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Analyzing the Effects of Low Impact Development Controls on the Hydrological Balance of a Highly Impervious Catchment Using Stormwater Management Model (SWMM)

Jan Ver D. Edra[a], Sergi S. Garbanzos[a,b], Rina Marie V. Pedrosa[c], Marvin Jade G. Genoguin[c], Marla M. Redillas[a,b,*]

[a]Hydraulics and Water Resources Engineering Division, Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University – Manila, 2401 Taft Avenue, Malate, Manila 1004, Philippines
[b]Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue, Malate, Manila 1004, Philippines
[c]Civil Engineering Department, Eastern Visayas State University, Corner Benigno Aquino Avenue, Tacloban City, 6500, Philippines
marla.redillas@dlsu.edu.ph

The continual increase of impervious surfaces in rapidly developing areas poses the risk of altering its natural hydrological cycle and the water balance. To counteract these issues, low impact development (LID) technologies have been adopted in urban areas as they could mimic predeveloped conditions in built-up regions. The objective of this study was to analyze the effects of LID controls on the hydrological balance of a highly impervious catchment using Storm Water Management Model (SWMM). Four different scenarios were defined: a pre-development scenario and three other post-development scenarios based on the historical stage of development in the site and their corresponding increase in impervious area cover. Three LID controls were used in the simulation, namely the infiltration trenches, rooftop disconnection, and permeable pavements. Simulations have shown that the infiltration decreases, and the runoff increases over time across the four development scenarios. The combination of the rooftop disconnection and infiltration trench on the site was effective, increasing infiltration by up to 13 % and decreasing the runoff by 46 %. The application of permeable pavements in the site also showed the same trend in an increase in infiltration by up to 64 % and a decrease in runoff by up to 90 % while allowing more capacity for stormwater storage. This research showed that LID structures can improve the water balance of the developing site, and this could contribute to the development of LID policies in developing countries.

1. Introduction

Urban spaces are currently growing at an exponential rate, further intensifying the use of impervious surfaces at the cost of reducing vegetation and green space. Of the observed impacts, issues regarding the increased quantity stormwater have been the most prominent (Kong et al., 2017). Heavy amounts of impervious cover severely affect the natural hydrology of a watershed, increasing total runoff volume and escalating rainfall runoff peaks (Shuster et al., 2005), as well as posing threats of flooding and deteriorating water quality (Adetoro et al., 2022). These unnatural changes also bring additional concerns toward the health of streams, disrupting their temperature, erosion, and ecosystem (Chin et al., 2013). The recent surge of precipitation intensity could also heighten its impacts and could further increase the magnitude and frequency of flooding (Fust and Schlecht, 2022).Low impact development (LID) is a new, innovative, and sustainable stormwater management technique that could return the hydrologic conditions of developed catchments to their predeveloped conditions (Li et al., 2023). The use of these technologies offers significant hydrological benefits particularly on the hydrological balance of the affected catchments, enhancing its infiltration and evapotranspiration while reducing runoff amounts (Yang and Chui, 2018). This change in water balance has heavily impacted developing countries, particularly tropical countries, in recent years due to continuous development and climate change (Noor, 2023).

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Recently, modelling techniques have become a popular tool in assessing the impact of LID on their respective watersheds. Bibi and Kara (2023) evaluated the performance of rain barrels and rain gardens to alleviate flooding in the software PCSWMM. This was part of their attempt to quantity the impacts of climate change across increasing urbanization rates in a town in Ethopia, where the two LID scenarios managed to decrease stormwater to around 32.8 % and 36.8 %, respectively. Suresh et al. (2023) assessed the effects of LID controls in mitigating the peak runoff and runoff depth in four watersheds, aiming to explore the effects of drainage modification and LID controls considering climate change and different watershed characteristics. The green roof scenario attained the best runoff reduction rates in the study, generating a reduction ranging from 34 % to 83 %. Kong et al. (2017) simulated a catchment using various urban scenarios and LID combinations to investigate the implications of incorporating green infrastructures in a developing city. These effects were also to be evaluated by a GIS-based SWMM software in a large scale. Like the other studies, their results have shown that the application of LIDs has reduced runoff volumes and runoff coefficients, and even delaying the peak of rainfall. The use of simulations can become a basis for the hydrological benefits of LID in developing countries. The aim of this study is to analyze the effects of LID controls on the hydrological balance of a highly impervious catchment using Storm Water Management Model (SWMM). This study promotes the use of modelling techniques in estimating the impacts of LID in these developing countries before they are applied in a pilot scale. Results of this study could be used as a reference for the future planning and implementation of pilot LID particularly in tropical countries, where peak rainfall is substantially increasing (Wasko et al., 2021) and expertise around the topic is not yet heavily explored. (Garbanzos and Maniquiz-Redillas, 2022a)

2. Materials and Methods

2.1 Study area

The study area was the Palo Municipal Hall (11°09.62167', 124°59.41832') located in Palo, Leyte, as shown in Figure 1. Palo is a coastal municipality in Leyte, Philippines which has a total area of 221.27 km^2. The area experiences a Type IV Philippine climate, which is defined as a climate with no pronounced dry season and maximum rain period. The municipal hall can be divided into the main municipal building and the parking area, and the area is almost fully impervious outside the few greeneries on the side. Only a short drainage pathway was observed in the site after site investigation and surveying locals, made of a 0.4 m x 0.4 m concrete culvert with steel gratings (Manning's n = 0.012). The drainage in the area was not refurbished after development occurred according to the locals, and this could cause issues if left without additional measures.

Figure 1: Location of the site area in Palo, Leyte

2.2 Rainfall scenarios

A 30-year set of rainfall data which covers the period from 1990 to 2012 was obtained for this study. These were recorded at a nearby rain gauge in Tacloban City, Leyte, approximately 9 km away from the site. The Weibull probability distribution method was then utilized in selecting the rainfall values to be used in the hydrological model. This distribution method provides a method to determine the probability of occurrence of rainfall using historical data. Among known distribution methods it also presents the highest values of percentiles, and it has been used by similar LID 2odelling studies (Garbanzos and Maniquiz-Redillas, 2022b). The 80th and 90th percentile were used in this study for comparison.

2.3 Hydrological model

Stormwater Management Model (SWMM) is a program that was developed in 1971 by the United States Environmental Protection Agency (USEPA), and it can simulate rainfall-runoff events and can be used in designing drainage systems (Hlustik, 2017). The municipal hall model was delineated into two sub-catchments, as shown in Figure 1, based on the available drainage plans provided by the local authorities. The first sub-catchment, designated as SC1, encompassed the main hall building and its surrounding area while the second sub-catchment, designated as SC2, covered the parking lot. Four development periods were then assessed based on historical geographic data from Google Earth, where each period was characterized by varying amounts of imperviousness. The development periods and their imperviousness values are summarized in Table 1.

Table 1: Imperviousness values for each development period

Period	Sub-catchment	
	SC1 imperviousness cover (%)	SC2 imperviousness cover (%)
Pre-development	15	15
Post-development (2003-2012)	60	65
Post-development (2012-2017)	85	80
Post-development (2017-current)	95	95

SWMM also has a LID module to simulate the effects of LID structures within the catchment. Three LID controls were focused on in this study based on their practical application in each sub-catchment. These included the rooftop disconnections (RD) and infiltration trenches (IT) for implementation on SC1 and permeable pavements (PP) on SC2. Simulations were then made with the SWMM base model based on the LID controls, two rainfall percentiles, and four development scenarios presented. A w/o LID, RD only, IT only, and RD+IT scenario was compared for SC1, while a w/o LID and PP scenario were assessed for SC2. In the LID scenarios, the RD was set to cover around 38% of the SC1, the IT covered 9% of SC1, and PP took 50% of SC2. These were based on limitations and available spaces for LID application in each sub-catchment.

3. Results and discussion

3.1 Rainfall analysis

Low impact development technologies operate best on rainfall events with small peak values and short duration (Zhu and Chen, 2017). The historical data has shown that rainfall in the area has been highly variable, although cumulative rainfall from the latter half of the data (2002-2012) appeared to have greater amounts compared to the other half, which further accentuate the increase in rainfall experienced in recent years. Using the Weibull distribution plot, historical rainfall data was ranked each year and evaluated at its 80th and 90th probabilities to obtain its percentiles. Figure 2 illustrates the Weibull probability of rainfall for each year. The 80th and 90th percentile for the rainfall were calculated at 10.6 mm and 22.2 mm respectively and were then simulated over 24 h in the succeeding simulations.

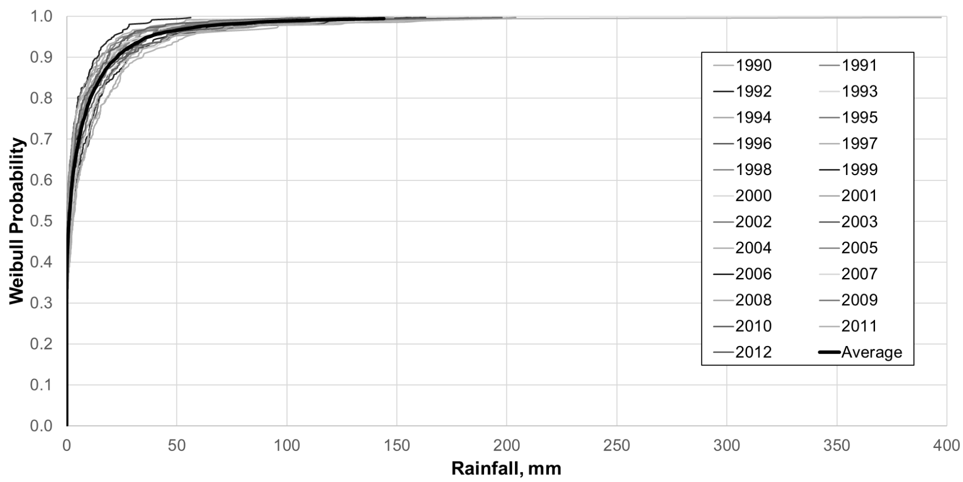

Figure 2: Weibull probability plot for daily rainfall in the years 1990-2012.

3.2 Water balance of the pre-and post-developed catchments

Figures 3a and b show the components of the water balance for each. With the lack of impervious covers, it was anticipated that the water balance in the system will have higher infiltration and less runoff (New Jersey Department of Environmental Protection, 2016). This held for both sub-catchments as they both reported decreased infiltration and increased runoff during the shift to a more developed scenario. When compared to the effects of the design storms that were simulated, the runoff was significantly increased by the rainfall at the 90th percentile. This is consistent with the research of Silva et al. (2019), which claims that LID controls have a limited capacity for larger amounts of rainfall. Most stormwater is converted to runoff in the current state of the municipal building.

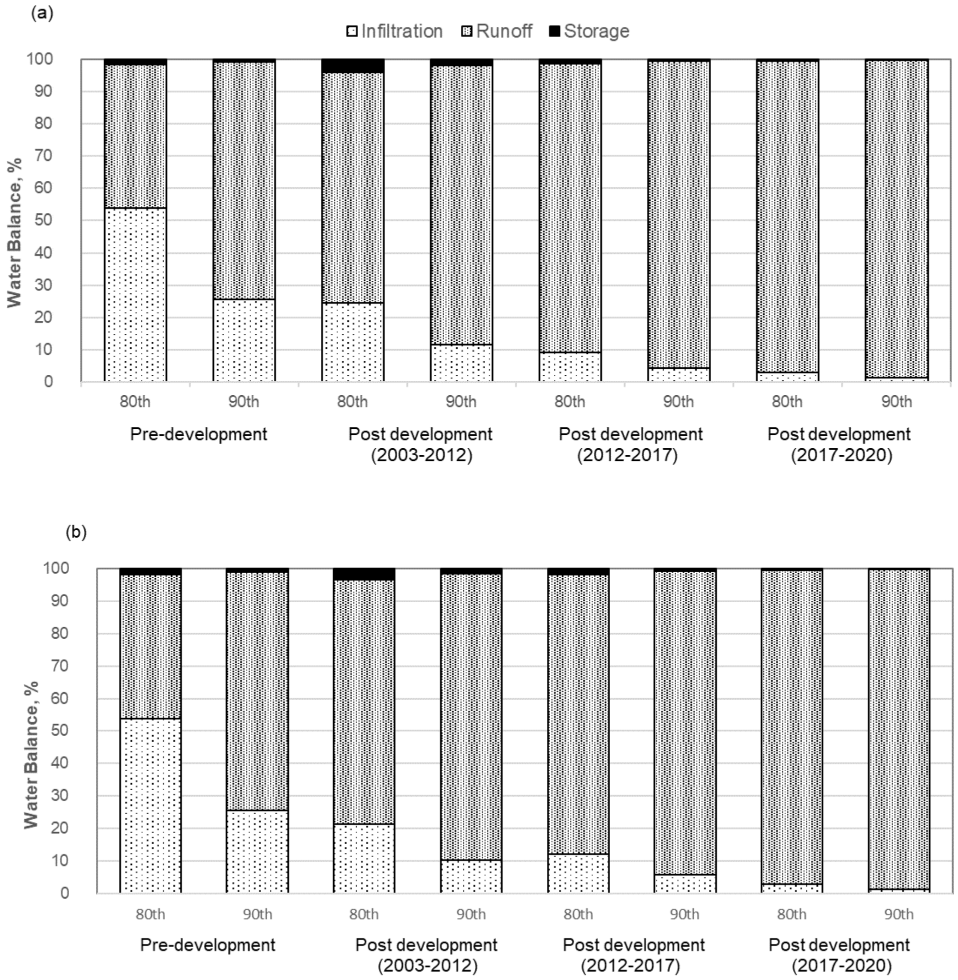

Figure 3: Water balance in (a) SC1 and (b) SC2 for each development period and rainfall percentile

3.3 Impact of LID controls on the hydrological balance of the catchments

Figures 4a and b show the simulation results of SC1. All no LID scenarios have shown a greater amount of runoff as compared to the predeveloped and LID scenarios, suggesting that the LID scenarios were effective in reducing the incoming volume. Results with the RD-only scenario, however, still retained a high runoff amount despite its application. This implies that rooftop disconnections are most effective in the retention of water during rainfall events, and it is in line with its function of redirecting stormwater to other LID controls as opposed to the treatment for infiltration. RDs are best when integrated into a treatment train with other LID techniques. Connecting it with the IT scenarios generated significant increases further, attaining a 26 to 46 % decrease in the 80th percentile and 22 to 38 % in the 90th percentile. The storage parameter also appears to increase with the application of LID controls. This was attributed to the first observation made in the figure which was the retentive capacity of the rooftop disconnection. The results of this study coincide with the results of Palla and Gnecco (2015) where the LID controls are expected to improve hydrologic performance with increasing land use conversions.

Figures 4c and d compare the three post-development periods in SC2. The results of the simulations show similar results from the previous two figures, having exceedingly high runoff amounts in the no LID scenarios and high infiltration amounts in the with LID scenarios. The distribution appears to be less varied in the 80th percentile than the 90th percentile, where differences between the three parameters are more distinct. The application of PP significantly improves all aspects, which could be tied to its capacity for storage and infiltration. The application of PP controls created a 67 to 90 % runoff decrease in the 80th percentile and a 76 to 90 % decrease in the 90th percentile. Subsequently, it has garnered a 55 to 64 % and 26 to 32 % increase in infiltration across the 80th and 90th percentiles, respectively, compared with the no LID scenario. Very little runoff variation can be observed over the three post-development periods with LID controls, and this could impact future rainfall events within the area. Results in the PP scenario in SC2 have generated better reduction potential as opposed to the RD+IT scenario in SC1, largely due to the available LID space that can be applied on the site. The difference in LID controls may have also contributed, as PP are generally good in reducing runoff and improving infiltration (Garbanzos and Maniquiz-Redillas, 2022a) compared to RDs which are better for redirecting flow to other pervious surfaces rather than reducing it itself (Rossman, 2015).

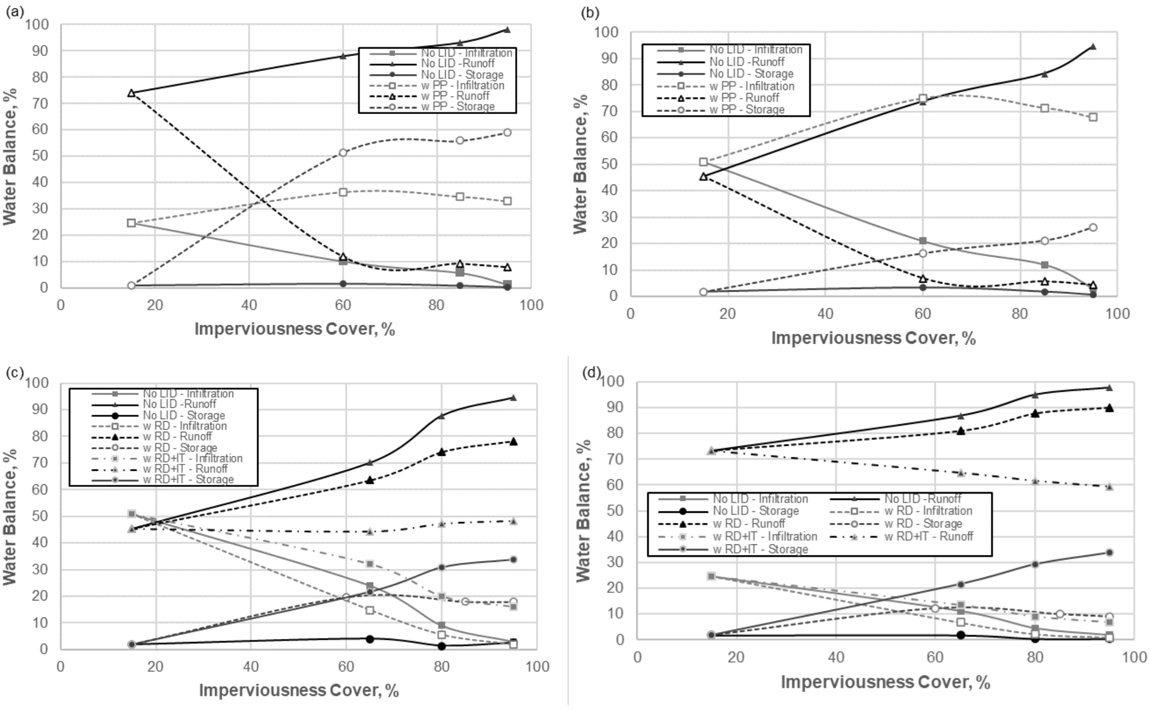

Figure 4: Hydrological balance of the SC1 scenarios with and without LID in the (a) 80th and (b) 90th and the SC2 scenarios with and without LID in the (c) 80th and (d) 90th percentile

4. Conclusions

This study aimed to analyze the effects of LID controls on the hydrological balance of a highly impervious catchment using Storm Water Management Model (SWMM). Rooftop disconnections, infiltration trenches, and permeable pavements have been implemented in the model across two sub-catchments and four development periods to compare their efficiency using rainfall percentiles of tropical weather. This study highlights the following results:

1. Satellite images have shown urbanization has been steadily increasing in the area, attaining a 50-55 % increase from the pre-development to the post-development period and a 15-25 % increase per succeeding post-development period.
2. Cumulative rainfall has significantly increased in recent years in the site compared to rainfall in the past. In recent years, cumulative annual rainfall has peaked at more than 4000 mm, which suggests that more extreme events have been observed in the latter half of the historical data.
3. The runoff amount generated from the urbanization and increased rainfall in the post-development periods are disproportionate, having runoff values taking up 72-98 % of the total water balance with only 1-26 % allowed for infiltration.

4. The application of LID controls has promoted infiltration and storage within the site while reducing runoff. The simulated values show that it had high variability, decreasing the runoff by 22-90 % and increasing the infiltration by 2-64 %, implying that the percentages are dependent on the characteristics of the site, the target rainfall design, and the LID types used.

This research explores the capabilities of LID and encourages its use in developing countries to manage stormwater. This study underlined the impacts of LID controls on the hydrological balance of the catchment, which is an important factor to consider in practical LID implementation. In future research, focusing on the other benefits and impacts of LID could guide engineers and designers in developing an optimal design for pilot studies or actual construction. The calibration and validation of data, which was not performed in this study, could also help generating in a better and more accurate result.

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