Effectiveness of Permeable Pavements and Vegetative Swales for Developing Sponge Cities

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Research Article

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Abstract

As communities grows, the area covered by rooftops and concreted surfaces increases. Rain water which would have infiltrated, flows across these impermeable surface carrying pollutants along the way. This causes frequent flash floods in urban areas. Effective storm water management is needed for the sustainable development of communities. In this study the runoff generation for a small catchment is quantified and the effectiveness of low impact development (LID) practices (permeable pavements (pp) & vegetative swales) in mitigating the runoff at the source itself is studied using Storm Water Management Model (SWMM). The most influential design storm and the soil type pertaining to the study area were the determining factors for evaluating the impact of LID's. The steady flow model and Hortons's infiltration parameters for the soil type in study area were adopted for the analysis. The permeable pavements and swales performed well in reducing the runoff but the swales were less efficient in reducing the runoff, and the runoff reduction potential of permeable pavements and swales are 4.48% and 2.05% respectively. Runoff reduction is more efficient in case of combination of permeable pavements and vegetative swales as LIDs. The percentage reduction in runoff is about 6.05% and the efficiency of the combination type LID is about 17%. The results from simulation show that the low impact development practices are efficient in mimicking the pre-development hydrologic conditions of the landscape to a great extent.

1. Introduction

An urban area is the core of all economic and administrative activities of a developed country. The progression in urbanization leads to the change in the landscape thereby affecting the natural hydrologic cycle of the landscape. The major natural disaster that the city may face is the urban flooding as all the natural course of the water have been disturbed due to the development in urban area. The increase in the imperviousness due to the rise of buildings and pavements lead to reduction of the infiltration of the precipitation and almost the whole of precipitation becomes runoff causing eventual flooding. The sponge city is based on low-impact development and construction model, and is supported by the flood control system, giving full play to the natural accumulation, penetration, purification and relaxation of green space, soil, rivers, and lakes.

Sponge city construction should adopt corresponding engineering and non-engineering measures according to the land use of different scales of rainwater (Shuhan et al.,2018). Mariana et al.(2018), states that the low impact development (LID) practices reduced the flood risk in a coastal region of South Brazil that witnessed high rainfall intensities. For this case study the best results were obtained when the combination of LID units namely detention ponds, infiltration trenches, and rain gardens were used. Low impact development (LID) is a landscape planning and implementing strategy for managing storm water at the source with decentralized micro-scale control measures. Since the emergence of LIDs, they are being successfully used to manage storm water runoff, water quality improvement, and for the protection of the environment (Laurent et al.,2012).

Storm water needs to be properly managed as it effects the hydrology of the landscape, the water quality and also the conventional storm water management system. The conventional storm water management system is efficient in removing the water quickly and prevents flooding but it creates a burden to the downstream water bodies as it increases the magnitude and frequency of floods. The storm water runoff can be effectively managed by reducing the quantity of storm water generated in the first place by maintaining and working with the hydrology of a site and controlling the storm water at the source itself (Minnesota storm water manual, 2006).

LID (Low Impact Development) practice like bio retention cells is effective in retaining large volumes of runoff and contaminants on site, and reduced concentrations of certain pollutants like metals. Porous pavements are effective in allowing storm water runoff through it. Green roofs retain a large percentage of rainfall (63% on average) in a variety of climates. The LID approach results in increased retention of storm water and contaminants on site, and helps recreating the predevelopment hydrologic function of the landscape. (Dietz, 2007).

SWMM, the storm water management model introduced by the EPA, was used for the dynamic rainfall-runoff simulation model for either single events or long-term (continuous) simulation of runoff quantity and quality, mainly from urban areas (Rossman, 2010). Chunlin Li et al.(2016) states that SWMM comprises four components, such as runoff, storage/treatment and transport. In order to achieve the analysis of urban flood disaster, different hydro information of the urban catchment is required in the establishment of SWMM, which are collected, processed and estimated as the model parameters (Nester et al., 2014). Rainfall–runoff (RR) models are used for various hydrological applications like the estimation of catchment runoff to analyzing the effect of change in land use on runoff. The methods of synthesizing the rainfall–runoff process is different for each model; a model classification also exist.

2. Methodology

In this study the software EPA SWMM Version 5.1.014 is used for modelling runoff. The surface runoff generated is quantified for a base case and by implementing the LID module. The runoff generated is studied in with and without LID case to understand the effectiveness of LIDs in runoff reduction. Here the LIDs considered are Permeable Pavements and Vegetative Swales. The input parameters for the SWMM includes the hydrologic, physical parameters derived from Arc GIS and rainfall intensities from Intensity Duration Frequency Curve.

3.1 Study Area Description

The study area identified is the college campus of Government Engineering College Barton Hill, Trivandrum located at 8.505157°N and 76.940817°E. To understand the applicability of SWMM this study area was selected since the data required for modelling was easily available and the campus has a highly varying topography. The study area includes many roads buildings, roads, and vegetation which resembles a semi urban catchment as shown in figure 1.

2.2 SWMM Modelling

A detailed Total station survey was conducted to find the location of each spatial feature in the campus. The elevation data from Total Station Survey was transformed to DEM using Arc GIS. All the parameters required for SWMM modeling were derived using geometry and hydrology tool. The natural drainage pattern of campus was derived from flow accumulation raster. Then the sub catchments were delineated and modelling was done. The delineated sub catchments is shown in figure 2. The parameters such as area width slope and imperviousness of each sub catchments were determined.

According to the land use land cover type of the sub catchments, Manning coefficient and Depression storage values were determined. Hortons Infiltration Parameters of the different soil types were taken from Hossain et al., 2019. The elevation of outlets is available from DEM. The modelling parameters estimated are shown in table 1.

Table 1 Modelling Parameters

Sub catchments	Area (m2)	Width (m)	Slope (%)	Imperviousness (%)	Pervious cover (m2)	N pervious (Manning" coeff)	N impervious (Manning" coeff)	D pervious	D Impervious
S1	880.97	21.21	126.51	80.71	169.92	0.15	0.0122	0.2	0.05
S2	3165.76	34.44	24.93	53.94	1457.91	0.24	0.0122	0.2	0.05
S3	1182.35	23.837	20.19	21.1	932.78	0.15	0.0123	0.2	0.05
S4	2268.87	37.05	23.26	61.822	866.21	0.24	0.0122	0.2	0.05
S5	3582.26	30.99	56.55	60.72	1407.22	0.24	0.0125	0.2	0.05
S6	10829.24	56.23	50.99	64.58	3835.7	0.24	0.0123	0.2	0.05

2.3 Preparation of design storms

The Intensity Duration Frequency Curve was plotted for different durations and the design storms were derived from the hourly rainfall data available from the year 2005 to 2018 from IMD. The IDF curves were generated using Gumbel's Type I distribution and shown in figure 3. Design storms in mm/hour for the Return Period 2-year was derived from IDF curves.

2.4 Runoff Modelling

The runoff was modelled by assuming the flow to be steady and Hortons Infiltration method is the routing model used. The evaporation loss is assumed to be zero and assumption was made that the study area is having a uniform composition of soil. As the modelling progressed all the flow from each sub catchments were routed to one single outlet to allow the mixing of flow and it is shown in figure 4. The LID module was implemented in SWMM as permeable pavements and vegetative swales as LIDs. The effectiveness of the LID in reducing the runoff is analyzed by considering with and without LID cases for 2-year design storm.

In this study permeable pavements and vegetative swales were selected as the LIDs as all the sub catchments have a fixed percentage of pavements that can be transformed to permeable pavements and also a fixed percentage of pervious area is transferred to swales. The 2-year design storm and the soil type loamy soil (pertaining to study area) is considered for the simulations of the LIDs to represent an average site behavior. The input parameters for LIDs were both assumed by referring various literature. For the surface layer the berm height was taken to be 150mm as the site is having an embankment of 150mm. Surface roughness for the concrete paver blocks were taken as 0.012(from SWMM User's Manual). The pavement and the storage layers are usually designed to be highly permeable, and 254 mm/h can be a reasonable value within the possible ranges [Bean et.al]. The soil layer and drain has been opted out in this study. The input parameters of LID were adopted as in Table 2. The cross section of permeable pavements and vegetative swales are shown in figure 5.

Table 2 Input parameters for LID

Input parameters for LID (Permeable Pavement & Vegetative Swales)				
Layer	**Parameters**	**Unit**	**Permeable Pavement**	**Vegetative Swales**
Surface	Berm Height	mm	150	150
	Vegetation Volume Fraction		0	0.1
	Surface's roughness		0.012	0.15
	Surface slope	%	1	0.8
Pavement	Thickness	mm	150	-
	Void Ratio		0.16	-
	Permeability	mm/hr	254	-
Storage	Thickness	mm	225	-
	Void Ratio		0.4	-
	Seepage Rate	mm/hr	3.3	-

The hypothetical analysis of permeable pavements was conducted by replacing the 100%,75%, 50%, 25% pavements to permeable pavements and for the swales the analysis was done for 5%, 10%, 15% and 20% of the area of the sub catchments. The swale parameters were both assumed and adopted from various literature and Low Impact Development Stormwater Management Planning and Design Guide. This study deals with 4 scenarios

1. Case 1: Base case – without LID
2. Case 2: With Single LID – Permeable Pavements (PP) Only
3. Case 3: With Single LID – Swales Only
4. Case 4: With Combination_1 LIDs – PP + Swales

In this study the runoff generated without any LIDs were taken as the base case for the analysis. In case 2 with Single LIDs, permeable pavements were selected as the LID as all the sub catchments have a fixed percentage of pavements that can be transformed to pedestrian ways. The SWMM routing with permeable pavements as LID was performed with a hypothetical analysis of replacing the existing pavement by 4 different ways, and the selection of a feasible percentage of permeable pavements as per the site constraints was selected. In case 3 with Single LIDs, Swales was introduced in an incremental fashion in each sub catchments. Then the most feasible percentage of swales for the site conditions is selected. In case 4 the combination of LIDs with permeable pavements and vegetative swales is being studied. The runoff reduction potential in each case and the effectiveness of the LIDs are measured by their efficiency in reducing the runoff.

$$\text{Efficiency in runoff reduction is given by} = \frac{(\text{Total Precipitation} - \text{Runoff generated}) * 100}{\text{Total precipitation}} \quad (1)$$

3. Results & Discussion

The surface runoff generated in case 1 is 271.262mm. In case 2 the surface runoff is highest for the 25% replacement of permeable pavements and least for the 100% replacement of permeable pavements as shown in Fig. 6. It indicates that the runoff reduction is maximum in case of 100% replacement which comes to about 9.28% when compared to the base case. The percentage reduction in runoff is 4.48% ,8.87% and 9.07% in case of 25%,50% and 75% replacement of permeable pavements as shown in Fig. 7.

In case 3 the surface runoff is highest for 5% swales of about 265.659mm and least runoff is generated for 20% swales of about 241.902mm. For 10% swlaes and 15% swales the runoff generated is 259.162mm and 247.378mm respectively and is shown in Fig. 8. The highest % reduction in runoff is achieved in case of 20% swales of about 10.82% and least is for the 5% swales of about 2.05%. The % reduction is about 4.46% and 6.88% in case of 10% and 15% swales respectively as shown in Fig. 9.

In case 4, a combination of 25 % permeable pavement and 5% swales is adopted. The 25% permeable pavement is selected as the feasible percentage due to site and budgetary constraints and the runoff generated is 259.086mm. 5% swales is selected as the feasible percentage as there is space constraints for the placement of swales beyond 5% and the runoff generated is 265.679mm as shown in Fig. 10. It can be seen that the reduction in runoff in case 2 (for 25% pp) is 4.48% and in case 3 (for 5% swales) it is 2.05% when compared to the no LID case. But in the 4th case when the combination of LIDs was used, the runoff generated is 255 mm which is the least so far. The percentage reduction in sub catchments ranges from 1–6% in case 2 (for 25% pp) and 1–2% (for 5% swales) in swales only case and 3–9% in case 4 which is the combination of LIDs. The efficiency in reducing the runoff is highest (17.07%) in case 4 where the combination of LIDs is used (Fig. 11). By comparing with no LID case we get a 6.05 % reduction in runoff. The swales are less efficient in reducing the runoff but we can use swales when there are space constraints in sub catchments. The efficiency of permeable pavements as LID is 16.33%.

4. Conclusion

- From the results, it can be stated that the LIDs are very much effective in reducing the runoff when compared to a case without LID.
- The efficiency in runoff reduction potential of the different cases is as below:

Case 4 (PP+Swales) <Case 2 single LID PP only<Case 3 single LID Swales only<Case 1, without LID.

- The capacity of the LID to store the runoff plays a major role in reducing the runoff. Out of the single LID, the permeable pavements has means to store storm water.
- The vegetative swales were less efficient in runoff reduction but it is a better choice when area is limiting.
- When there are areas available for converting to parking slots, we can have permeable pavements as a better option.
- By using the combination LID case 4, the runoff was effectively reduced by a percentage of about 6.05%.

The LID input parameters can be subjected to field study and can be calibrated for more reliable results. The unavailability of gauged data also might have resulted in inaccurate results. Besides these limitations SWMM software is a reliable tool in quantifying the runoff and the LID module was quite efficient in studying the effectiveness of the various LIDs in reducing the runoff cycle.

5. Declarations

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Conflict of interest/ Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

Not Applicable

Code availability

Not Applicable

Author Contributions:

Writing - Original Draft Preparation, Investigation, Visualisation, Software: Aruna V

Conceptualization, Methodology, Supervision, Validation: Dr. Suja R

Software, Reviewing & Editing: Rajalakshmi C R

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Figures

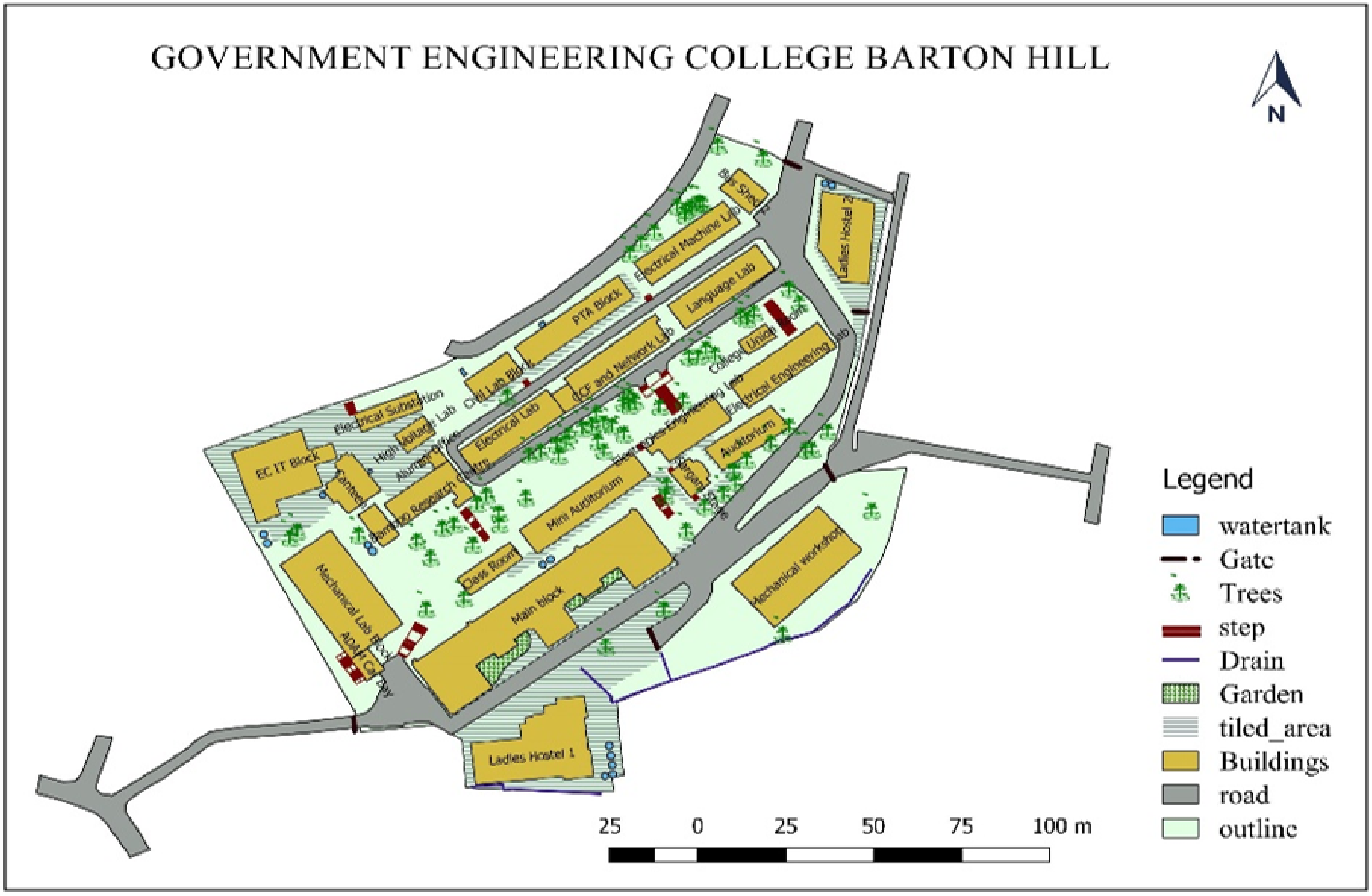

Figure 1

College Campus Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

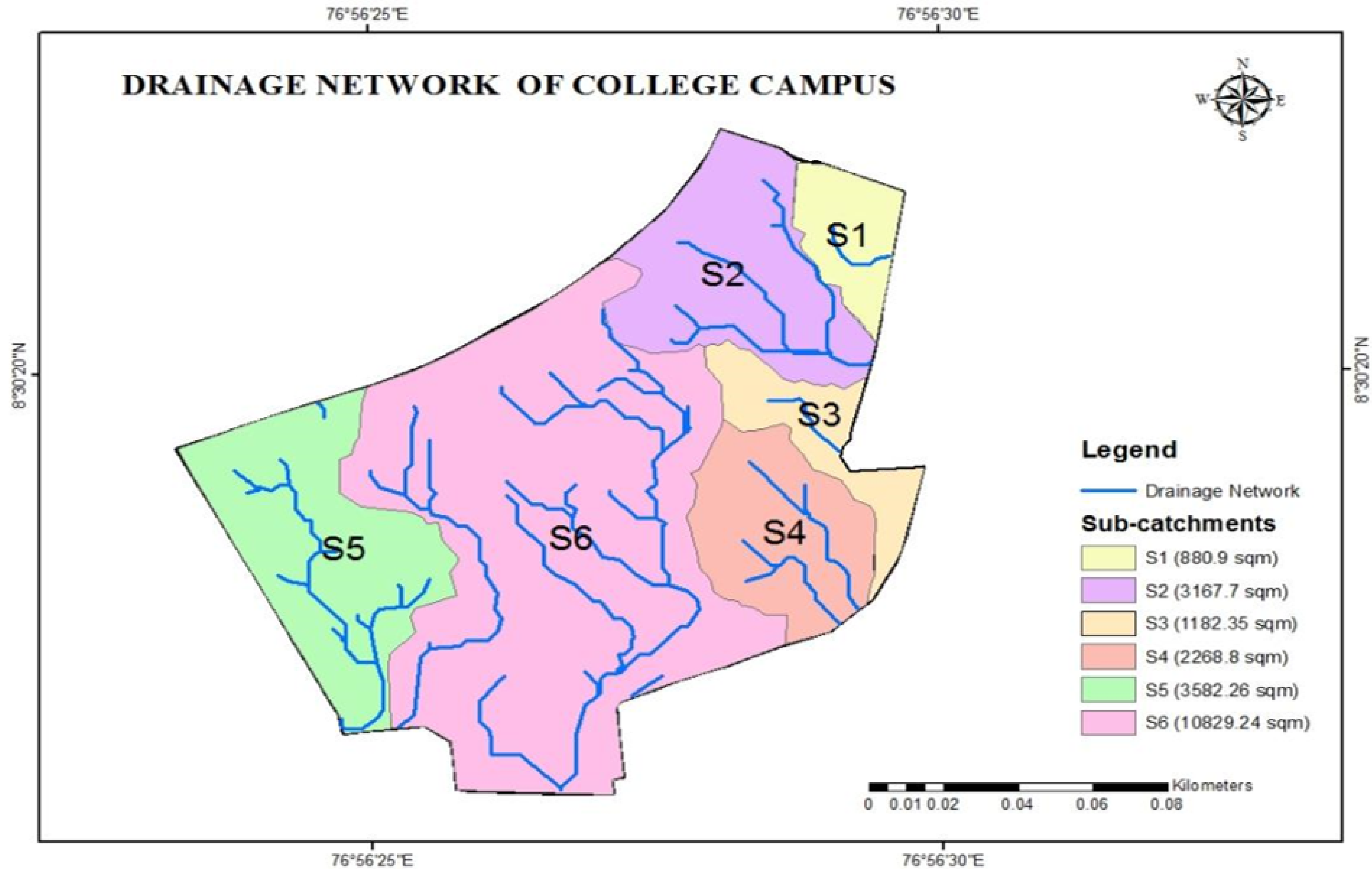

Figure 2

Drainage map of GEC Barton Hill College Campus Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

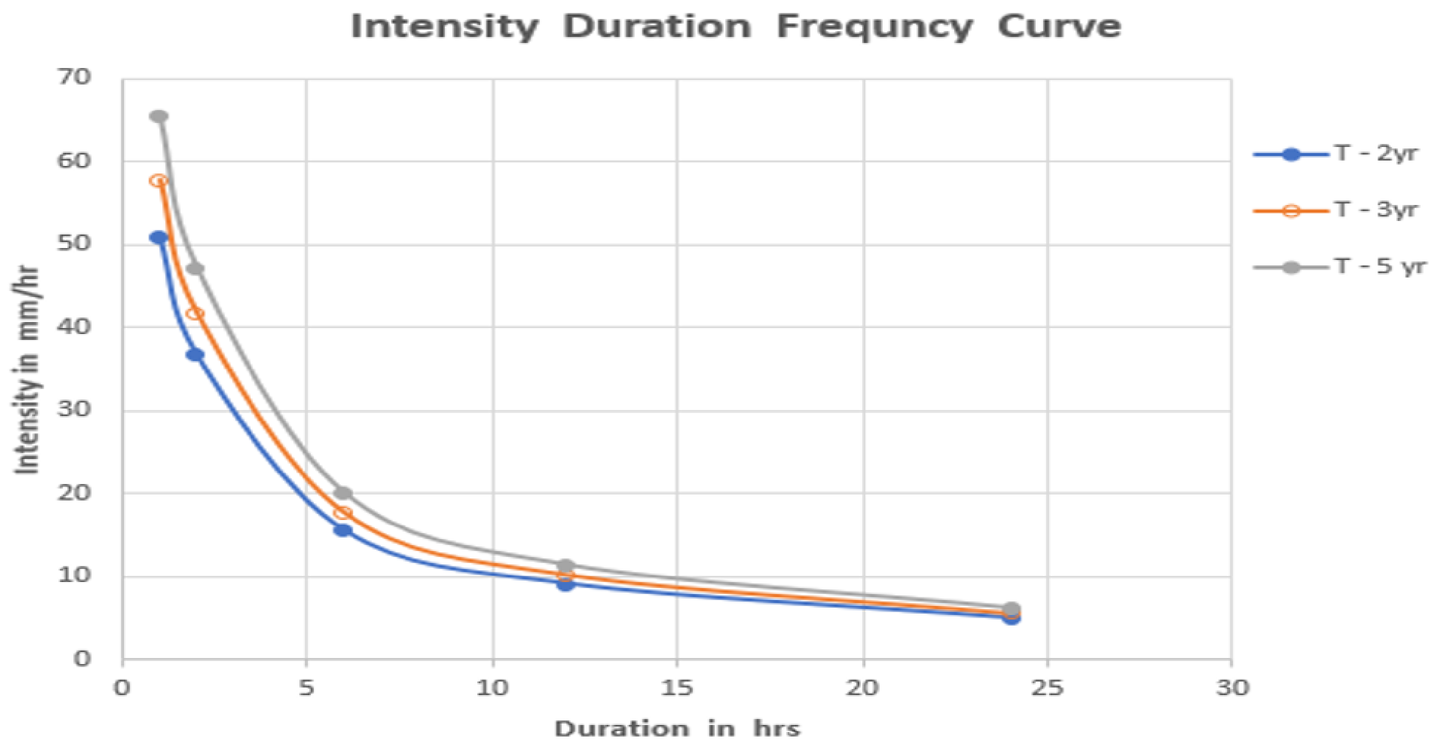

Figure 3

Intensity Duration Frequency Curve

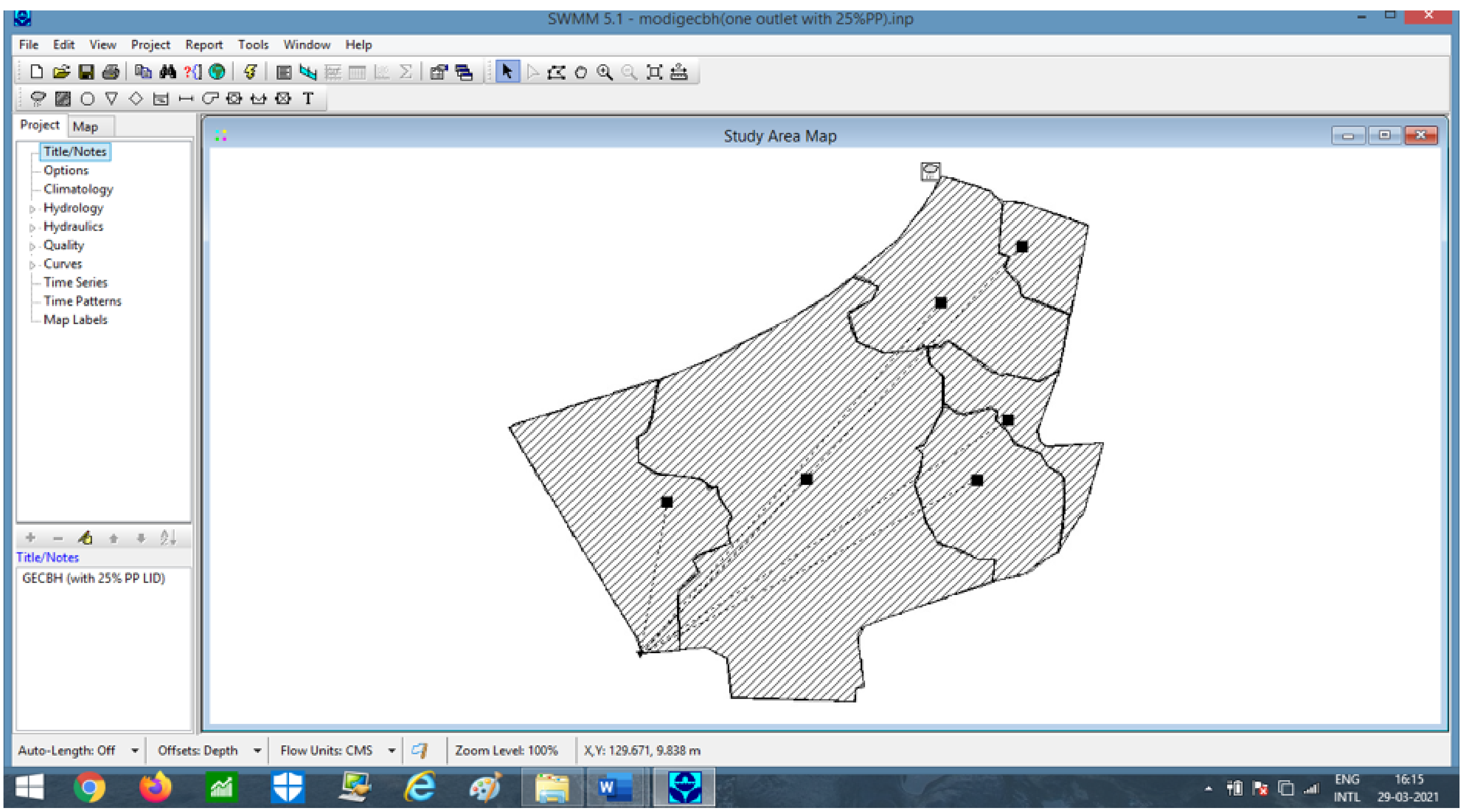

Figure 4

Study Area Map developed in SWMM Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

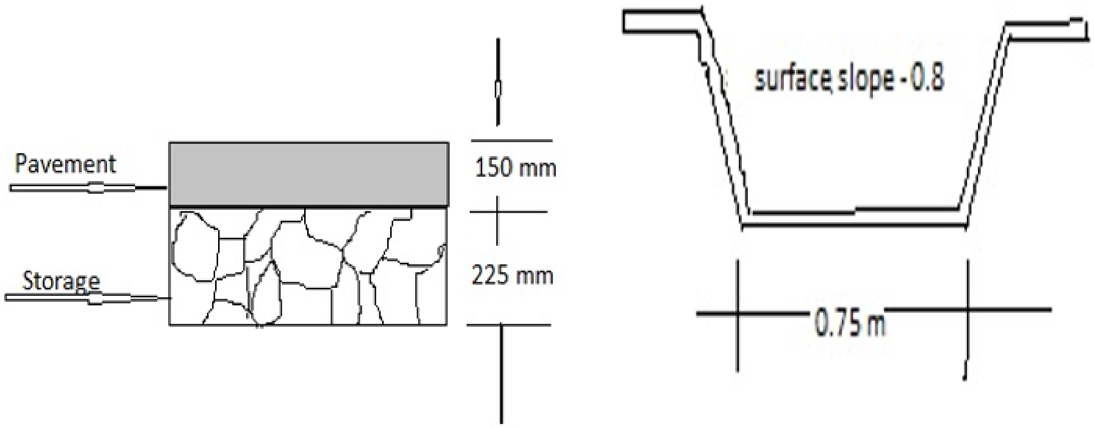

Figure 5

Cross section of permeable pavements and vegetative swales

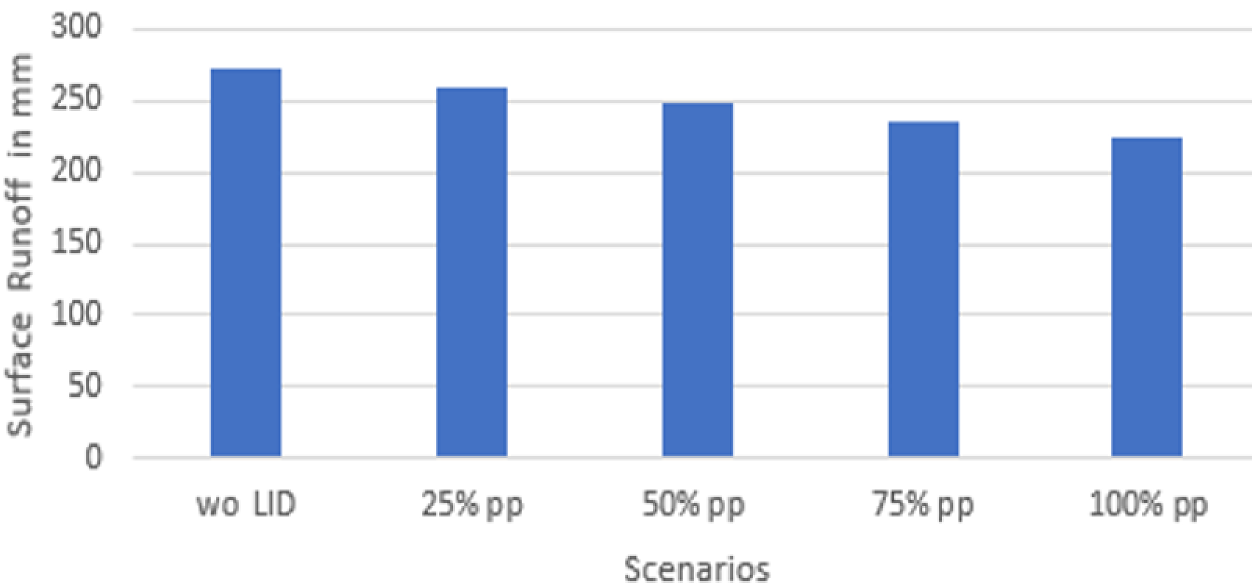

Figure 6

Surface Runoff for various % of permeable pavements

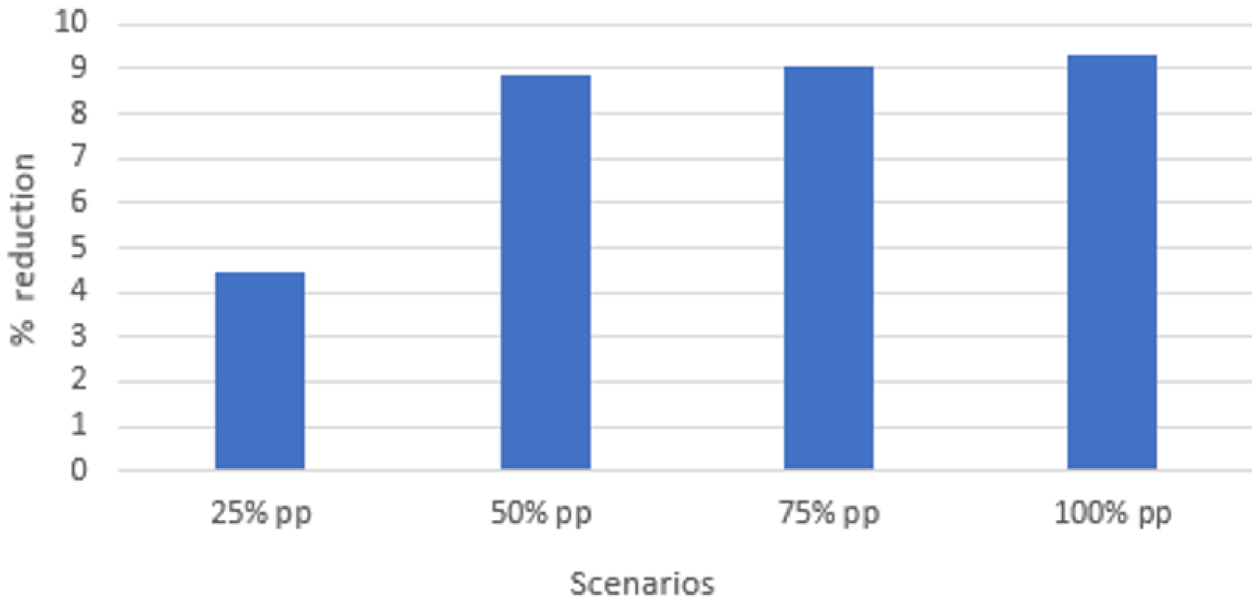

Figure 7

Percent reduction in various cases of permeable pavements

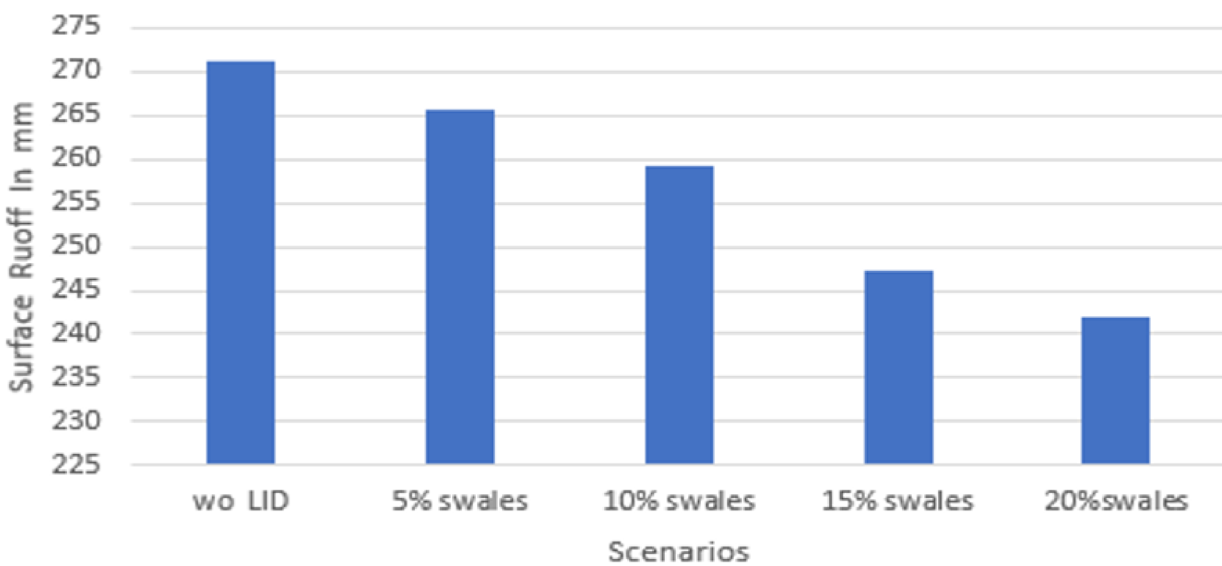

Figure 8

Surface Runoff for various % of swales

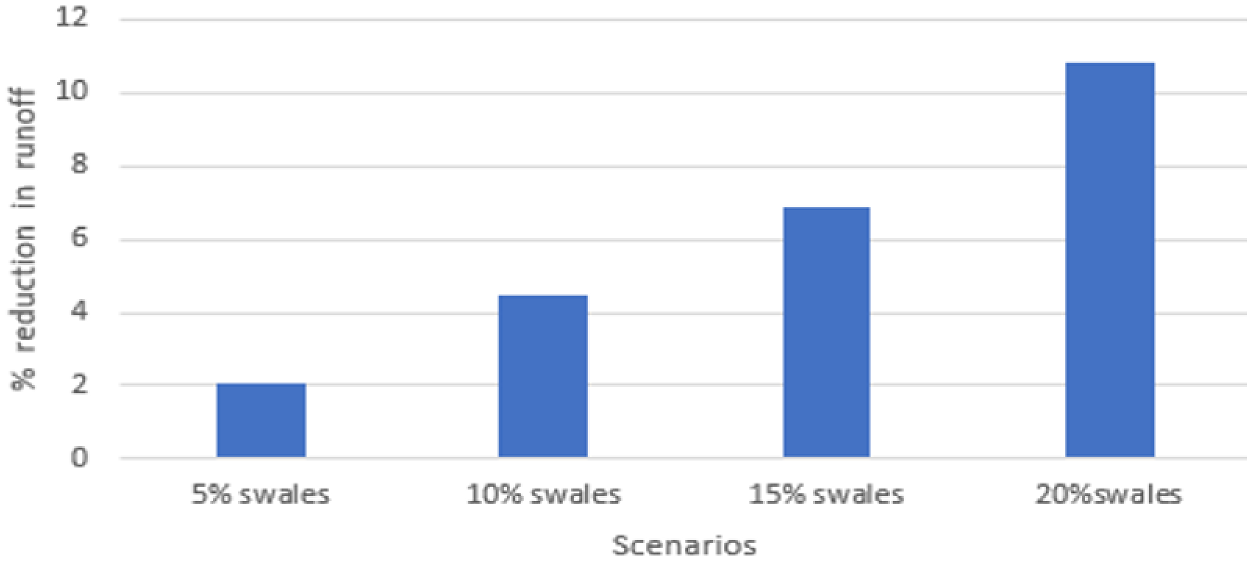

Figure 9

Percent reduction in runoff in various % of swales

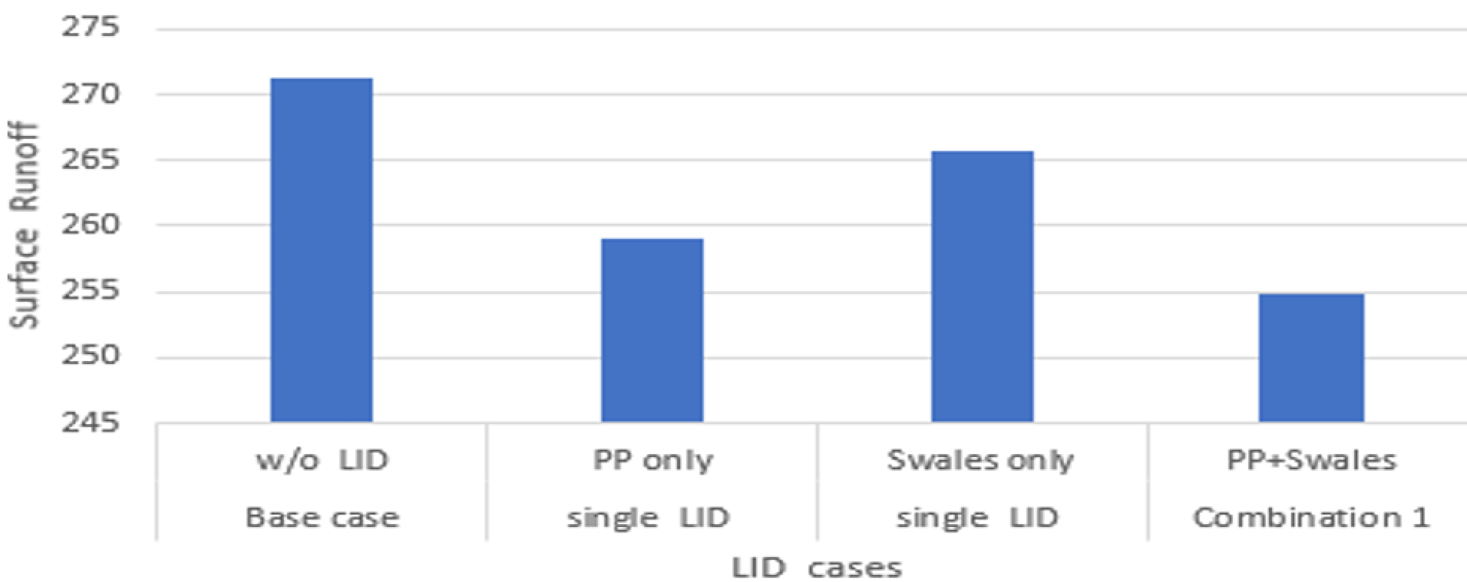

Figure 10

Surface Runoff in various cases

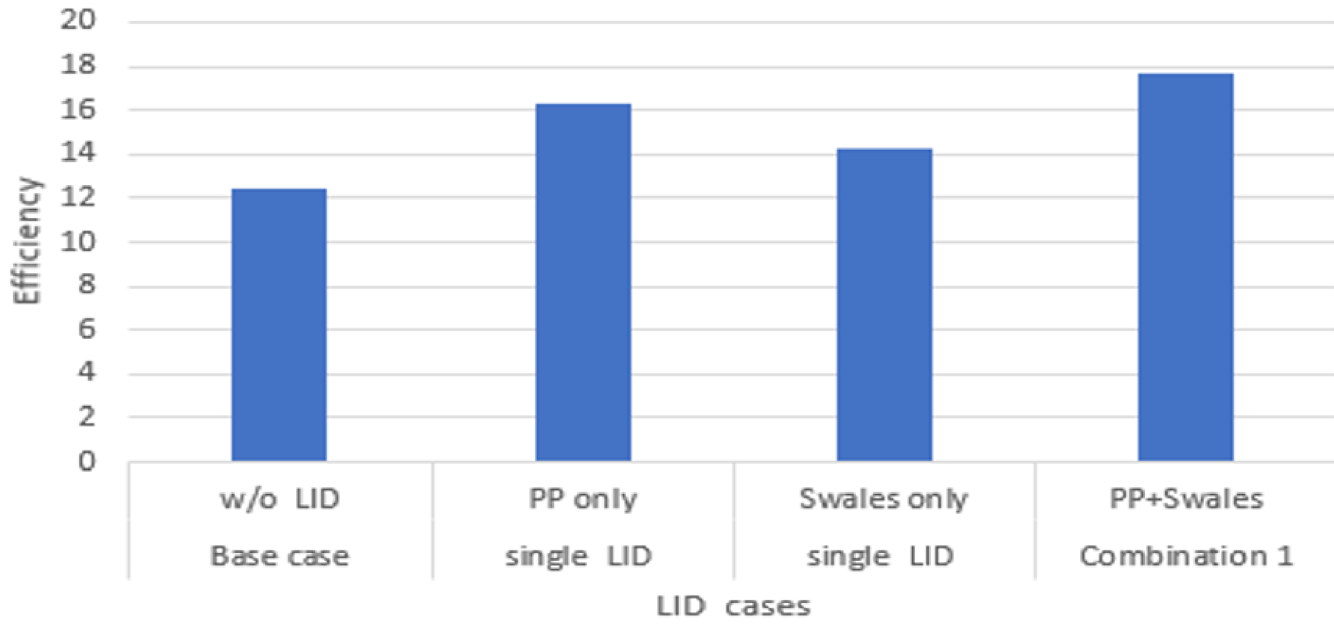

Figure 11

Efficiency in Runoff Reduction in various cases