DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

IJES
Indonesian Journal of Environmental Sustainability

Published by : Center For Environmental Studies UIN Ar-Raniry Banda Aceh

SCENARIO-BASED SWMM MODELING OF LOW IMPACT DEVELOPMENT FOR RESILIENT URBAN DRAINAGE

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Received : 10 May 2026 Accepted : 23 May 2026 Published : 21 July 2026

ABSTRACT

Urban drainage systems in Meulaboh City face increasing challenges due to rapid urbanization, extensive impervious surfaces, and inadequate stormwater management. This study evaluated the performance of the existing drainage system and assessed the effectiveness of Low Impact Development (LID) practices using the EPA SWMM 5.2.4 model. Hydrological and hydraulic simulations were conducted under existing conditions and three LID scenarios: rain barrels, permeable pavement, and vegetative swales. Results showed that drainage channels S30, S53, S63, S71, and S107 experienced overflow due to insufficient channel capacity, sedimentation, and limited infiltration areas. LID implementation reduced runoff volume and peak discharge compared to existing conditions. Rain barrels achieved the highest runoff reduction (11–16%), followed by permeable pavement (up to 12%), while vegetative swales showed limited effectiveness (<1%). Although overflow was not completely eliminated, the findings demonstrate that LID practices can significantly improve urban drainage performance and provide a sustainable approach to stormwater management in Meulaboh City.

Keywords : Surface runoff, Stormwater management, Hydrological modeling, Urban drainage

ABSTRAK

Sistem drainase perkotaan di Kota Meulaboh menghadapi tantangan yang semakin meningkat akibat urbanisasi yang pesat, permukaan kedap air yang luas, dan pengelolaan air hujan yang tidak memadai. Studi ini mengevaluasi kinerja sistem drainase yang ada dan menilai efektivitas praktik Pengembangan Berdampak Rendah (Low Impact Development/LID) menggunakan model EPA SWMM 5.2.4. Simulasi hidrologi dan hidraulik dilakukan dalam kondisi yang ada dan tiga skenario LID: tong penampung air hujan, perkerasan permeabel, dan parit vegetatif. Hasil menunjukkan bahwa saluran drainase S30, S53, S63, S71, dan S107 mengalami luapan akibat kapasitas saluran yang tidak mencukupi, sedimentasi, dan area infiltrasi yang terbatas. Implementasi LID mengurangi volume limpasan dan debit puncak dibandingkan dengan kondisi yang ada. Tong penampung air hujan mencapai pengurangan limpasan tertinggi (11–16%), diikuti oleh perkerasan permeabel (hingga 12%), sedangkan parit vegetatif menunjukkan efektivitas yang terbatas (<1%). Meskipun luapan tidak sepenuhnya dihilangkan, temuan ini menunjukkan bahwa praktik LID dapat secara signifikan meningkatkan kinerja drainase perkotaan dan memberikan pendekatan berkelanjutan untuk pengelolaan air hujan di Kota Meulaboh.

Kata kunci: *Aliran permukaan, Pengelolaan air hujan, Pemodelan hidrologi, Drainase perkotaan*

 DOI : 10.22373/ijes.v4i1.10021
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Introduction

Urban flooding is a growing problem in rapidly urbanizing cities due to increased precipitation, climate change, and land-use change et al., 2023). Conversion of natural land into impervious surfaces reduces infiltration and increases surface runoff, often exceeding the capacity of conventional drainage systems during intense rainfall events. In many developing cities, flooding is further worsened by poor drainage maintenance, sedimentation, and limited channel capacity (Hassan et al., 2022). Climate change has also increased the frequency of short-duration, high-intensity rainfall, raising flood risk in urban areas (Fowler et al., 2021).

Traditional drainage systems focus on rapid runoff conveyance but often neglect natural hydrological processes such as infiltration and groundwater recharge. In contrast, Sustainable Urban Drainage Systems (SUDS) and Low Impact Development (LID) aim to restore these functions through infiltration, storage, and evapotranspiration. LID practices can reduce runoff volume and peak discharge, improve stormwater quality, and support sustainable urban water management (Rossman & Simon, 2022). LID practices include rain barrels, permeable pavements, vegetative swales, bioretention systems, and green roofs (Chang, Lu, Chui, & Hartshorn, 2018; Silva, K. Najjar, W. A. Hammad, Haddad, & Vazquez, 2019; Stec & Słyś, 2023).

Previous studies have also demonstrated that Low Impact Development (LID) measures can effectively reduce runoff volume and peak flow in urban catchments. For example, rain barrels can reduce peak runoff by 11–51%, depending on site conditions (Purnagusti et al., 2024). In addition, rainwater harvesting systems can reduce overall flood volumes (Gee & Sojka, 2022). Permeable pavements and vegetative swales have been reported to reduce runoff by up to 27,5%–100% and peak flow by about 15,9% (Xie et al., 2017). Bioretention and swales can reduce peak runoff by about 25% while improving water quality (Kuok et al., 2024).

Hydrological and hydraulic modeling is essential for evaluating drainage system performance and the effectiveness of LID strategies (Yang et al., 2020; Zhu & Chen, 2017). The Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) is widely used due to its ability to simulate runoff generation, infiltration, channel flow, and LID processes under various rainfall conditions (Rezaei et al., 2019). Previous studies using SWMM have identified drainage systems prone to overflow and supported flood mitigation planning (Pratama et al., 2023). In addition, SWMM has been used to evaluate urban drainage performance and assess flood mitigation strategies under different hydrological conditions, revealing that certain drainage segments require redesign due to overflow occurrences.

Previous studies have identified urban flooding as a recurring issue in Meulaboh City, Indonesia (Safriani et al., 2022). The increasing extent of impervious surfaces has significantly increased surface runoff, while the drainage system often becomes overloaded during heavy rainfall, leading to channel overflows, road inundation, and disruptions to daily activities. Drainage performance is further reduced by sedimentation, waste accumulation, and limited maintenance. Several channels lack sufficient capacity to convey peak flows, leading to frequent flooding

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

in surrounding areas. This highlights the need for improved and adaptive stormwater management strategies.

Field observations indicate that high-intensity rainfall events lasting approximately one hour frequently trigger flooding in the urban area of Meulaboh. In residential areas, flood depths range from 10–30 cm and persist for 40-60 minutes, whereas along the Meulaboh City National Road, depths increase to 30-50 cm and may persist for 2-3 hours or more (shown in Figure 1).

Figure 1. Field Observations at the Research Location

These flooding conditions are caused by high design rainfall, an undersized and inefficient drainage system, and a high proportion of impervious surfaces (approximately 85%) in residential and commercial areas. This land-cover condition increases surface runoff and limits infiltration capacity, thereby intensifying flood occurrence (Safriani et al., 2022).

Although LID has been widely studied, applications in medium-sized tropical cities remain limited, particularly in Indonesia. Most studies focus on single techniques or large cities, while combined scenario-based evaluations under local conditions remain limited (Hidayah, Widiarti, Wiyono, & Dermawan, 2024; Koc, Ekmekcioğlu, & Özger, 2021; Putri, Hidayah, & Ma'ruf, 2023). Therefore, this study evaluates urban drainage performance in Meulaboh City using EPA SWMM 5.2.4 and assesses three LID scenarios: rain barrels, permeable pavements, and vegetative swales. This study aims to determine the reduction in runoff volume and peak discharge, and to support sustainable urban drainage management.

Methods

Study Area

This study was conducted in the urban area of Meulaboh City, Johan Pahlawan District, West Aceh Regency, Aceh Province, covering approximately

DOI : 10.22373/ijes.v4i1.10021
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64,304 ha, including Kuta Padang, Ujong Baroh, and Ujong Kalak. This area was chosen because it is a rapidly developing urban center dominated by residential, commercial, and government office land uses. Rapid urban development has increased the impermeable surface area and reduced the soil's ability to absorb rainwater, often causing flooding during heavy rainfall. Furthermore, the relatively flat topography and low soil permeability increase surface runoff, which can lead to drainage overflows and urban flooding. These conditions indicate strong potential for implementing LID strategies to improve urban drainage performance and resilience.

Research Framework

This study employed a quantitative approach integrating hydrological analysis, hydraulic simulation, and LID scenario modeling using the EPA SWMM5.2.4. The research involved field surveys, secondary data collection, rainfall analysis, and drainage system modeling to evaluate existing drainage performance. Subsequently, several LID scenarios were simulated and compared to assess their effectiveness in reducing runoff volume and peak discharge. The research framework adopted in this study is illustrated in Figure 2.

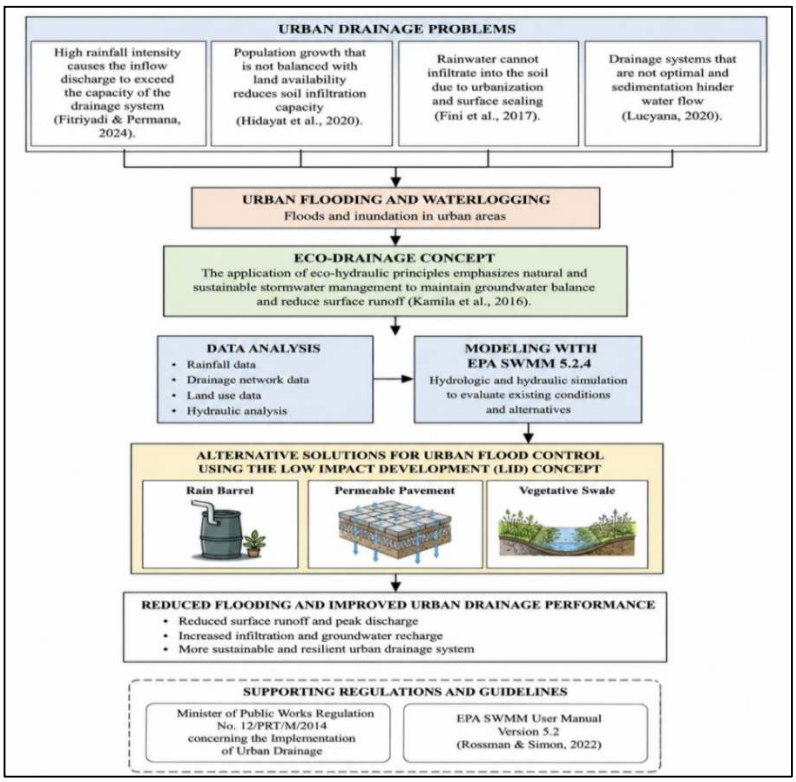

Figure 2. Research Framework

Data Collection

Primary data were collected through field observations and direct measurements of the drainage network. The surveyed parameters included channel dimensions, channel length, flow direction, channel slope, and invert elevations at

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ISSN 3046-885X

drainage junctions. Measurements were conducted using measuring tapes, waterpass instruments, and slope measurement applications. Field observations also identified several drainage issues, including sediment buildup, channel blockages, and overflow occurrences in parts of the drainage network. Secondary data used in this study included:

1. Daily maximum rainfall data from BMKG Nagan Raya Station for the period 2015–2024.
2. Land-use maps and slope maps are used to determine runoff coefficients and imperviousness.
3. Urban drainage network maps obtained from the Public Works and Spatial Planning Agency (PUPR) of Aceh Barat Regency.
4. Soil infiltration characteristics and hydrological parameters obtained from the literature and the standard.

Hydrological Analysis

Rainfall frequency analysis was conducted to determine the design rainfall for several return periods. Four types of probability distributions were used Log Pearson Type III. Statistical parameters such as mean, standard deviation (S_d), coefficient of variation (C_v), Kurtosis (C_k) and skewness coefficient (C_s) were calculated to determine the distribution that best fits the rainfall data. The design rainfall was then calculated for return periods of 2, 5, 10, 25, 50, and 100 years.

$$S_d = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} \quad \ldots\ldots(1)$$

$$C_v = \frac{S_d}{X} \quad \ldots\ldots(2)$$

$$C_k = \frac{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^4}{S_d^{\,4}} \quad \ldots\ldots(3)$$

$$C_s = \frac{n.\sum_{i=1}^{n}(X_i - \overline{X})^3}{(n-1)(n-2).S_d^{\,3}} \quad \ldots\ldots(4)$$

$$\text{Log}X_T = \overline{\text{Log }X} + K_T.S_d \quad \ldots\ldots(5)$$

Where: S_d = Standard deviation; X = Rainfall value for each; α = Average value of rainfall variables; n = Number of data; C_s = Skewness coefficient; C_k = Kurtosis coefficient; Log XT = Logarithmic value of the planned rainfall with a return period of T years; $\overline{Log\ x}$ = Average value of the calculated logarithmic value of the rainfall variable; and K_T = Log Pearson III frequency factor value for a return period of T years depending on the C_s value.

DOI : 10.22373/ijes.v4i1.10021
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Rainfall intensity was estimated using the Mononobe equation based on the maximum 24-hour rainfall records. These calculated intensities were used to build the Intensity-Duration-Frequency (IDF) relationship. The intensities were then converted into an hourly rainfall hyetograph using the Alternating Block Method (ABM). The ABM creates the hyetograph by dividing the total storm duration into equal time intervals and arranging the calculated rainfall intensities in descending order, placing the highest (peak) intensity at the center of the duration, with progressively lower intensities alternating before and after the center. This produces a more realistic rainfall distribution. This method allows for a conservative estimate of catchment and drainage system responses. The final rainfall hyetograph was entered into EPA SWMM as a time series using the Rain Gage component for hydrological simulations.

$$I = \frac{R_{24}}{24} \cdot \left(\frac{24}{t}\right)^{\frac{2}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where: I = rainfall intensity (mm/hour); R_{24} = maximum daily rainfall (during 24 hours) (mm); and t = duration of rainfall (hours).

The runoff coefficient (C) is determined based on the type of land use and surface conditions in each sub-watershed. This value is calculated by multiplying the runoff coefficient for each land type by its area, then dividing by the total watershed area. Impervious surfaces, such as roads and buildings, have a higher runoff coefficient than vegetated areas or permeable surfaces.

$$C = \frac{\Sigma_{i-1}^{n} C_i . A_i}{\Sigma_{i-1}^{n} A_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Where: A_i = land area with soil cover type i; C_i = runoff coefficient for soil cover type i; and n = total land surface area.

Peak runoff discharge for each subcatchment was estimated using the Rational Method:

$$Q = 0{,}00278.C.I.A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Where: Q = the design discharge (m^3/s), C = the runoff coefficient, I = the rainfall Intensity (mm/h), and A is the catchment area (ha). This method was selected because the study area represents a relatively small urban catchment in which rainfall intensity can be assumed uniform throughout the storm duration.

EPA SWMM Modeling

Hydrological and hydraulic simulations were performed using EPA SWMM 5.2.4 to represent the existing urban drainage systems. The model, developed from field data, included interconnected subcatchments, junctions, channels, and outlets, with inputs such as land use, topography, soil properties, and channel geometry. Infiltration was simulated using the Curve Number (CN) method, while unsteady

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

flow conditions were represented using the Dynamic Wave routing method. The model was first run under existing conditions to identify overcapacity and overflow-prone channels, which were then selected as locations for implementing LID scenarios.

Low Impact Development (LID) Scenarios

Three LID techniques were evaluated in this study: rain barrels, permeable pavement, and vegetative swales. Rain barrels are used to temporarily store rooftop runoff before it enters the drainage system. Permeable pavement enhances infiltration in impervious areas such as parking lots and road shoulders, thereby reducing surface runoff and peak discharge. Vegetative swales are shallow, vegetated channels that reduce runoff velocity, enhance infiltration, and filter sediments before water enters the drainage network. The effectiveness of each LID scenario was assessed by comparing existing and modified conditions, focusing on reductions in runoff volume, peak discharge, and overflow occurrences.

The design parameters of the rain barrel used in the SWMM simulation are presented in Table 1. The storage depth and drain characteristics were selected based on previous studies and adapted to local rainfall conditions. These parameters control the temporary storage and delayed release of rooftop runoff, thereby reducing peak discharge entering the drainage network.

Table 1. Rain Barrel Parameters

Parameters	Amount
Storage	
Barrel Height (mm)	1564
Drain	
Flow Coefficient	11,972
Flow Exponent	0,5
Offset (mm)	100
Drain Delay (hrs)	6

Source: Adapted from (Purnagusti et al., 2024; Zhang et al., 2023)

The physical properties of the permeable pavement system used in the model are summarized in Table 2. Parameter values, including pavement thickness, void ratio, and hydraulic conductivity, were selected based on established design guidelines and previous studies. Pavement thickness and void ratio determine the storage capacity of the pavement system, whereas hydraulic conductivity influences the infiltration rate through the pavement layers. These parameters collectively influence the storage and infiltration capacity of the permeable pavement system, thereby promoting temporary stormwater retention, increasing infiltration into the underlying soil, and reducing both runoff volume and peak discharge.

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Table 2. Permeable Pavement Parameters

Parameters	Amount
Surface	
Berm Height (mm)	25
Vegetation Volume (fr)	0
Surface Roughness (n)	0,12
Surface Slope (%)	1
Soil	
Thickness (mm)	500
Porosity (volume fraction)	0,5
Field Capacity (volume fraction)	0,10
Wilting Point (volume fraction)	0,024
Conductivity (mm/hr)	1,18
Conductivity Slope	40
Suction Head (mm)	45
Storage	
Thickness (mm)	250
Void Ratio	0,43
Seepage Rate (mm/hr)	600
Clogging Factor	0
Pavement	
Thickness (mm)	150
Void Ratio	0,25
Permeability (mm/hr)	200

Source: Adapted from (Bai, Li, Zhang, Zhao, & Zeng, 2019; Sehrawat & Shekhar, 2025)

The vegetative swale parameters adopted in the simulation are presented in Table 3. Soil thickness, hydraulic conductivity, and vegetation characteristics influence infiltration capacity and runoff attenuation within the swale system.

Table 3. Vegetative Swales Parameters

Parameters	Amount
Surface	
Berm Height (mm)	0
Vegetation Volume (fr)	0,1
Surface Roughness (n)	0,3
Surface Slope (%)	1
Soil	
Thickness (mm)	600
Hydraulic conductivity (mm/h)	091
Suction head (mm))	50
Porosity (fr)	0,467
Field capacity (fr)	0,121
Wilting point (fr)	0,057

Source: Adapted from (Polytechnique Montreal et al., 2021; Rossman & Simon, 2022)

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Results and Discussion

1. Existing Drainage System Characteristics

The urban drainage system in Meulaboh City consists of interconnected open channels that convey stormwater runoff from various land uses. Rapid urbanization and increasing impervious surfaces have reduced infiltration and increased runoff generation. Combined with relatively flat terrain and reduced channel capacity due to sediment and debris accumulation, these conditions increase the risk of flooding during heavy rainfall events.

The hydraulic performance of the drainage system was evaluated using the EPA SWMM 5.2.4 model based on field observations and drainage network data. This model simulates runoff generation and routing through the drainage network. Figure 3 presents the drainage network and sub-watershed layout used in the analysis. As illustrated in the figure, the study area is dominated by impervious surfaces that limit infiltration and increase surface run off.

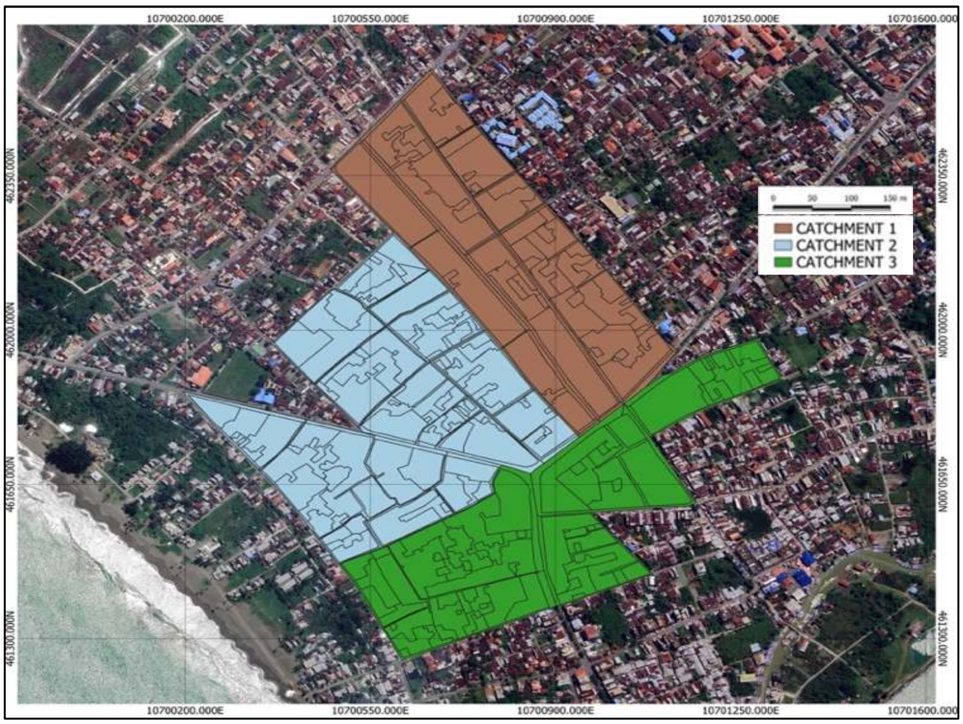

Figure 3. Research Location Layout

Figure 2 presents the drainage network and subcatchment configuration incorporated into the SWMM model. The network conveys runoff from various urban land uses to downstream outlets, forming the basis for the hydraulic performance.

2. Hydrological Analysis

Rainfall Frequency Analysis

Rainfall frequency analysis was conducted using annual maximum daily rainfall data for the period 2015–2024 from the BMKG Nagan Raya Station. Several probability distributions were tested using Log Pearson Type III to determine the most appropriate distribution for estimating the planned rainfall. The results indicate

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that rainfall depth increases with longer return periods, reflecting a higher potential for surface runoff and flood risk during extreme precipitation events. These design rainfall values were subsequently used as input parameters for hydrological simulations in SWMM. This study used a 5-year return period because it is appropriate for drainage system planning in areas less than 300 ha, namely 64,304 ha. The obtained R_{24} value was 202,417 mm.

Rainfall Intensity Distribution

The Log Pearson III distribution analysis yielded a daily maximum rainfall (R_{24}) of 202,417 mm for a 5-year return period. This value was used to construct an Intensity-Duration-Frequency (IDF) curve using the Alternating Block Method (ABM), which then served as the basis for an hourly rainfall hyetograph. In the ABM method, the peak rainfall intensity is positioned at the midpoint of the storm duration to provide a more conservative and accurate simulation of the drainage system response. The 6-hour rainfall duration was chosen because it represents short-duration extreme rainfall events that commonly occur in urban areas, making it suitable for evaluating the capacity and performance of the drainage system under high-intensity runoff. The results of the hourly rainfall distribution calculations for the 5-year return period are presented in Figure 4.

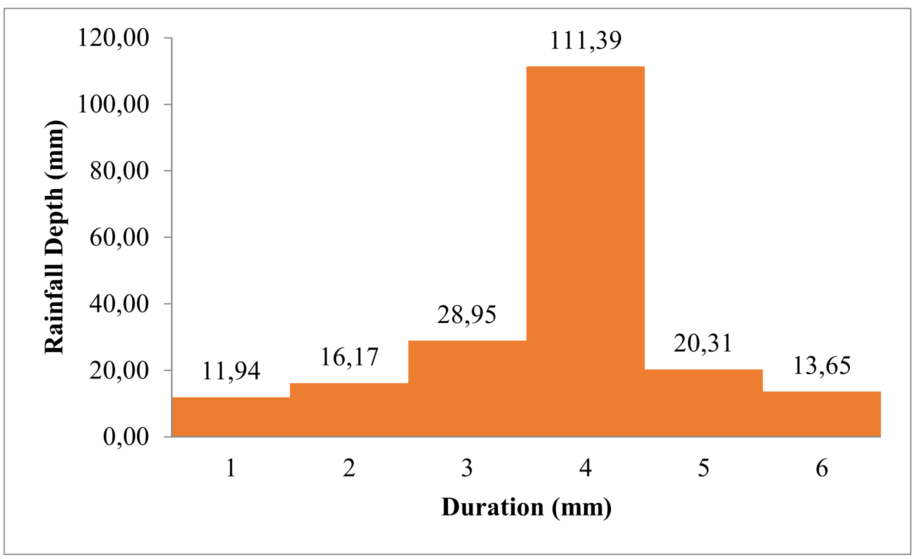

Figure 4. 5 year return period hyetograph chart

Figure 3 shows that rainfall distribution patterns over the 5-year return period are uneven, with the highest intensity generally occurring for a duration of around 3-4 hours. The analysis yielded a rainfall depth of 111,39 mm, with a total rainfall of 202,417 mm over the 5-year return period.

3. Existing Drainage System Performance

SWMM Simulation under Existing Conditions

Hydrological and hydraulic simulations with EPA SWMM 5.2.4 under existing conditions indicated that several drainage channels experienced surcharge

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and overflow during design storm events. The most critical conduits were identified as S30, S53, S63, S71, and S107, where runoff discharge exceeded channel capacity. Simulation results of the existing drainage system (without LID measures) revealed that several channel segments exceeded their hydraulic capacity during the design storm event, with depth-to-full-depth (d/D) ratios greater than 1.0, indicating overtopping. These overflow conditions were primarily attributed to insufficient channel dimensions, sedimentation, reduced conveyance efficiency, and high runoff generation from impervious urban surfaces. The results demonstrate that the existing drainage network is unable to adequately convey peak runoff, leading to localized flooding in critical areas of the catchment.

As shown in Figure 5, the hydraulic conditions of the drainage network at 4:15 hours indicate several locations where runoff exceeded the system's capacity. The figure highlights the spatial distribution of runoff, surcharge, and overflow within the subcatchments, nodes, and conduits during the peak storm period.

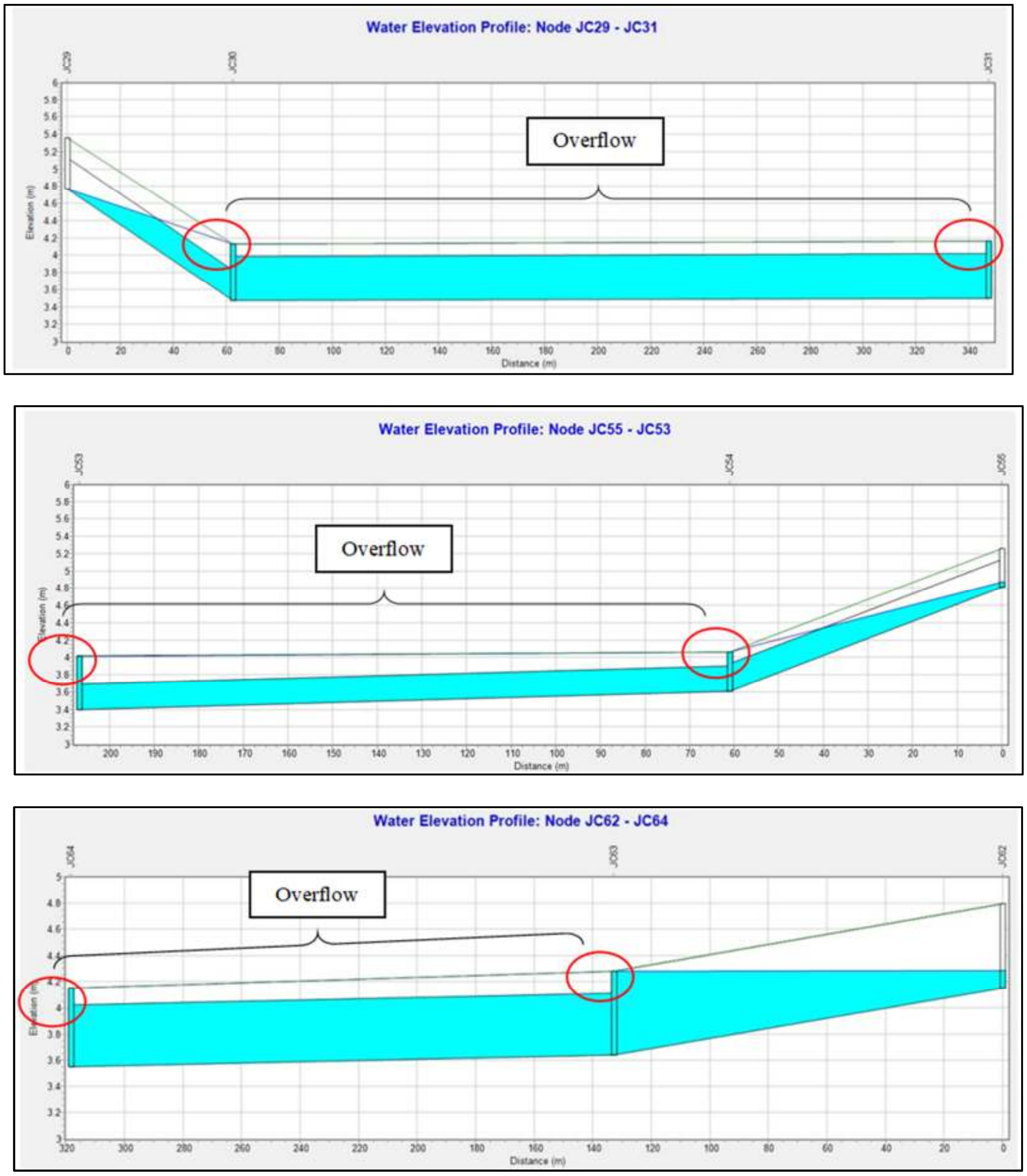
Figure 5. Results of Running Subcatchment, Node and Conduit with a Duration of 4:15 Hours

Prolonged rainfall simulations showed increased runoff in five subcatchments (≈16% of the total), with discharge ranging from 0,05 to 0,50 m³/s. This increase was mainly observed in highly impervious areas with low infiltration capacity and limited vegetation, which resulted in faster runoff concentration and increased inflow to the drainage system. Overflow also occurred in 5 of 125 drainage channels (4%), affecting both secondary and tertiary networks with total lengths of 470,38 m and 518,99 m, respectively. These results indicate that parts of the existing drainage

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

system lack sufficient hydraulic capacity under prolonged or extreme rainfall conditions.

To further examine the surcharge and overflow conditions shown in Figure 4, water surface elevation profiles were evaluated at several critical channel sections. These profiles highlight locations where channel capacity was exceeded during the design storm event. The results are presented in Figure 6.



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ISSN 3046-885X

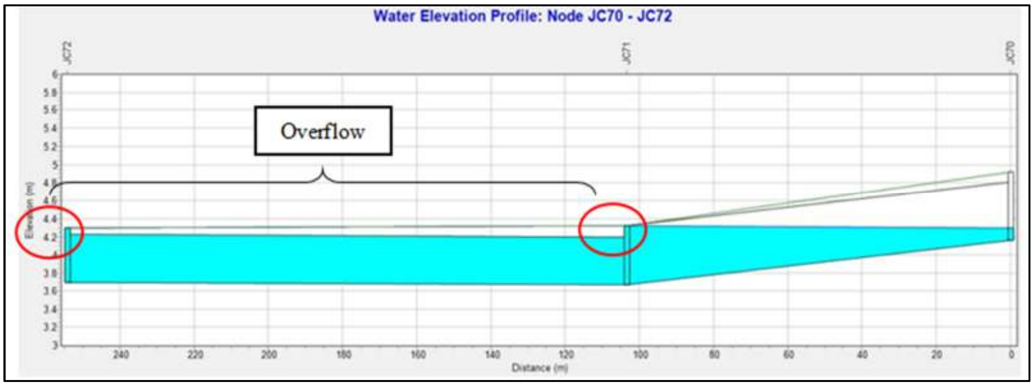

Figure 6. a) Water Elevation Profile Node JC29-JC31; b) Node JC55-JC53; c) Node JC62-JC64; d) Node JC70-JC72

Table 4. Conduit Overflow

SC	Total Channel Length (m)	Channel Type	Channel/ Conduit	Overflow Channel Length (m)
1	6331,57	Secondary Channel	S30	284,84
2	7934,63	Tertiary Channel	S53	145,79
		Secondary Channel	S63	185,54
		Tertiary Channel	S71	150,77
3	4615,31	Tertiary Channel	S107	222,43
		Total Overflow Channel Length		989,37

As a result, localized flooding may occur without full channel capacity being reached. Simulation results indicate that longer rainfall duration increases runoff generation, inundation potential, and channel overflow. These findings emphasize the need to reassess existing drainage capacity and adopt sustainable stormwater management strategies, such as Low Impact Development (LID), to enhance system performance and reduce flood risk.

Runoff Characteristics

SWMM simulations indicated a rapid increase in runoff after rainfall onset, with peak runoff occurring within 3–4 hours in most subcatchments. Variations in runoff response were primarily influenced by land use, imperviousness, and infiltration capacity. As shown in Figure 7, an inverse relationship exists between infiltration and runoff, whereby subcatchments with lower infiltration capacity generated higher runoff volumes. Lower infiltration capacity results in higher runoff volumes, which increases inflow to the drainage network and contributes to hydraulic overloading during intense rainfall events.

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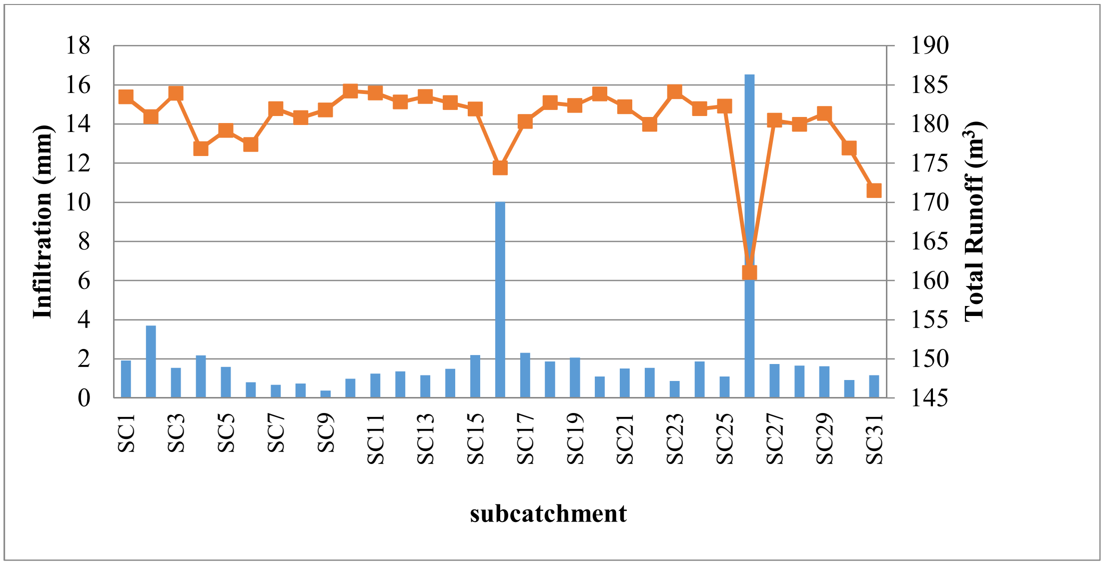

Figure 7. Correlation graph between infiltration and runoff

Figure 7 shows that higher infiltration areas produce lower runoff, while impervious areas generate higher runoff due to limited infiltration capacity. Even vegetated areas still produce considerable runoff under high-intensity rainfall, indicating limited overall infiltration effectiveness. Runoff variation is mainly controlled by rainfall intensity and land use, particularly impervious surface coverage. These findings highlight the need for improved stormwater management through increased permeability and sustainable drainage practices.

Table 5. Correlation of Catchment Area Function with Land Use

SC	Area Function	Catchment Area (m²)	Built-up Area (Impervious)	Open Area (Pervious)
1	Commercial and dense residential area	198.089,45	145.707,76	52.381,70
2	Urban area, dense residential area, and school zone	253.331,97	196.714,09	56.617,88
3	Office area, industrial area, and dense residential area	191.617,59	139.822,50	51.795,09

Source: Authors’ analysis based on GIS land-use mapping and field survey data (2026)

Catchment 2 has the highest imperviousness (78%), yet only ~6% of channels experience overflow, indicating that overflow is more controlled by drainage capacity than by land cover alone. However, impervious areas remain prone to high runoff during heavy rainfall. LID is recommended to reduce runoff and improve infiltration.

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4. Low Impact Development (LID)

For the selection and planning of LID techniques, a land use analysis was conducted in the study area to identify site characteristics that influence the effectiveness of their implementation. Figure 8 shows that the study area is predominantly composed of pervious, impervious surfaces, and road networks, which strongly influence surface runoff generation and flow pathways.

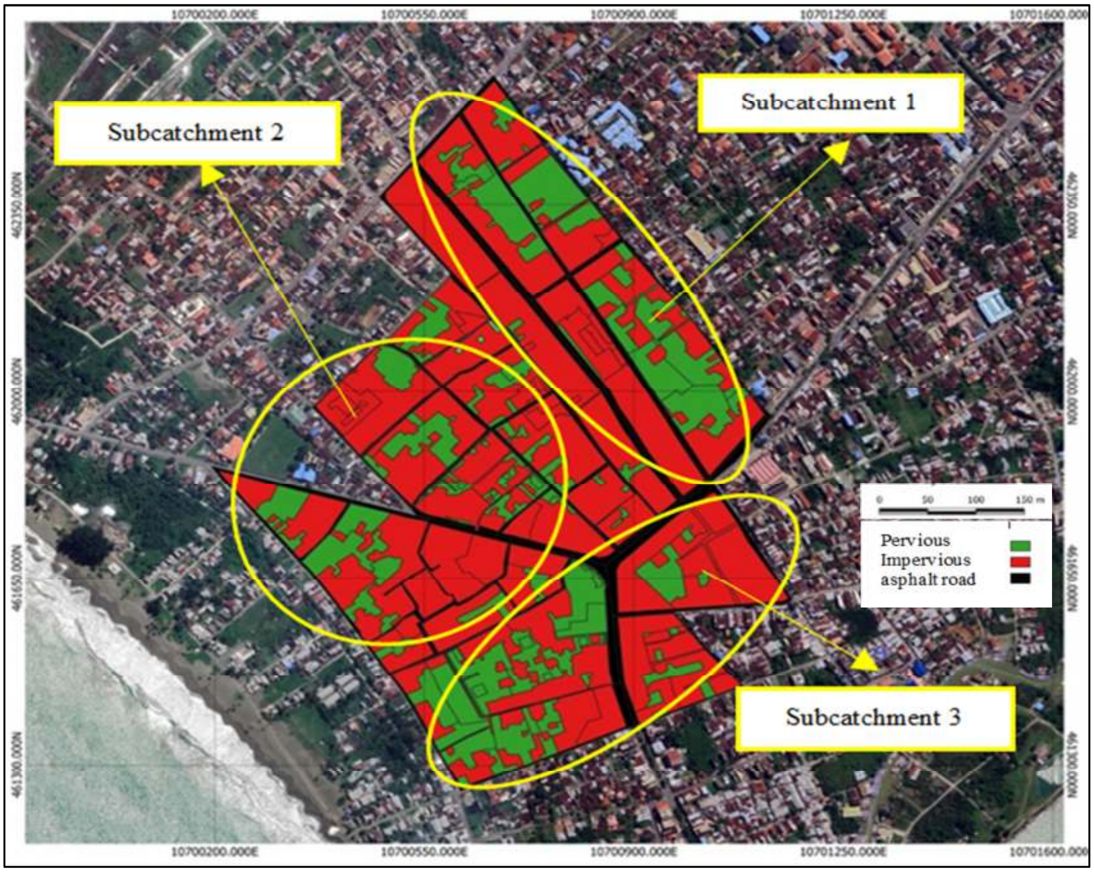

Figure 8. Land use map at the study location

The simulation results demonstrated that all LID scenarios reduced runoff volume and inundation compared with the existing drainage condition. However, the magnitude of reduction varied among the evaluated techniques. Scenario 1 (Rain Barrels), Scenario 2 (Permeable Pavement), and Scenario 3 (Vegetative Swales) exhibited different levels of effectiveness depending on their storage and infiltration capacities, as discussed in the following sections. These scenarios were evaluated to assess their effectiveness in reducing surface runoff and inundation within the study area, as shown in Figure 9.

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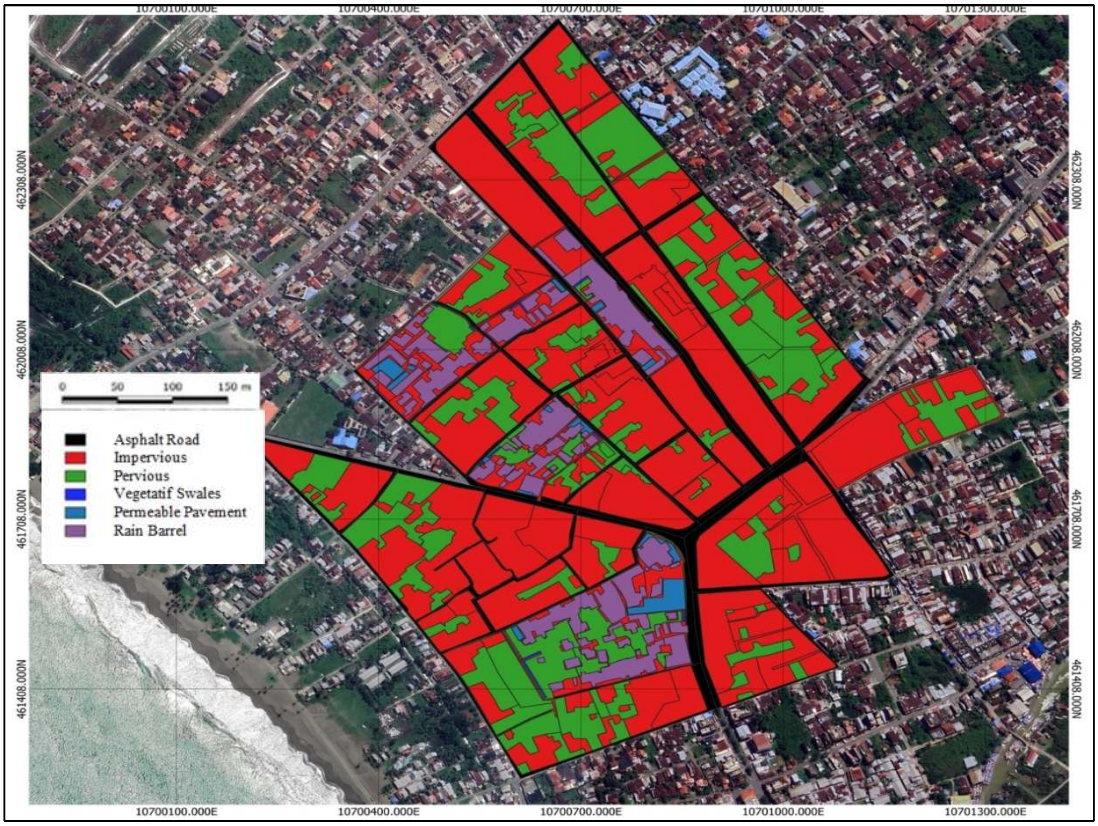

Figure 9. LID Technique Implementation Plan for Subcatchment

Simulation results show that LID implementation can reduce surface runoff volume in most subcatchments. Rain barrels reduce peak discharge by capturing initial runoff, permeable pavement increases infiltration in impermeable areas, and vegetative swales slow surface flow before it enters the drainage system. Table 6 shows that rain barrels provide the most effective runoff reduction, ranging from 11% to 16%. Permeable pavement offers lower reductions, ranging from approximately 3% to 12%. Vegetative swales showed limited effectiveness due to dominant land use and a small coverage area in the study area.

Table 6. Comparison of Runoff Reduction Percentages for Each LID Technique Applied

Subcatchment (SC)	Runoff Reduction (%)		
	Rain Barrel (RB)	Permeable Pavement (PP)	Vegetative Swales (VS)
SC 8	16%	3%	0,16%
SC 14	11%	4%	–
SC 16	11%	12%	0%
SC 18	12%	5%	0,07%
SC 27	12%	12%	0,02%

The results of this study are consistent with previous research demonstrating the effectiveness of LID techniques in reducing surface runoff. Purnagusti et al.,

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

(2024) reported that rain barrels effectively reduced runoff in residential areas dominated by roof surfaces, with an average reduction of 12%. Similarly, Xie et al., (2017) found that permeable pavement reduced runoff discharge by up to 27%, although its effectiveness varied depending on infiltration conditions and the extent of permeable coverage. These findings indicate that the performance of LID practices performance is strongly influenced by land-use characteristics and local hydrological conditions.

In contrast, Kuok et al., (2024) found that vegetative ditches were more effective at reducing flow velocity and improving water quality than at substantially reducing runoff volume, with peak runoff reductions reaching 25%, whereas in the present study, the reduction was only <1%. The differences in effectiveness in this study were mainly influenced by variations in land use, soil infiltration capacity, topography, and the extent of ditch application across the study area. In this study, the dominance of impervious surfaces and limited infiltration capacity reduced the effectiveness of runoff reduction. The higher runoff reduction was achieved because the land conditions and vegetative swale design better supported infiltration and flow retention.

Although individual LID techniques can reduce surface runoff, they are insufficient to fully eliminate overflow conditions in the existing drainage system. Therefore, LID implementation should be combined with drainage channel optimization, including adjustments to channel dimensions and depth, to improve the system's capacity to convey runoff under design rainfall conditions (Table 7).

Table 7. Downstream Water Depth in Overflowing Channels Before and After Optimization

Channel	Upstream Depth (cm)		Downstream Depth (cm)	
	Before	After	Before	After
S30	37	50	66	80
S53	28	45	30	60
S63	40	50	53	65
S71	46	50	60	75
S107	32	50	43	60

The results of the Subcatchment, Node, and Conduit operations after LID implementation and optimization are shown in Figure 10.

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

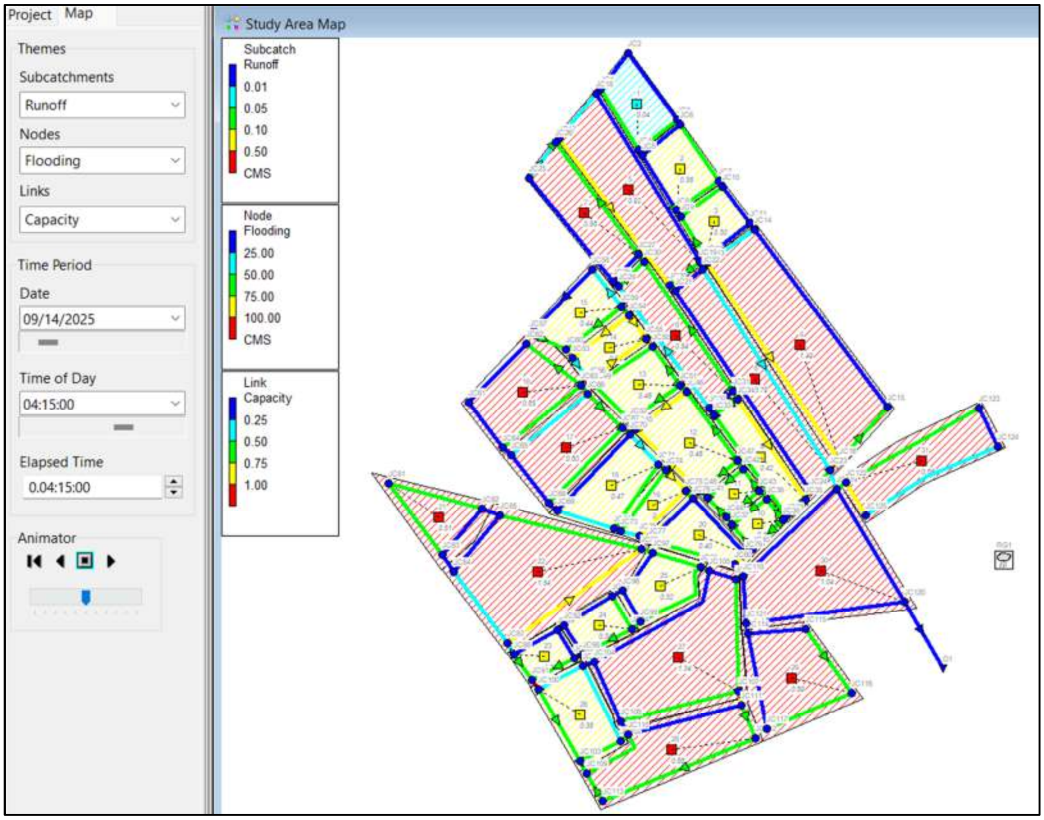

Figure 10. Running results after channel optimization and LID implementation

Figure 10 shows the condition of the subcatchment after adjusting the channel depth. The simulation results indicate that runoff in the previously overflowing subcatchment has been significantly reduced or eliminated. This indicates that channel normalization can improve the capacity and hydraulic performance in conveying runoff, thereby reducing the potential for water accumulation in the study area.

Surcharged still occurs at several points in the channel (yellow line), indicating that the system's hydraulic capacity has been exceeded under certain conditions. However, overflow is influenced not only by the channel's cross-section. Backwater effects caused by limited downstream channel capacity, differences in water surface elevation, and flow obstructions such as sedimentation and waste accumulation contribute to increased water levels and overflow at channel nodes, highlighting the need for further investigation of backwater dynamics and their influence on urban drainage system performance.

Future studies should evaluate the combined application of multiple Low Impact Development (LID) practices, such as rain barrels, permeable pavements, and bioretention systems, under different return periods and climate change scenarios. In addition, economic feasibility, maintenance requirements, and long-term performance should be assessed to support the sustainable implementation of LID practices in tropical urban areas.

DOI : 10.22373/ijes.v4i1.10021
ISSN 3046-885X

Conclusion

Simulation results using EPA SWMM 5.2.4 indicate that the urban drainage system in Meulaboh is not fully capable of accommodating planned rainfall runoff. Several channels, namely S30, S53, S63, S71, and S107, experienced overflow due to limited channel capacity, high impervious surface coverage, sedimentation, and inadequate stormwater management.

The implementation of Low Impact Development (LID) measures, including rain barrels, permeable pavement, and vegetative swales, effectively reduced runoff volume and peak discharge. Rain barrels showed the highest effectiveness, reducing runoff by 11%–16%, followed by permeable pavement, which reduced up to 12%, while vegetative swales provided relatively limited runoff reduction. These differences in performance were influenced by land-use characteristics, impervious surface coverage, and the site conditions where each LID technique was implemented.

Although LID implementation did not completely eliminate channel overflows, it significantly improved drainage system performance and demonstrated its potential as a sustainable approach to urban runoff management. Therefore, integrating LID techniques into urban drainage planning is recommended, particularly in flood-prone areas. Future studies should evaluate various rainfall scenarios and combined LID strategies while considering technical, economic, and maintenance aspects to support more effective and sustainable implementation.

Acknowledgements

The authors would like to express their sincere gratitude to the Dean of the Faculty of Engineering and to Teuku Umar University for their support and facilitation throughout this research. Appreciation is also extended to all parties who contributed to the completion of this study, including colleagues and field survey teams who provided valuable assistance during data collection and analysis.

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