenarios is shown in Figure 5, while the results for the comparison with multiple LID scenarios are shown in Figure 6. A slight decrease was observed for all LID scenarios as compared with the no LID scenario, which indicates that a portion of the runoff was redistributed in the study site. Larger reductions were seen in the 80th percentile than in the other rainfall scenarios as LIDs were more effective in smaller rainfall amounts. The results of the 90th percentile, however, did not follow this trend. Modeling results in this percentile had closer values to the 95th and 99th percentile than the 80th percentile, likely due to the varying LID sizes inputted in different rainfall percentiles. Like the peak flow reduction assessment, the BR+IT and BR+IT+PP scenarios excelled in all rainfall percentiles, where the lowest runoff coefficient is lesser by about 0.29 for the 80th percentile, 0.15 for the 90th percentile, 0.16 for the 95th percentile, and 0.14 for the 99th percentile than the no LID scenario. In a similar manner, the multiple LID scenario from the study of Ben-Daoud et al. (2022), which is a combination of permeable pavements and rain barrels, also generated the greatest runoff coefficient reductions (50 %) in their study given greater rainfall values in varying land types.

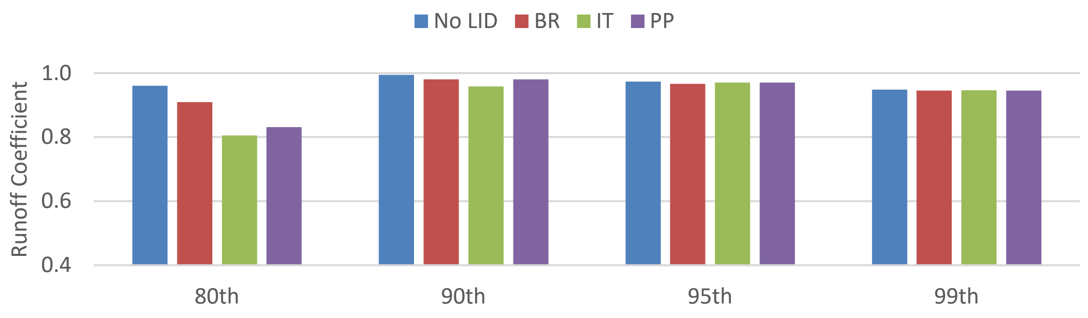

Figure 5: Runoff coefficient of the no LID scenario vs. the single LID scenarios

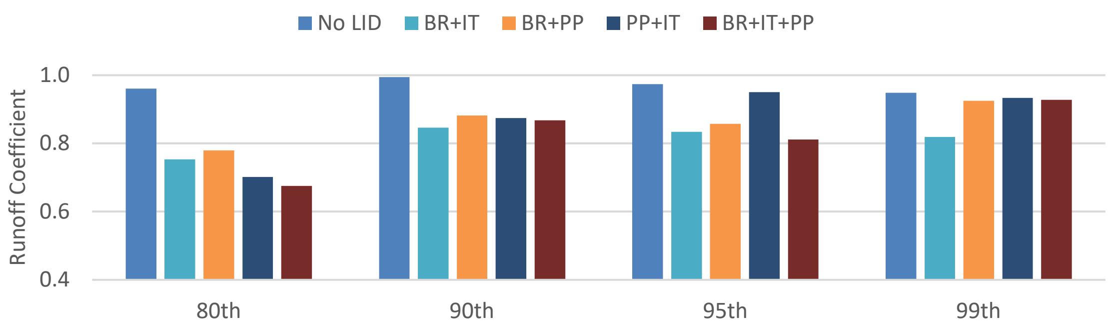

Figure 6: Runoff coefficient of the no LID scenario vs. the multiple LID scenarios

4. Conclusions

The application of LID in the study site has shown evident reductions in the peak flows and runoff coefficients. At most, the modeling results of this study have shown that LID controls in the site can reduce the peak flow of the no LID scenario by up to 32 % and decrease the runoff coefficient by 0.29 from its original value. The BR+IT and BR+IT+PP scenarios produced the best efficiencies among all LID scenarios, with the single LID scenarios (BR, PP, IT) generating the least reductions in comparison across all presented rainfall percentiles. The use of LID may contribute to alleviating the widespread stormwater issues in affected areas. In the Philippines, where LID is still not yet fully explored, research can provide valuable information for the future application, implementation, and optimization of LID controls.

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