SINAYA
A Philippine Journal for Senior High School Teachers and Students

Science and Technology

# Assessment of the Feasibility of Permeable Pavement for Sustainable Stormwater Management Using SWMM

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**Abstract:** The advancement of urbanization in the Philippines changed natural lands into impervious surfaces and aided the contamination of surface runoff and nearby water bodies. Low Impact Development (LID) technologies were introduced as an alternative to conventional drainage systems, specifically permeable pavements. Such technology is beneficial for stormwater runoff reduction, ground infiltration enablement, and stormwater treatment. This research was conducted to investigate the feasibility of permeable pavement for sustainable stormwater management in a university setting, particularly in De La Salle University – Laguna Campus. The Storm Water Management Model (SWMM) was utilized to simulate different rainfall scenarios on selected little to no vegetation regions with increasing permeable pavement area coverage. The findings showed that the LID surface area to subcatchment area (SA/CA) ratio is inversely proportional to the total runoff reduction observed in all rainfall scenarios. The total runoff reached zero when the SA/CA ratio was at least 50%. The permeable pavement was concluded to be effective in surface runoff infiltration, reduction, and storage which is beneficial for long-term stormwater management and flood prevention strategies. The study can be used in future investigations and applications of similar LID technologies.

**Keywords:** LID; permeable pavement; stormwater; SWMM; water balance

## INTRODUCTION

In the Pacific and East Asian region, the Philippines is considered one of the countries with the highest urbanization rates, as the country increased its urban population by at least 50 million individuals in the last five decades (World Bank Group, 2017). Urbanization causes land conversion to accommodate the increasing needs of the population. This results in increased impervious surfaces, which alter the natural hydrologic cycle by preventing infiltration and evapotranspiration (Haustein, 2010; McGrane, 2015). Aided by global warming, higher evaporation and precipitation rates occur and trigger uneven rainfall distribution, resulting in extreme weather conditions such as prolonged flooding and drought (Fishman, 2016). Countries in tropical regions are more prone to experience such a phenomenon due to extreme heatwave exposure (Intergovernmental Panel on Climate Change, 2018). Due to this issue's aggravation, the Philippines has been assessed as one of the most susceptible countries to climate change due to the higher probability of extreme weather (Amnesty International UK, 2020). An average of 19.4 tropical cyclones (TC) enter the Philippine Area of Responsibility annually, with Luzon experiencing the most TC-associated rainfall (Cinco et al., 2016). An increasing trend in economic losses and damage is observed during the wet season due to intense and recurrent flooding, especially in metropolitan areas. Currently, sustainable flood management practices are yet to be established in the Philippines (Arcangel, 2018).

Presently, the Philippines utilizes a conventional drainage system designed to collect and transport water runoff from urban areas to nearby receiving water bodies as quickly as possible (Zhou, 2014). Conventional drainage system is prone to pollution and clogging; hence, runoff does not drain immediately, causing street floods to occur. Urban drainage networks are essential for economic development as it aids the interaction between living organisms and the water cycle by providing water supply to humans and diverting excess rainwater from the local drainage system (Jamal, 2017). Without such, the accumulation of untreated wastewater or rainwater that contains numerous pollutants and toxic chemicals could cause flooding, damage, and even health risks.

For that reason, sustainable stormwater management practices and technologies, such as Low Impact Development (LID), emerged to mitigate hydrologic hazards and to improve environmental quality (United States Environmental Protection Agency [EPA], 2020a). LID is a biomimicry land development strategy that maintains the natural movement of water through stormwater infiltration, evapotranspiration, and collection (EPA, 2020b). LID also allows water pollution reduction, aquifer replenishment, and water reuse (Talebzadeh et al., 2021). Additionally, LID is essentially designed for runoff peak and volume reduction, groundwater recharge, stream protection, increased infiltration, and water quality assessment through pollutant removal (Hunt et al., 2010).

Under LID is permeable pavement (PP), is primarily designed for peak runoff, runoff volume, and pollutant reduction (Selbig & Buer, 2018). The utilization of PP can reestablish a more natural hydrologic balance and reduce runoff volume by trapping and slowly releasing precipitation into the ground instead of allowing it to flow into storm drains and out to receiving bodies of water. PP is one of the most efficient alternatives for impervious surfaces due to its high durability and low maintenance cost (Scholz & Grabowiecki, 2007). Many studies have concluded that the performance of PP is dependent on rainfall conditions, particularly rainfall intensity (Collins et al., 2008; Hou et al., 2008; Valavala et al., 2006). More recent findings have also found that PP reduces almost 90% of runoff volume in arid regions, 70% in humid regions, and 31% to 100% in semi-arid regions (Alam et al., 2019; Liu & Chui, 2017). Additionally, PP can filter about

90% to 96% of suspended solids in runoff (Brown et al., 2009). Although most results vary, many studies suggest that PP is 50% to 90% effective in peak runoff, runoff volume, and pollutant reduction with additional advantages such as surface temperature cooling. The implementation of LID technology, specifically PP, would also be beneficial in decreasing water pollution and recurrent flooding in the Philippines, especially during wet season. However, LID is yet to emerge in the Philippines due to insufficient public awareness of sustainable drainage systems and their benefits. Moreover, despite continuous technological advancements, the utilization of computer-aided efficient drainage designs for urban planning is not yet widespread.

Along with the continuous rise of urbanization in the Philippines, impervious surfaces remain abundant in newly developed areas. Impervious surfaces pertain to surfaces that do not allow water to pass through to the underlying soil to perform infiltration (Chithra et al., 2015). These types of pavements are accompanied by various disadvantages, such as collecting harmful chemicals and toxic wastes that may be transferred to streams, which can affect the health of living organisms. Once rainwater runoff flows through these impervious surfaces, it carries unfiltered water that obtains pollutants and goes into storm drains and bodies of water, causing water pollution. Thus, to address these complications, an assessment of the feasibility of PP for sustainable stormwater management was conducted in a university setting using the United States (US) Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM).

For the simulation, SWMM 5.1 by the US EPA was used. Similar to the study conducted by Frias and Maniquiz-Redillas (2021), three sites with varying areas in De La Salle University (DLSU) – Laguna Campus are selected to apply different LID approaches, including PP. Simulations included only the $80^{th}$, $90^{th}$, and $95^{th}$ percentile rainfall data input. For each simulation, the percent area covered by PP are adjusted at increments of 10% per trial, starting from 0% to 100% coverage. Only the 95th percentile was used for further statistical analysis.

The study focused only on one kind of PP mix based on the standard SWMM parameters of PP, which has uniform composition. Only one model was used in the simulation, and it was assumed to be in perfect condition when the test run was conducted. Other factors that may affect the efficiency of PPs were not considered, such as construction time and age. Also, the quality of the runoff was not discussed in this study. Due to the limitations brought by the pandemic, no on-site experimentation and investigation was conducted. Instead, simulation and statistical analyses were used as alternative means to gather data and gain results.

Assessing PPs would provide urban planners with the most suitable modifications in an area. Similar PP and SWMM simulations are cost- and time-efficient due to its minimum budget and workforce requirement for implementation and maintenance. In the case of a wide-scale PP implementation project, the site locations used in the study would only need fewer simulations and data, as it had already been assessed previously. There would also be low to almost zero risks of construction failure since the prospect PP design was already tested via simulations. Furthermore, this would benefit the surrounding ecosystem and maintain the natural hydrologic cycle of the assessed site locations because of the minimized flooding occurrences and water contamination, resulting in balanced water distribution and reduced wastewater.

This assessment aims to determine the advantages of PP in runoff volume reduction; to evaluate the capabilities of each PP subcatchment at the 80th, 90th, and 95th rainfall percentile; and to identify the effectiveness of each PP area at every 10% increment of area coverage from 0% to 100%.

## METHODOLOGY

### Site Description

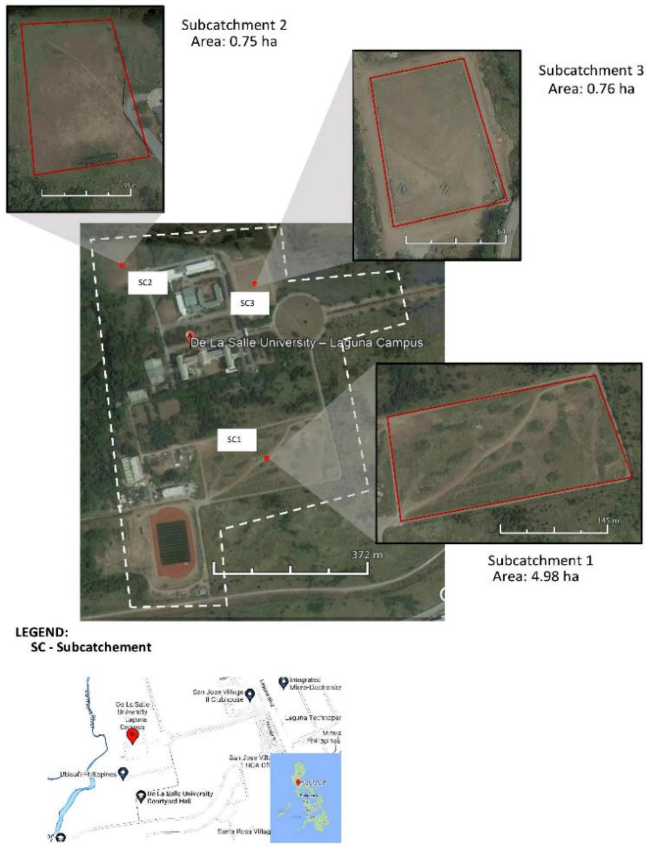


**Figure 1**. Site map displaying a satellite view of the DLSU – Laguna Campus with the chosen subcatchment areas highlighted and their corresponding areas indicated.

De La Salle University (DLSU) – Laguna Campus is a 50-hectare suburban area located at 14.5642°N 120.9910°E, approximately 10 kilometers west of Laguna Lake (De La Salle University-Science and Technology Complex [DLSU-STC], 2021). Figure 1 shows a satellite view of the campus acquired using Google Earth Pro. Due to the limitations caused by the pandemic, no on-site ocular inspection was conducted; thus, real-time data on aspects such as climatology, land usage, land slope, and soil composition were not acquired. Instead, the site characteristics obtained using Google Earth Pro were deemed accurate and updated. Default simulation inputs were utilized for the remaining site characteristics that were not acquired.

**Table 1**. Site description of each subcatchment selected for the SWMM simulation

| | Location | Size (ha) | Brief Description |
|---|---|---|---|
| S1 | 14°15’35 N, 121°02’40 E | 4.89 | A large area of land containing small areas covered with vegetation |
| S2 | 14°15’51 N, 121°02’28 E | 0.76 | A small area of land that has a minimal vegetative cover |
| S3 | 14°15’49 N, 121°02’39 E | 0.75 | A small plot of land that is mostly barren |

Three sites within the campus with little to no vegetation were chosen as subcatchments for the simulation. Table 1 presents these subcatchments, namely subcatchment 1, subcatchment 2, and subcatchment 3, which have respective areas of 4.89 ha, 0.75 ha, and 0.76 ha. Aside from areas, no distinct differences among the three subcatchment areas were observed. The subcatchment areas were assumed to be pre-developed areas with no established drainage network to apply PP in the area.

The standard parameters of PP systems acquired from the study of Zhang and Guo in 2014 were encoded into the LID properties utilized during the simulation. Due to the lack of real-time data about the site, the PP was assumed to be in a perfect state. Factors that may alter the PP’s performance were neglected. Only the surface area to subcatchment area (SA/CA) ratio of the scenarios was simulated at every 10% increment of 0% to 100% SA/CA during 80$^{th}$, 90$^{th}$, and 95$^{th}$ percentile rainfall events.

**Table 2**. Standard parameters for the permeable pavement systems encoded in the simulation

| System Components | Parameter | Value | Unit |
|---|---|---|---|
| Surface layer | Storage depth | 1.5 | mm |
| | Vegetation cover fraction | 0 | |
| | Surface roughness | 0.015 | |
| | Surface slope | 1% | |
| Pavement layer | Thickness | 1-200 | mm |
| | Void ratio | 0.16 | |
| | Impervious surface fraction | 0 | |
| | Permeability | 254 | mm/h |
| | Clogging factor | 0 | |
| Storage layer | Height | 450 | mm |
| | Void ratio | 0.63 | |
| | Filtration rate | 3.3 | mm/h |
| | Clogging factor | 0 | |
| Underdrain system | Drain coefficient | 1,000 | |
| | Drain exponent | 0.5 | |
| | Drain offset height | 0-400 | mm |
| Native soil | Suction head | 88.9 | mm |
| | Conductivity | 3.3 | mm/h |
| | Initial deficit | 0 | |
| Other | Area | 1,000 | $m^2$ |
| | Width | 30 | m |
| | ET rate | 0.13 | mm/h |

## Data Collection and Analysis

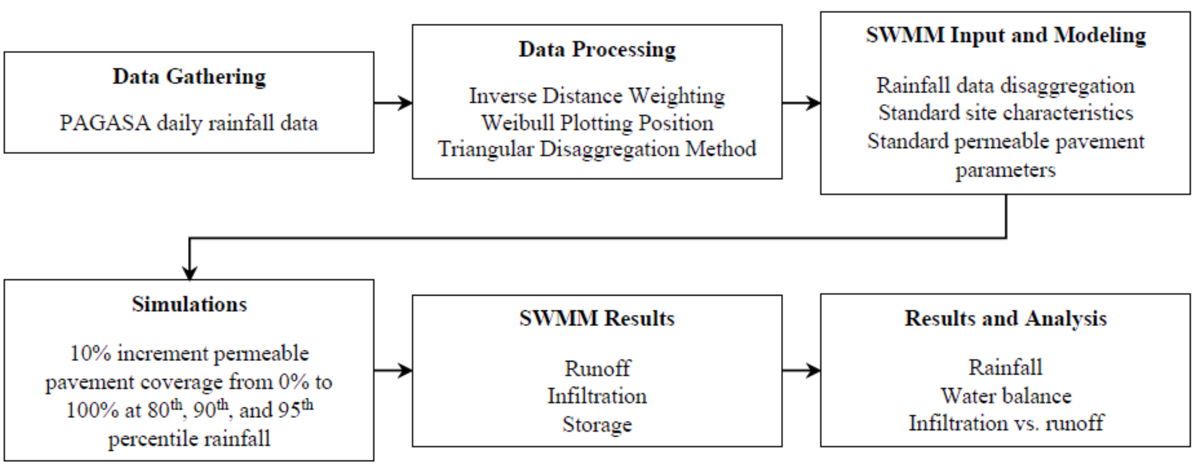


**Figure 2**. Flowchart of the data collection and analysis process

Daily rainfall data from two sites near the DLSU – Laguna Campus, namely the National Agrometeorological Station – University of the Philippines Los Baños (NAS-UPLB) and Ambulong, Batangas, were collected from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). The rainfall data collected was subjected to inverse distance weighting to estimate the rainfall distribution at the DLSU – Laguna Campus. Meanwhile, the average monthly rainfall and its standard deviation were calculated using Excel. The data underwent a Weibull cumulative distribution analysis using the formula shown in Equation 1 to determine the 80$^{th}$ , 90$^{th}$, and 95$^{th}$ percentile rainfall distribution.

$$P = \frac{m}{N+1} \qquad \text{Equation 1}$$

Where *P* is the percentile rank, *m* is the data rank, and *N* is the number of rainfall data.

Since the SWMM rainfall input only accepts hourly values, the daily rainfall data collected was disaggregated into hourly values using the triangular disaggregation method acquired from the US EPA (2018) Hydrologic Simulation Program-Fortran (HSPF).

After the rainfall data processing, the processed rainfall data, along with the site characteristics and standard parameters of PP, were encoded in SWMM. For the required input data that were not acquired, the default SWMM input values were utilized instead. The satellite view of the campus, as shown in Figure 1, was used to design the PP drainage system used in the simulation, which can be seen in Figure 3. The simulation proper focused on assessing the feasibility of PP at every 10% increment of 0% to 100% PP area coverage at 80$^{th}$, 90$^{th}$, and 95$^{th}$ percentile rainfall and the results from each scenario were collected.

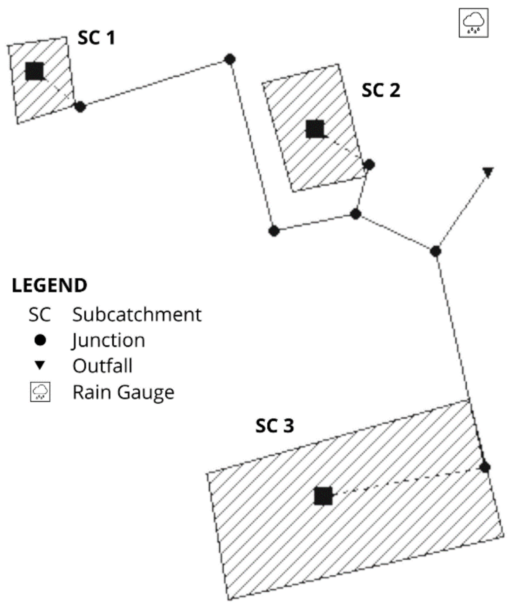


**Figure 3.** SWMM model of the three subcatchments in DLSU – Laguna Campus

The raw data from the simulation were tabulated into Microsoft Excel to apply formulas and create graphs to draw conclusions. First, storage was calculated by subtracting the sum of the resulting total infiltration and runoff from the total precipitation present in the subcatchment area. Next, these data were normalized by dividing the values for each water balance element by the total precipitation based on its respective percentile. The resulting values were then plotted using the regression curve to observe the common trends on the effects of the change in SA/CA ratio on the resulting amount of each water balance element.

# RESULTS AND DISCUSSION

## Rainfall Characteristics

The 1991 to 2018 daily rainfall data of NAS-UPLB and Ambulong, Batangas, were subjected to inverse distance weighting to predict the rainfall distribution within the DLSU – Laguna Campus. Based on Figure 4, a high amount of rainfall occurred from May to December, while the dry season was observed from January to March. Also, based on the same figure, on average, July was the wettest month, and February was the driest month. Standard deviation was also conducted from these data sets, and results showed that February had the least standard deviation while July had the greatest, suggesting that these values were near and far from the calculated mean rainfall, respectively.

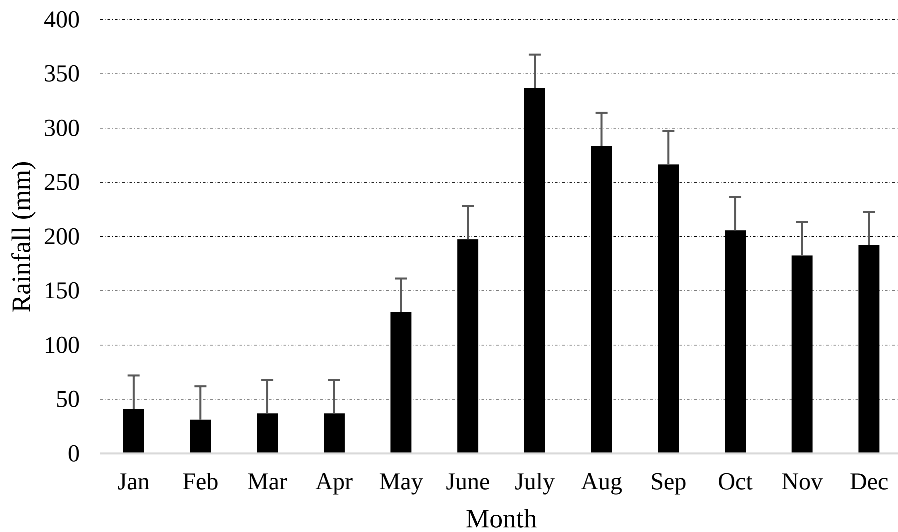


**Figure 4.** Processed monthly rainfall data from PAG-ASA (1991-2018) with their standard deviation

The data were subjected to a Weibull cumulative distribution analysis and were plotted to calculate the 80th, 90th, and 95th percentile rainfall. The resulting 80th, 90th, and 95th percentile rainfall values were 4.80 mm, 15.09 mm, and 28.89 mm, respectively.

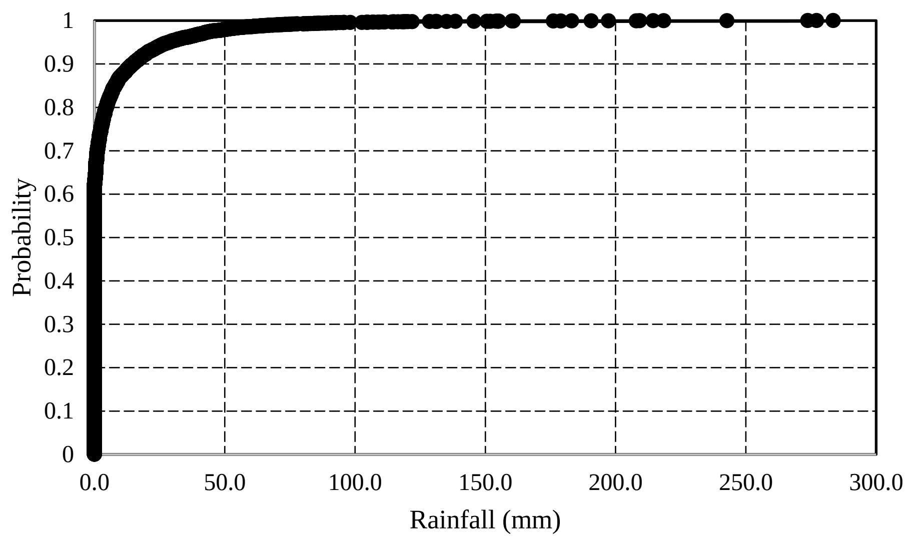


**Figure 5.** Cumulative distribution of processed rainfall data using Weibull analysis

SWMM requires hourly rainfall data input; thus, further data processing was conducted. Based on the assessment of Gao et al. (2012) on different disaggregation methods of daily precipitation for hydrological simulation, the US EPA (2018) HSPF triangular disaggregation method can be applied to this study to convert the daily rainfall data into hourly values. As shown in Figure 6, the data were distributed proportionately. It was inferred that the peak rainfall for the 80th, 90th, and 95th percentile rainfall events occurred in the middle of the day. However, the disaggregated rainfall data shown in Figure 6 might differ from actual rainfall events considering external factors. The disaggregated data were then encoded in SWMM for the simulation proper.

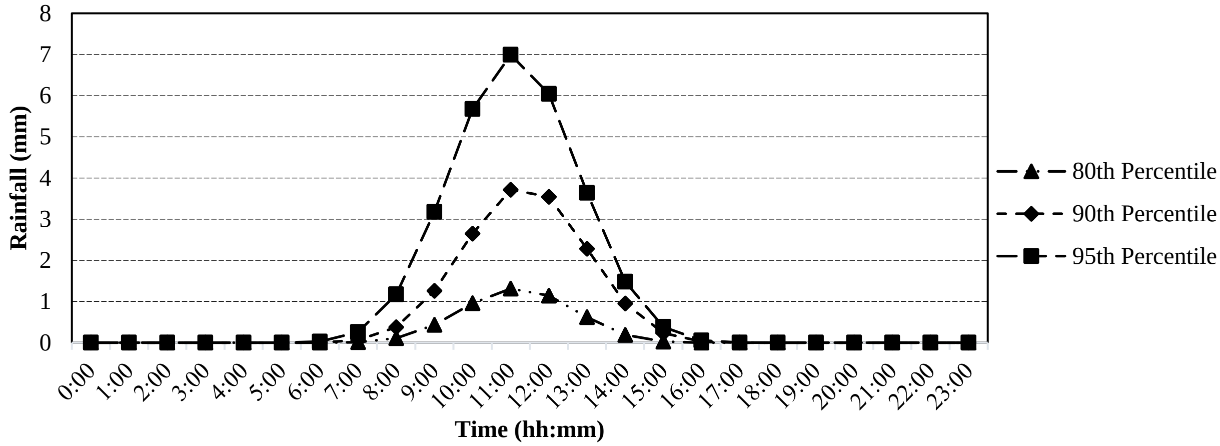


**Figure 6.** Disaggregated rainfall data at 80th, 90th, and 95th percentile

**Water Balance**

In this study, three elements of water balance were assessed in this study, namely, total infiltration, total runoff, and storage. Other elements of water balance were not included due to the lack of real-time data. The total infiltration and total runoff were gathered from the results of the simulations while the storage was calculated by subtracting the total infiltration and total runoff from the total precipitation of its respective percentile. The SA/CA ratio was the only factor tested for the changes in runoff reduction and stormwater collection that was utilized and modified. Since all the three subcatchment areas produced similar results at all percentiles, only one subcatchment area was used to represent the results. Subcatchment 1 was selected because it covered the largest area compared to the other subcatchments. Regression curves were then later plotted to determine the changes observed on the water balance elements as the SA/CA ratio increased based on each percentile used.

In Figure 7, it was observed that the initial runoff before the PP was applied was more than 90%, while the total infiltration was less than 10% of the precipitation at 80th percentile. Once the increment of 10% SA/CA ratio was applied, the total runoff immediately dropped to 0% while the sum of the total infiltration and storage reached 100% composition. These values remained constant as the SA/CA ratio increased to 100%, in which the subcatchment area was entirely covered with PP. The graph of the total infiltration reached its peak when the SA/CA ratio was between 10% and 20%. After it reached its peak, the graph of the total infiltration declined. In contrast, the graph of the storage increased as more area was covered by PP in comparison to the subcatchment area. Additionally, the total runoff and the sum of the total infiltration and storage intersected at 4% SA/CA ratio, meaning water balance was obtained at this SA/CA ratio.

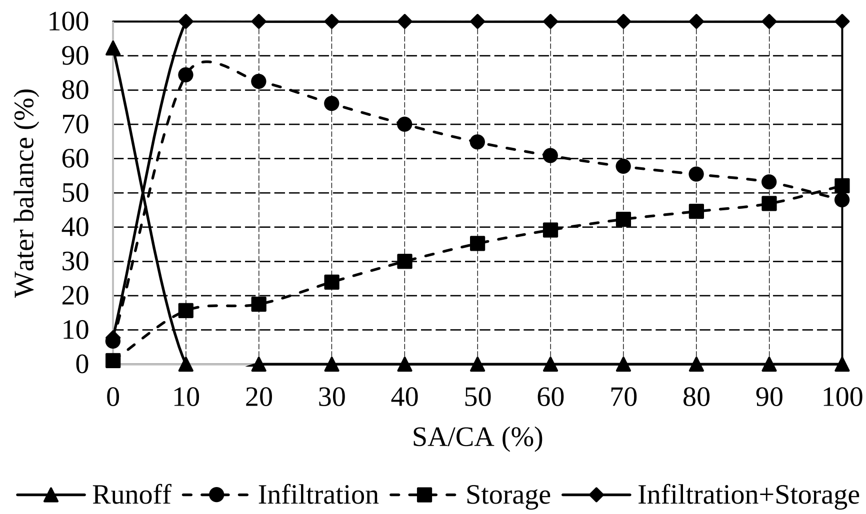


**Figure 7.** Water balance elements with respect to SA/CA ratio at 80th percentile rainfall

As seen in Figure 8, at least 95% runoff and at most 5% infiltration were observed at the selected areas before PP was applied for the 90th percentile rainfall. The increase of the SA/CA ratio reduced the total runoff, reaching 0% runoff and 100% sum of total infiltration and storage at 30% SA/CA ratio. Peak total infiltration occurred between 30% and 40% SA/CA ratio and, similar to the trend observed on the 80th percentile rainfall, total infiltration decreased while the storage increased as the SA/Ca ratio continued to increase until it reached 100% coverage.

Furthermore, the balance between the total runoff and the sum of the total infiltration and storage occurred near the 10% SA/CA ratio.

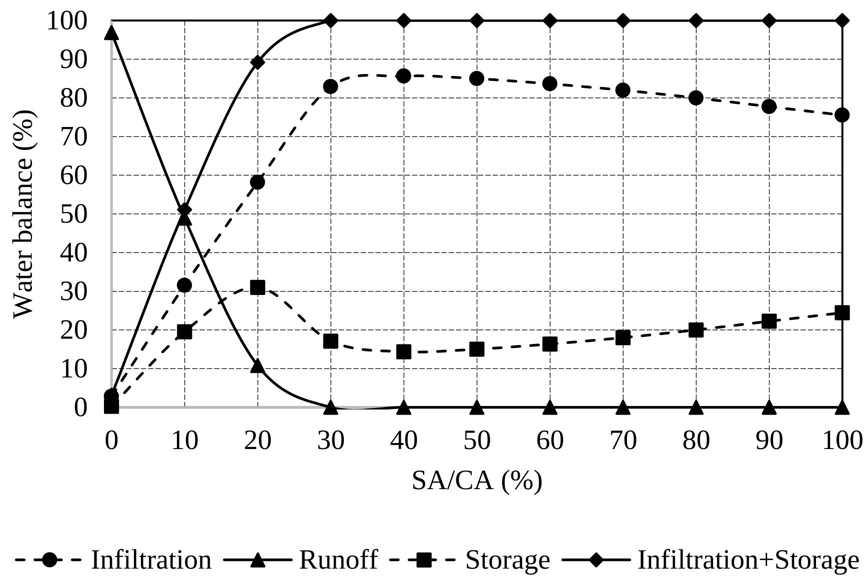


**Figure 8.** Water balance elements with respect to SA/CA ratio at 90% percentile rainfall

For Figure 9, the total runoff at 0% SA/CA ratio was near 100%, while total infiltration was near 0%. Similar to the results from the 80$^{th}$ and 90$^{th}$ percentile rainfall, the total runoff was reduced by the increase of the SA/CA ratio and eventually reached zero runoff at 50% SA/CA ratio. At the same time, the sum of the infiltration and storage components increased until the subcatchment captured all the rainfall. Next, peak infiltration was observed at 70% SA/CA ratio, and the amount of water stored increased further as the area increased. Lastly, the total runoff and the sum of the total infiltration and storage intersected at 19% SA/CA ratio.

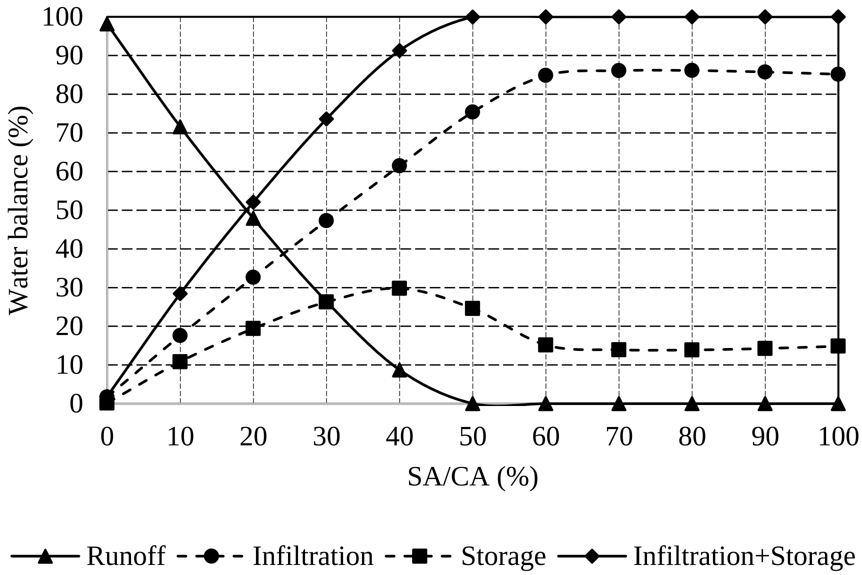


**Figure 9.** Water balance elements with respect to SA/CA ratio at 95th percentile rainfall

In summary of all three figures, runoff was mostly observed in all three percentiles at more than 90% composition of the water balance since the selected subcatchment areas have minimal vegetation; thus, these results could be set as the control group to compare with the other results once PP was applied as its area coverage increased. Next, it was observed that once the first 10% SA/CA ratio was implemented at 80th percentile rainfall, it reached 0% total runoff, implying that the PP was successful in capturing all the rainfall as shown on the line for the sum of the total infiltration and stored rainfall. The result for the 80th percentile capturing all rainfall may be due to the small amount of rainfall present in the 4.80 mm, causing the PP to capture precipitation easily.

Next, increasing the SA/CA ratio at all percentiles decreased the runoff until it approached a specific value. For instance, the amount of water stored at 10%, 30%, and 50% SA/CA ratio at 80th, 90th, and 95th percentile rainfall, respectively, increased as the SA/CA ratio further increased; these are the SA/CA ratios after the peak infiltration where all precipitation was taken. Also, similar studies show that the amount of area covered by PP can improve its effectiveness in other fields. In the study of Choi et al. (2015), the increase in the area covered by LID caused PP to be more effective in pollutant removal and runoff reduction. The study of Jin et al. (2010) also found similar results, in which the increase of the area covered by the sunken lawn and permeable brick can effectively reduce the runoff coefficient and increase the amount of water stored. From these collected values and similar studies, it can be concluded that PP can be an effective means to reduce runoff and store rainfall, as zero runoff can be observed as the SA/CA ratio reaches a certain value. Also, the amount of rainfall stored increased as the area covered by PP increased, meaning more rainfall is successfully filtered and stored which can later be utilized as a water source.

Lastly, the intersection of the total runoff and the sum of the total infiltration and storage were found within 0% to 20% SA/CA ratio in Figures 7, 8, and 9. Upon data interpolation, the intersections were found to be at 4%, 10%, and 19% SA/CA ratio for 80$^{th}$, 90$^{th}$, and 95$^{th}$ percentile rainfall, respectively. These ratios can be considered as the optimal SA/CA ratios for their respective percentiles since there was an equal amount of water inflow and outflow within the PP system, thus, achieving water balance. For this study, the 95th percentile rainfall was used as the standard percentile because it had the nearest value to actual rainfall events.

## CONCLUSIONS

In conclusion, PP is an effective method for reducing runoff and an alternative water source once it captures and filters rainfall. First, based on Figure 3, the 80$^{th}$, 90$^{th}$, and 95$^{th}$ percentiles were 4.80 mm, 15.09 mm, and 28.89 mm. Second, in Figure 4, peak rainfall occurred in the middle of the day, but these data were influenced into being distributed proportionally. Third, based on the simulation results, PP can be utilized as a feasible means to minimize rainwater runoff as illustrated on Figures 7, 8, and 9. The total runoff continuously decreased until it reached 0% when the SA/CA ratio reached a particular value, specifically, 10%, 30%, and 50% for Figures 7, 8, and 9, respectively. Fourth, from the same figures, it was observed that increasing the SA/CA ratio resulted in the increase of the culmination of the other water balance elements discussed until all rainfall was infiltrated and stored in the pavement. Lastly, the optimal SA/CA ratio where water balance was observed was at 4%, 9%, and 19% for 80$^{th}$, 90$^{th}$, and 95$^{th}$ percentile rainfall, respectively, since these were the intersections of the total runoff and the sum of the total infiltration and storage. Since the 95$^{th}$ percentile is deemed as the standard percentile, the most ideal SA/CA ratio is 19%.

Based on these results, PP can be a possible solution to reduce runoff and, at the same time, harvest filtrated stormwater. This study can be utilized as a framework for future researchers involving the usage of PP for urban development. Future studies may incorporate factors that affect the performance of a pavement that were not considered in this study, such as the occurrence of clogging, the composition of the PP, the volume of rainfall, the age and quality of the PP, the nature of the precipitation and its pollutants, the presence of evapotranspiration, and many other factors. Actual hourly rainfall data from rainfall stations can be collected and applied on SWMM while data from actual test runs on the subcatchment areas can be gathered and later compared with the simulation results of this study.

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## ACKNOWLEDGMENTS

The research proponents would like to express their gratitude, first, to the institution, De La Salle University Integrated School for providing the opportunity to contribute to society and the country through this research. Second, to previous and fellow researchers, especially the authors of similar studies, for their hard work which aided the proponents in constructing the contents of this study. Third, to their adviser and co-author, Dr. Marla C. Maniquiz-Redillas, for her continuous guidance and support throughout the composition of this study. Lastly, to their adviser's research assistants, Rey Angelo Frias, Miguel Enrico Robles, and John Joshua Castro, for their additional suggestions and contributions which aided the improvement of the progress and content of the study.

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