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Optimisation of Coupled Green Roof and Permeable Pavement for Flash Flood Mitigation

Bentalha Chakib [1)*]

[1)] *Department of Hydraulic Engineering, Abou Bakr Belkaid University, Tlemcen, Algeria.*
* *Corresponding Author. E-Mail: c_bentalha@yahoo.fr*

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ABSTRACT

In recent years, urban pluvial floods have significantly increased, because the rain storm cannot be fully assimilated by a city's drainage system. Climate change and rapid urbanization have contributed significantly to the increase in flood risk. To mitigate floods, low impact development (LID) technologies are sustainable drainage solutions for urban storm water management. This study aims to choose the optimal LID design through twelve scenarios consisting of permeable pavement (PP) and green roof (GR) in different proportions, which were applied in the Boudjlida district of Tlemcen province in Algeria. The optimal scenario is the one that can minimize the peak flow and the run-off volume with the lowest budget. To attain this objective, the Storm Water Management Model (SWMM) is first used to quantify the storm water run-off in sub-catchments and maximum flow in pipes. Then, the cost-effectiveness (CE) method is used to assess the economic benefit of different designs of LID practices in urban areas. The economic benefit is a criterion that balances hydrological performance and costs. This study found that out of 12 LID scenarios proposed, the scenario N° 9 which was constituted by 100% of permeable pavement and 50% of green roof was the optimal scenario. Also, for all combined scenarios, the reduction rate of run-off is between 40.68% and 17.52% and for peak flow, the reduction ranged from 62.23% to 29.52%, indicating the LID control is a powerful tool to mitigate inundations.

Keywords: Green roof, Permeable pavement, Optimisation, Flood, Cost-effectiveness, SWMM model.

INTRODUCTION

For the last decades, urban pluvial floods have become a serious and unavoidable problem in Algeria. The Bab El Oued and Wadi M'zab flash floods are the most catastrophic floods that marked the country during the 2000s causing 760 deadths for the first disaster and 47 deaths for the second (Miloud & Olga, 2023; Hafnaoui et al., 2020). The expansion of urbanization has contributed significantly to the increase in flood risk. Forest and farmland are replaced by buildings, asphalt roads and commercial and industrial areas. These transitions have led to a rapid increase in the impervious area, and the natural hydrological cycle has changed greatly, such as the reduction of infiltration and evapotranspiration and the increase of run-off volumes (Bentalha, 2023). In Algeria, the urban population rate went from 68.2% in 2011 to 74.8% in 2022 (Dallaa et al., 2022). Because of the demographic growth, Algerian cities have undergone major transformations, such as the rapid increase of impervious area as a result of realization of buildings, roads and economic infrastructure.

Climate change has also contributed substantially to the occurrence of urban floods (Almawas et al.,2024). Based on the 5th Assessment Report of the Intergovernmental Panel for Climate Change (IPCC) for the Mediterranean region, where Algeria is located in its south, precipitation with a return period of 20 years will now occur within 15 to 18 years and the precipitation intensity will increase 10% to 20% in the future (Clarisse, 2015). For a return period of one year, an increase of 20% in the intensity of precipitation is expected, whereas for a return period of two years, an increase of 30% is estimated. These alterations will restrict the behaviour of the urban drainage systems, leading to an increase of floods (Clarisse, 2015). Moreover, flooding causes surcharging of manholes and pipes, and may contaminate the groundwater through infiltration and pollute received waters (Hamouz et al., 2020). The common effects of urbanization and climate change represent a significant challenge to resilient cities (Lamichhane & Senjel., 2024).

To reduce the risk of floods, low impact development (LID) technologies are among the solutions to efficiently control rainwater. These technologies aim to replicate as closely as possible the natural flow of water (Bai et al., 2019). LID control practices are designed to capture surface run-off and provide some combination of detention, infiltration, and evapotranspiration to it. Nowadays, the Algerian cities are in a desperate need of these technologies. For example, Abdelkebir et al. (2021) studied the importance of using LID control as a tool to decrease inundations in Guelma province, situated in the north-east of Algeria. However, there are some challenges and obstacles that prevent the integration of LID control into urban planning, such as the financial cost of implementing this infrastructure, limited technical expertise for LID design strategies, missing these tools in building codes and community acceptance of integrating LID control into the surrounding environment.

LID controls include green roofs, bioretention cells, infiltration trenches, rain barrels, roof-top disconnection, rain gardens and porous pavements.

In this study, permeable pavement and green roof were chosen to mitigate the flood problems in Tlemcen, located in the north-west of Algeria.

Green roof practices are designed to capture surface run-off and provide some combination of detention, infiltration, and evapotranspiration to it (Fig. 1) (Rossman, 2022). Green roofs are becoming an alternative to impermeable roofs aiming to integrate the built infrastructure into the landscape and it’s made up of a vegetation layer, a substrate layer and a drainage layer (Aviva et al., 2018). Based on the thickness of the substrate layer, there are two types of green surface; extensive surfaces and intensive surfaces. The maximum depth of the substrate layer for extensive green roof surfaces is 150 mm, but for intensive green roof surfaces, it is more than 150 mm (Mentens et al., 2006).

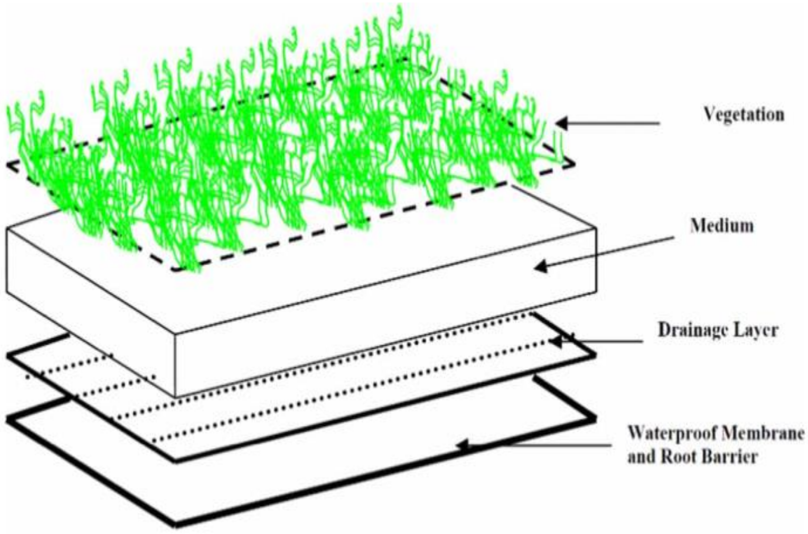

Figure (1): Conceptual model of green roof (Aviva et al., 2018)

Permeable pavement is a well-structured solution for rainwater absorption and is fabricated by highly porous materials (Fig.2). It can be used in walkways, roads, playgrounds, or parking lots, among others (Madrazo et al., 2023). Permeable pavement is designed to capture water on the pavement surface, treat this water while passing it through aggregate layers, store, and infiltrate this water into the groundwater system (Upeka et al., 2019).

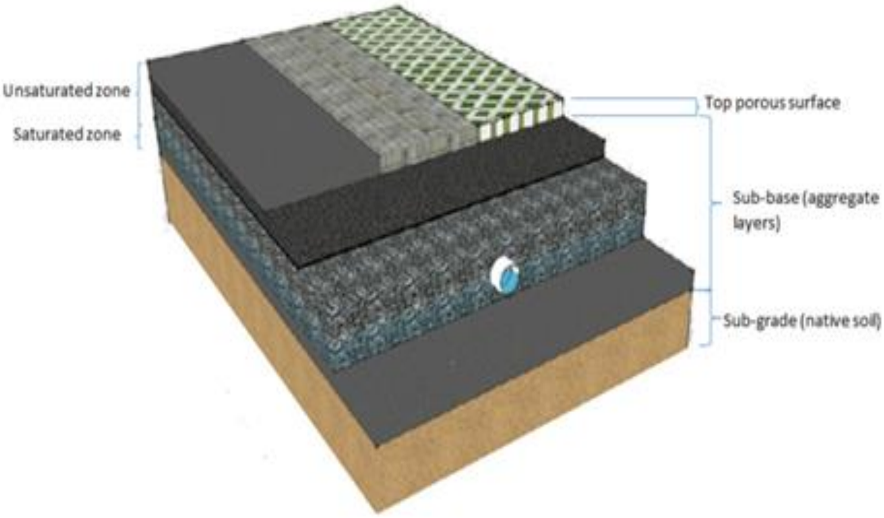

Figure (2): Typical permeable pavement (Upeka et al., 2019)

The hydrological performance of LID practices has been further researched through simulation and laboratory studies. Hamouz et al. (2020) showed from a PCSWMM model, that the peak flow reduces when the area for the green roof increases. Stovin et al. (2015) found from experiments on nine green-roof test beds, that the retention efficiency was greater than 80% with a rainfall depth (P) as little as 10 mm, but it was significantly lower when P > 10 mm. Ronja et al. (2021) used SWMM to improve the representation of the coupled soil–vegetation system of green roofs. Mentens et al. (2006) assessed that rainfall-retention capability on a yearly basis, which may range from 75% for intensive green roofs to 45% for extensive green roofs. Also, the retention of rainwater on green roofs is lower in winter than in summer. Alam et al. (2019) assessed the hydrologic performance of three types of permeable pavement: porous concrete pavement (PCP), permeable interlocking concrete pavement (PICP), and interlocking block pavement with gravel (IBPG). They found that PCP is the most effective type regarding run-off reduction regarding to the other types of pavement. Shouhong et al. (2014) examined the reliability of the LID module of SWMM for simulating the run-off-reduction performance of permeable pavements. Madrazo et al. (2023) explored the hydraulic performance of the permeable pavement module defined in the storm water management model.

Many studies have been conducted to explore the environmental benefits of LID practices, such as retention of storm water run-off and reduction of peak flow, but a few studies focused on the economic cost of LID control and optimization of LID combinations. Bai et al. (2019) analyzed the comprehensive performance of the LID combined scenario based on two aspects: environmental benefits and economic benefits. Shakya and Ahiablame (2021) added another aspect, which is social benefits, to choose the optimal scenario. Amirhossein et al. (2023) used the SUSTAIN model, as well as the TOPSIS and COPRAS methods for optimizing LID scenarios. Yu et al. (2020) and Hou et al. (2022) evaluated the hydrological performance and identified the optimal LID design by using the SWMM model and the life-cycle cost (LCC) method.

In this paper, twelve LID scenarios were proposed and each scenario was constituted by the permeable pavement (PP) and the green roof (GR) with different proportions (Table 1). The Storm Water Management Model (SWMM) with the Low Impact Development (LID) Control Module (version 5.2.1) was used to simulate these LID scenarios. This study aims to optimize the scheme of these LID facilities by using the hydrological cost-effectiveness metrics, as well as to demonstrate the necessity of LID control to decrease floods in Algerian cities.

Table 1. Parameters of green roof in storm water management model (SWMM) (Bai et al., 2019)

Surface	**Berm height (mm)**	**Vegetation volume fraction**	**Surface roughness**	**Surface slope (%)**
	50	0.2	0.13	1
Soil	Thickness (mm)	Porosity	Field capacity	Wilting point
	200	0.5	0.3	0.1
Drainage Material	Thickness (mm)	Void fraction	Roughness	-
	60	0.43	0.03	-

MATERIALS AND METHODS

Study Site

City 46 villa is a residential zone located in Boudjlida town. It is administratively attached to the municipality of Tlemcen, located in the Wilaya (province) of the same name (Fig. 3). The latitude and longitude for Tlemcen are 34° 52' 0.59" north and 1° 19' 12" west. Geographically, it is bordered to the north by the Mediterranean Sea, by the provinces of AinTemouchent and Sidi Bel-Abbes in the north-east and the east, from the west by Morocco and from the south by the province of Naâma. The climate of Tlemcen is typically the Mediterranean climate. It is hot and dry in summer, rainy and cold in winter. The monthly distribution of precipitation (Fig.4) shows that the wettest months are January, November and March. June, July and August are practically dry. The rains are irregularly distributed in time and in space with an annual average ranging from 306 mm to 424 mm (Ghezouane., 2023). Due to urban expansion and an increase of economic activity in Tlemcen, LID practices are becoming more essential to prevent flood damage.

The sanitation network of this city is unitary. The combined drainage network corresponding to this catchment consisted of 9 main collectors with a total length of 3 13m and 8 junctions (Ghezouane, 2023).

SWMM Model

The Storm Water Management Model (SWMM 5.2.1) is a dynamic rainfall-run-off model, developed by the United States Environmental Protection Agency (EPA) for urban/sub-urban areas. The run-off component of this software operates on a set of sub-watershed areas that transform the input data of precipitation into run-off-flow and-pollutant loads (Rossman, 2022). The SWMM is used for the simulation of water quantity, quality and LID controls in urban areas (Kourtis et al., 2018). After simulation, SWMM maps the run-off in each sub-catchment, as well as the flow rate, the velocity and the flow depth in each conduit. SWMM is a free software widely used for analyzing the capability of LID practices to handle run-off (Bai et al., 2019; Ronja et al., 2021).

The characteristics of green roof and permeable pavement applied in this work are presented in Tables 1 and 2, respectively. The Dynamic Wave model was used for hydraulic calculation.

Infiltration computations for the entire study area were based on the Curve Number (CN) method. The CN is a dimensionless parameter determined by two factors; soil type and land use. SWMM (5.2.1) uses the curve number developed by the Soil Conservation Service (SCS), currently known as the Natural Resources Conservation Service (NRCS) (Rosman, 2010). Referring to the SCS table, CN =85 is appropriate for residential zones, while CN=74 is appropriate for green areas. Since the CN of permeable pavement was not mentioned in that table, the CN of gravel, which is 76, was taken for permeable pavement. With the implementation of LID infrastructure in the study site, the land was becoming heterogeneous and in this case, the weighted CN is estimated as the ratio between the sum of each CN value multiplied by its fraction and the total area of the catchment.

Figure (3): Location of the municipality of Tlemcen in Tlemcen province, Algeria

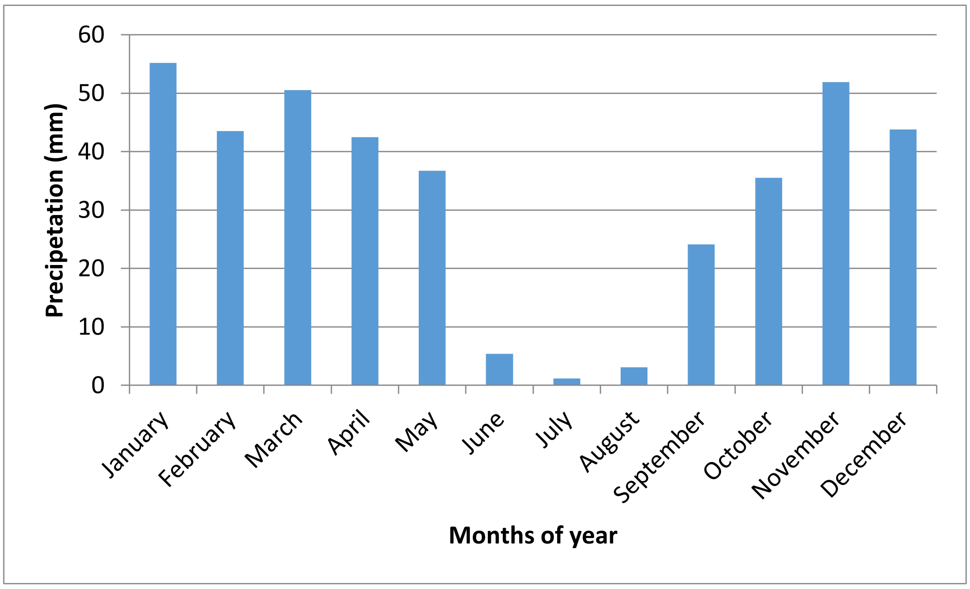

Figure (4): Monthly distribution of precipitation

In SWMM, the design storm is an input data for hydrologic simulation. The design storm used in our calculations is a double triangle with a rainfall duration of 5 hours (Fig. 5). The double triangle represents a synthetic rainfall and it's derived from an IDF (Intensity Duration Frequency) curve. As the sewerage network of the region was sized for a return period of 10 years, this period was chosen to design the storm water. The present work used the IDF formula cited by Marc et al. (2010) for a return period of 10 years, applicable in the north of Algeria:

$$I = 4\, t^{-0.5} \tag{1}$$

where

I: rainfall intensity (mm/min);

t: rainfall duration (min).

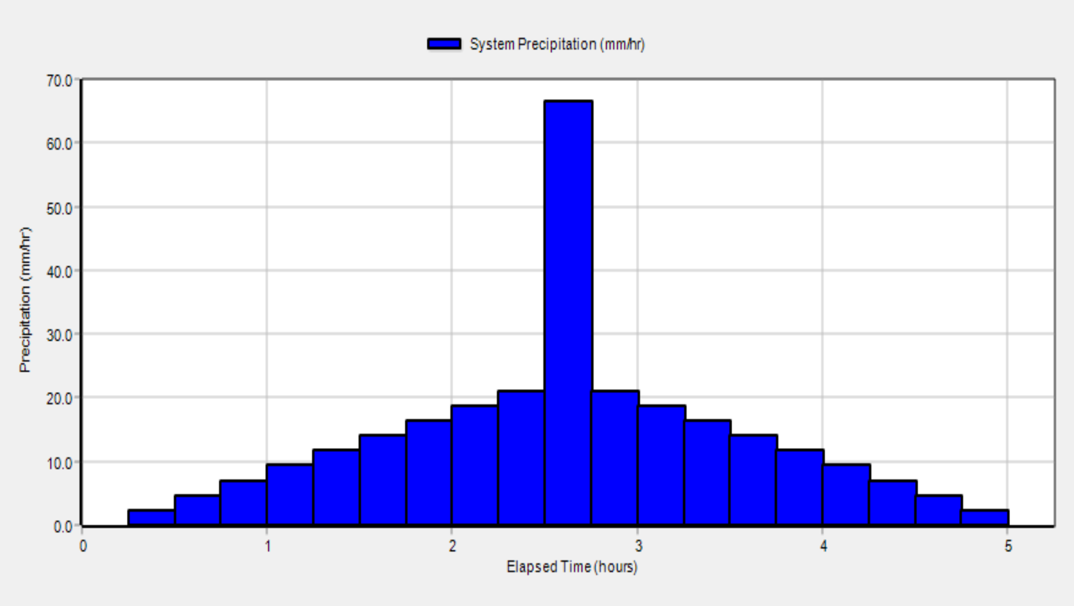

Figure (5): The double-triangle storm design

Table 2. Parameters of permeable pavement in storm water management model (SWMM) (Bai et al., 2019)

Surface	Berm height (mm)	Vegetation volume fraction	Surface roughness	Surface slope (%)
	25	0	0.12	1
Soil	Thickness (mm)	Porosity	Suction head	
	150	0.5	45	
Pavement	Thickness (mm)	Void fraction	Permeability (mm/h)	
	60	0.13	200	
Storage	Thickness (mm)	Void fraction	Seepage rate	Clogging factor
	250	0.43	600	0
Drain	Flow coefficient	Flow exponent	Offset height (mm)	
	0.69	0.5	6	

Equation (1) summarizes the precipitation data collected throughout northern Algeria over a long period, which makes it very useful when the local rainfall measurements are inadequate. The frequency analysis of extreme daily rainfall of two stations located not far from the study area and covering the long period, showed that the total rainfall amount calculated by the Gumbel distribution was ranging from 63.6 mm to 66 mm for a return period of 5 years and from 75.4 mm to 81 mm for a return period of 10 years. The data of the first station, which is Bensekrane station, covers the period from 1924 to 2006 (Belarbi 2010), while the second, which is Hennaya station, covers the period from 1985 to 2010 (Bensayah & Lekhel, 2017).

Several sewerage networks in Tlemcen have been dimensioned using this formula, like the sanitation networks of Chetouane and Marsaa Ben M'hidi (Fandi & Benazza, 2017; Bensayah & Lekhel, 2017).

The study area of approximately 1,23ha was divided into 8 sub-catchments, defined as a function of land use and surface slope (Fig. 6). The houses which are only suitable for converting into green roofs occupied 46.7% of the total area. The permeable pavement can be applied on sidewalks representing about 10% of the total area. The input parameters for the SWMM model are presented in Table 3.

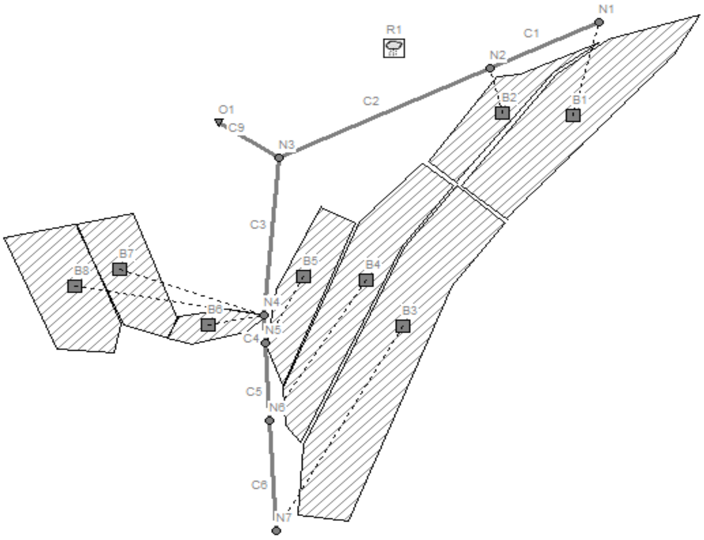

Figure (6): Division of the study area into sub-catchments by SWMM

Table 3. Input parameters for the SWMM model

Sub-catchments	Values
Area	1,23 ha
slope	Min 0.5% max 4%
Impervious area	75%
Curve Number	Min: 78 Max: 85
Manning for impervious area	0.011
Manning for previous area	0.1
Conduits	Values
length	318 m
Diameter	Outer:315 mm and inner:290 mm
Manning	0.01

LID Scenario Design

Depending on the land uses, green roof and permeable pavement are widely used in residential zones consisting of houses, sidewalks and roads (Bai et al., 2019). Based on the study of Ahiablame and Shakya (2016), the coupling between two or three LID practices including permeable pavement is more effective in flood mitigation than individual LID scenarios. So, in this study, combined LID scenarios were adopted. First, sixteen LID scenarios were proposed and each scenario was constituted by the permeable pavement (PP) and the green roof (GR) with different proportions ranging in intervals of 25% from 25% to 100%. Such intervals were used by Ahiablame and Shakya (2016) for creating the individual LID scenarios and Bai et al. (2019) created the combined LID scenarios with intervals of 20%. After simulation by SWMM software, twelve scenarios (Table 4) were selected, because they could eliminate the surcharging of the pipe network.

Table 4. LID infrastructure implementation scenarios

LID	SC	1	2	3	4	5	6	7	8	9	10	11	12
GR	(%)	100	100	100	100	75	75	75	75	50	50	50	50
	Area (ha)	0.57	0.57	0.57	0.57	0.42	0.42	0.42	0.42	0.28	0.28	0.28	0.28
PP	(%)	100	75	50	25	100	75	50	25	100	75	50	25
	Area (ha)	0.12	0.09	0.06	0.03	0.12	0.09	0.06	0.03	0.12	0.09	0.06	0.03

Hydrological Cost-effectiveness

Cost-effectiveness analysis is an indicator that is used to estimate the performance of each LID design taking into account both aspects of hydrological performance and the cost (Hou et al., 2022), The hydrological performance is determined by two parameters; reduction of peak flow and reduction of total run-off volume. The life-cycle cost of every LID scenario is the sum of the initial construction cost and material cost and the annual operation and maintenance cost. Table 5 shows the cost of green roof and porous pavement, which is a function of the LID surface area (A) and the cost of operation and maintenance (O and M) at year 25 (Zhang et al., 2013).

Table 5. Costs for porous pavement and green roof (Zhang et al., 2013)

LID control	Construction cost ($)	Annual (O&M) cost ($)
Porous pavement	59.29×A	4.73×A
Green roof	123.52×A	5.70×A

Due to the lack of this technology in Algeria, the cost of all LID design was calculated by this table.

The hydrological cost-effectiveness (CE) can be expressed by following equation (Yangzi et al., 2021):

$$CE = \frac{(\Delta Q_P + \Delta V)/2}{PVC\ A_{SC}} \tag{2}$$

where PVC and A_{SC} are the present value and the surface area of the LID scenario, respectively, ΔQ_p and ΔV are the peak flow and the total run-off volume reduction computed with the following equations (Yangzi et al., 2021):

$$\Delta Q_P(\%) = \frac{Q_{Pbase} - Q_{PSC}}{Q_{Pbase}} \times 100 \tag{3}$$

$$\Delta V(\%) = \frac{V_{base} - V_{SC}}{V_{base}} \times 100 \tag{4}$$

where Q_{Pbase} and V_{base} are the peak flow and run-off volume of the baseline scenario, respectively. Hence, Q_{PSC} and V_{SC} are those for the LID scenario. The baseline scenario means before the addition of the LID control. A higher cost-effectiveness value indicates a better performance at the exact investment cost.

RESULTS AND DISCUSSION

The most available hydrological data includes annual precipitation, monthly precipitation and daily precipitation, but the hourly precipitation or hourly run-off is practically missing, and then the simulated results were not calibrated with the observed run-off event. It should be noted that there are some studies that have been conducted for determining the most preferable LID scenario without calibrations, like the study carried out by Amirhossein et al. (2023) and that carried out by Bai et al. (2019), but if sufficient data is available, the calibration is more recommended to enhance the validity of the results (Amirhossein et al., 2023). Nevertheless, to determine the accuracy of the SWMM results, the total precipitation obtained by SWMM was compared with that obtained by frequency analysis of annual extreme daily rainfall data. The comparison shows that the simulated rainfall depth differences was 69.27 mm between the rainfall depth for a return period of 5 years and that for a return period of 10 years for the two mentioned gauging stations. It’s obvious that the probability of exceedance for the simulated rainfall depth is greater than 80%; so, it can be considered as the extreme rainfall.

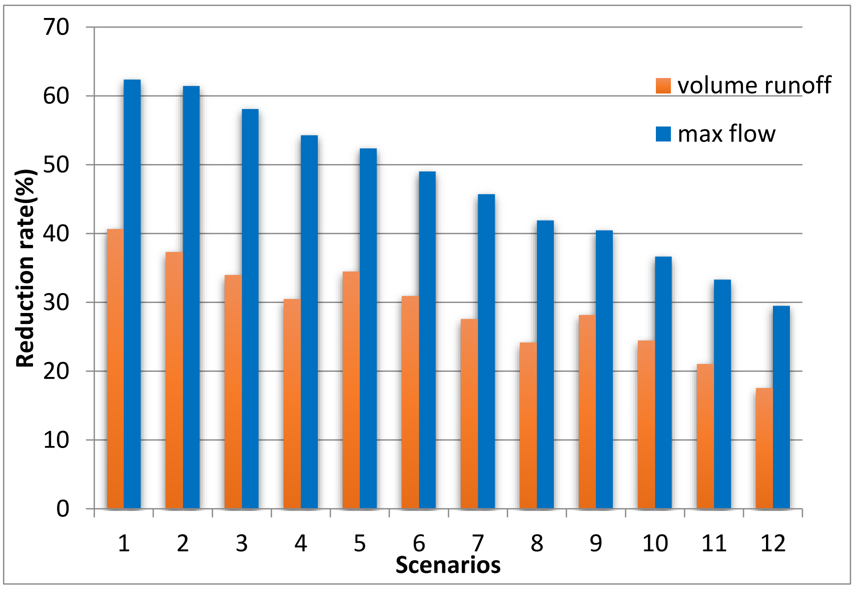

Figure (7): Reduction rates of run-off volume and peak flow

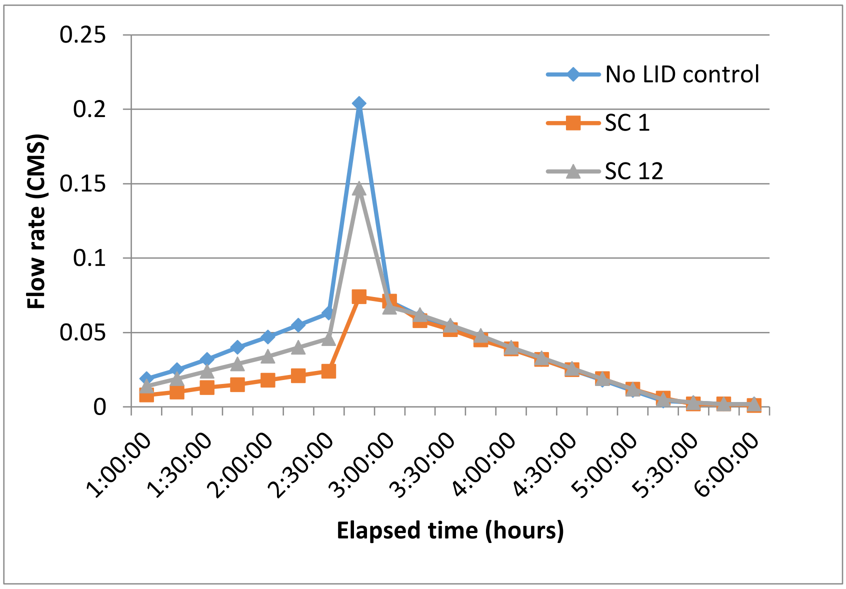

Figure (8): Flow rate at outfall

The hydrological performance is used to evaluate the efficacy of different LID scenarios in flood mitigation. Fig. 7 shows the reduction rates of run-off volume and peak flow for all scenarios. As can be seen from this figure, the reduction rate of run-off is between 40.68% and 17.52% and for the peak flow, the reduction ranges from 62.38% to 29.52%, meaning that the combination of the two LID practices is better for controlling run-off. This result is similar to that presented by Ahiablame and Shakya (2016). This figure indicates also that SC1 had the best performance with 40.68% reduction of water run-off and 62.38% reduction of maximum flow. In contrast, SC12 was the least efficient compared to the other scenarios. At the outfall and with baseline scenario, the maximum flow reached 0.204 m^3/s; then, this value went down to 0.074 m^3/s for SC1 and to 0.147 m^3/s for SC12, confirming the different behaviours of these scenarios (Fig.8). SC1 was composed by 100% GR and 100% PP, while SC12 was composed by 25% PP and 50%GR. It is evident that the reduction rates increase with increasing the LID proportion of the maximum construction area.

Abduljalil and Yonass (2021) found that the performance of LIDs in reducing total run-off volume varies with the type and combination of LIDs utilized. Moreover, from Fig. 7, the maximum flow reduction decreases with decreasing the green-roof proportion, which means that green roofs perform best in the reduction of the peak flow. These results are qualitatively similar to those presented by Palla et al. (2008), who found through simulation that when converting 10% of the impermeable rooftop into green roofs, the peak flow reduces by 5%, and for 100% conversion, the reduction of maximum flow is 51%.

The high hydrological performance of the combined LID does not mean high cost-effectiveness. For example, SC1 had the best performance, but the price is expensive (Fig. 9).

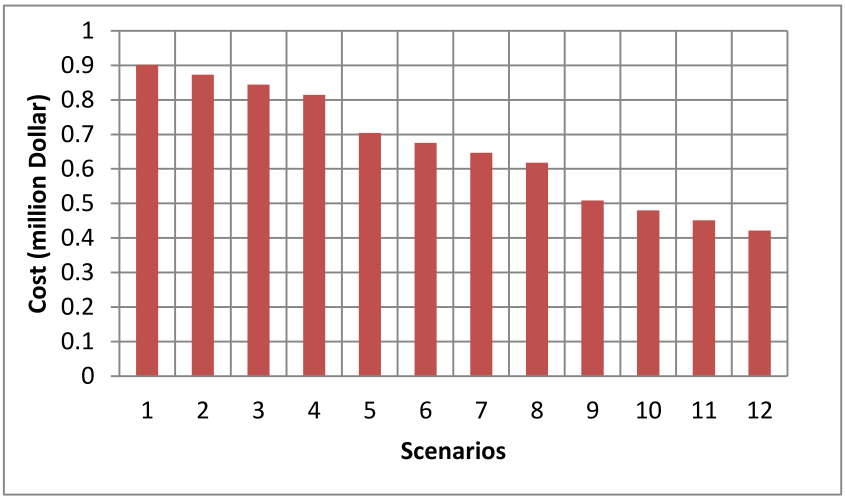

Figure (9): Costs of the twelve LID scenarios

The cost-effectiveness of all schemes is depicted in Fig. 10. In terms of cost-effectiveness evaluation, the order is SC9 > SC10 > SC5 >SC6 >SC11 >SC1>SC2 >SC7>SC3 > SC12 > SC2 > SC4, thus SC9 (100% PP+50% GR) is the most cost-effective scenario. From Figure 7, with SC9, the rate of decrease reached 26.5 % for run-off and 38.72% for flow rate. According to several studies (Yu et al., 2020; Amirhossein et al., 2023; Ahiablame & Shakya., 2016), with the optimal scenario, the reduction of run-off ranges from 17% to 40%; thus, the optimal scenarios can be defined as the design which reduces run-off at least 17% with a reasonable cost.

SC1 (100% PP+100% GR) has the lowest cost-effectiveness, demonstrating that increasing the area of LID control in the catchment may not be the best solution which considers both economic cost and hydrological performance.

These results showed that the green roof had the lowest cost-effectiveness, but the highest hydrological performance. According to the study of Upeka et al. (2019), the permeable pavement is more cost-effective than the green roof, which means that it was able to bring the peak run-off down to the pre-development level with the least budget. Ahiablame and Shakya (2016) found that by including PP in LID scenarios, the storm water run-off is more controlled, because during the simulation, the highly impervious area was treated with no clogging by the permeable pavement. However, this study indicated that under large storms, the effectiveness of the LID systems decreases, especially when the area being treated is relatively small. It should be noted that the optimal LID scenarios differed among districts due to changes in land use and climate, posing another challenge for decision makers to choose the appropriate LIDs; thus, this work gives guidelines for planners to determine the best LID combination with a reasonable cost.

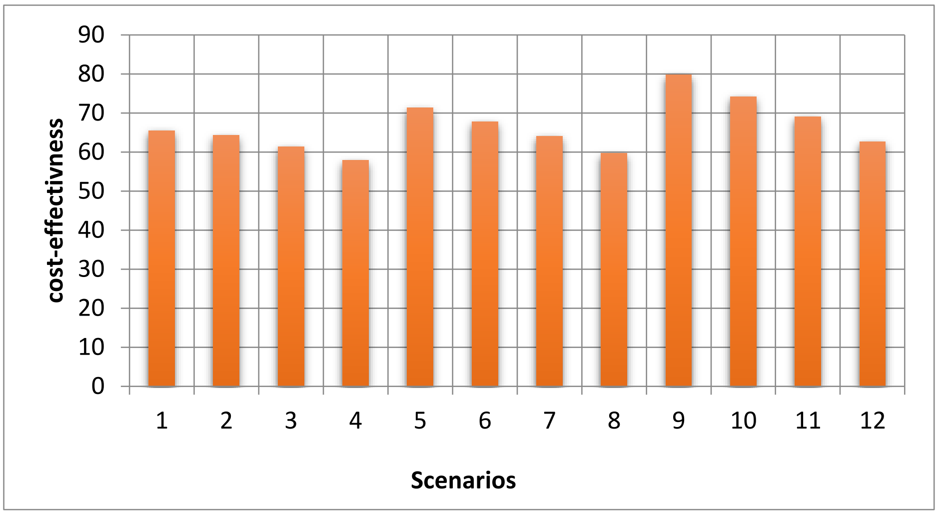

Figure (10): Cost-effectiveness of each LID scenario

In order to explore the environmental benefit of SC 9, Fig. 11 shows the longitudinal water surface profile between node N5 and the exit (outfall) before and after the implementation of the green roofs and the permeable pavement. Fig. 11a displays how the surface of the water in manholes rises above the top of the sewer pipe, and the sewer is under pressure between node 5 and the exit. Due to the large volume of run-off during storm events, sewer pipes are surcharged. However, by converting the roof surface and the grey pavement into a green roof and a permeable pavement, respectively, the combined drainage network is partially filled and can handle run-off (Fig. 11b).

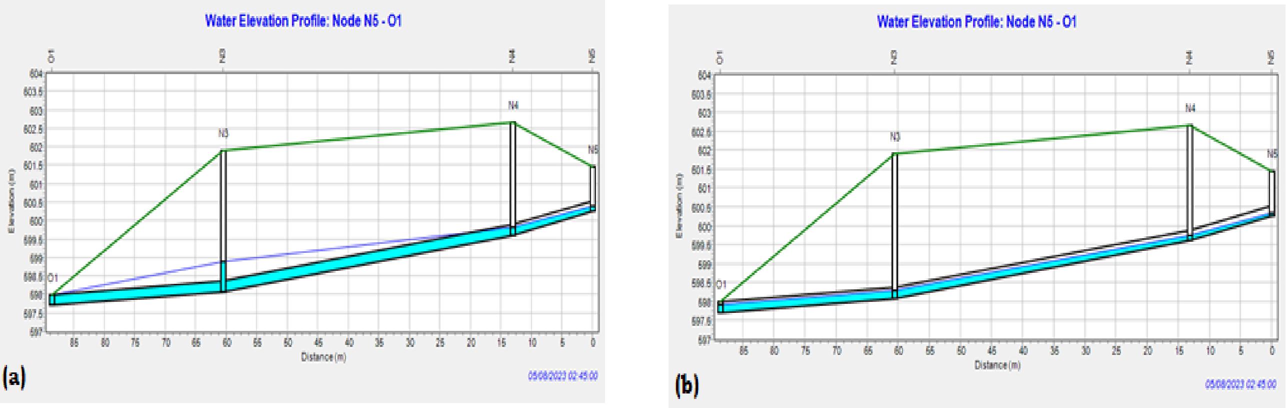

Figure (11): Longitudinal profile: (a) without LID control, (b) with LID control (SC9)

Fig. 12 compares the total run-off in the sub-catchements and the maximum flow in ducts before and after the implementation of SC 9. This figure shows that the coupling between the green roof and the permeable pavement is very efficient in reducing run-off in most sub-catchments. Likewise, the flow rate of water decreased in pipes after the implementation of SC9. The reduction is due to the absorption of water in the green-roof system and due to the high hydraulic conductivity of the porous pavement (Mentens et al., 2006; Lee et al., 2010).

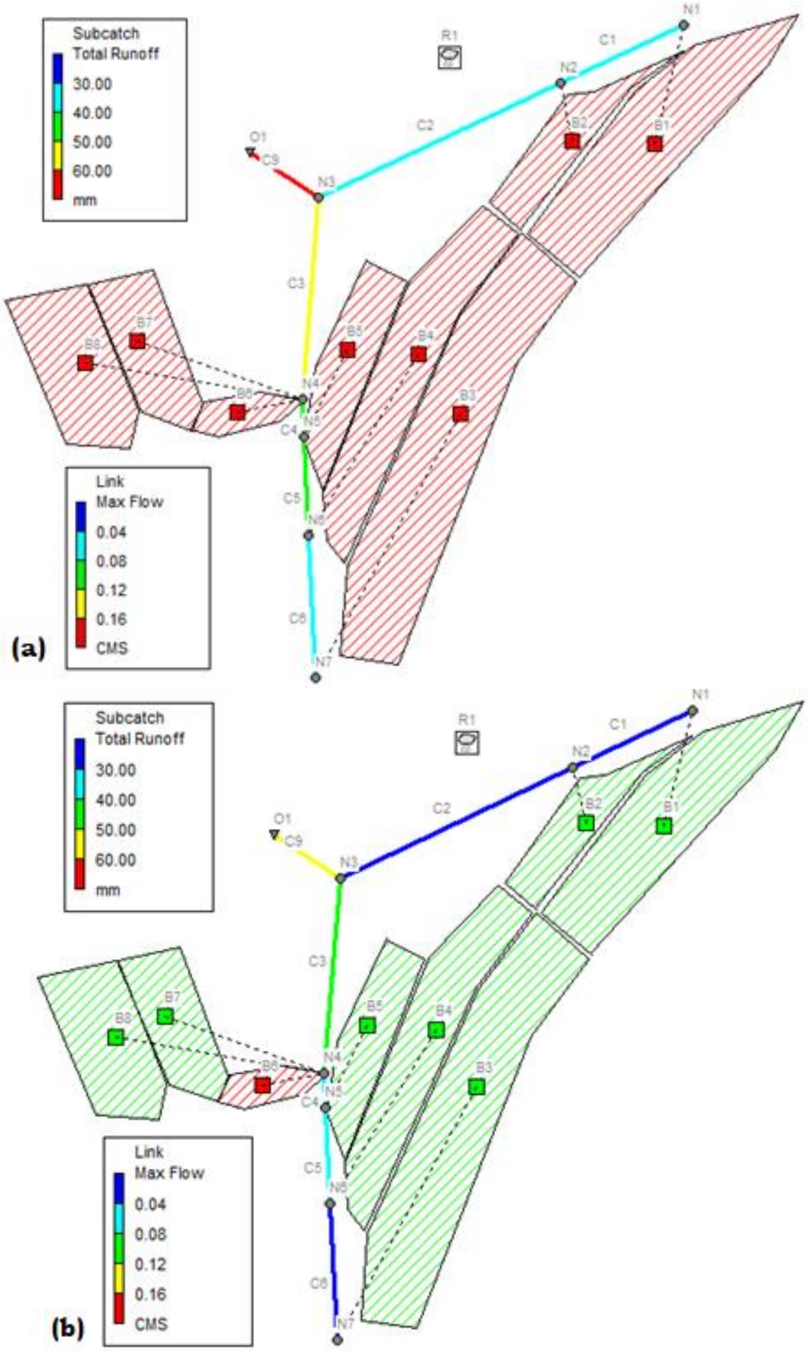

Figure (12): Total run-off and maximum flow: (a) without LID control, (b) with LID control (SC9)

CONCLUSIONS

Low impact development (LID) technologies are becoming among the solutions for reducing high run-off during rainfall. In this study, twelve LID scenarios were simulated by the SWMM model. These scenarios were realized by the permeable pavement (PP) and the green roof (GR) with different proportions. The numerical results of this research showed that SC1 had the best hydrological performance with 38.92 % reduction of water run-off and 60.78 % of maximum flow, while SC12 was the least efficient compared to the other scenarios. However, SC1 is very expensive compared to the other scenarios. The high hydrological performance of the combined LID does not mean high cost-effectiveness. Through this study, it was shown that the optimal scenario was SC9 due to its great cost-effectiveness.

The findings of this numerical study confirmed that LID facilities better mitigate peak run-off during rain events. Further calibration and validation with observed run-off flow should be intended to improve the accuracy of this computational hydrological analysis. Future research should be conducted to select the optimal scenario consisting of more than two LID controls under different return periods, especially in big cities. Also, it is good to use other methods, like the principal component analysis and the correlation analysis (PCCA), to determine the performance of LID units by including many factors, such as the reduction of run-off and peak flow, water quality, costs and the social impact. Overall, the SWMM cost effectiveness approach can help decision-makers determine the best LID design for local communities.

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