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EFFECTIVENESS OF SELECTED LOW IMPACT DEVELOPMENT (LIDS) FOR SUSTAINABLE STORMWATER MANAGEMENT IN FAST-URBANIZING RESIDENTIAL AREAS

Adeniyi Ganiyu Adeogun[1*], Abubakar Sanni[2], Habeeb Oladimeji Ganiyu[1]

[1]*Department of Civil Engineering, Kwara State University, Malete, 241104, Nigeria*

[2]*Department of Civil Engineering, Kwara State Polytechnic, Ilorin, 240003, Nigeria*

Corresponding Author's Email:** adeniyi.adeogun@kwasu.edu.ng*

Abstract

The global trend of urbanization has led to the widespread conversion of natural land cover to impermeable surfaces. This, in turn, is hindering water infiltration and exacerbating runoff from precipitation. This phenomenon has detrimental effects on the natural environment and water quality. To address these issues of stormwater generation, this study employed the Storm Water Management Model (SWMM) in conjunction with MapWindow Geographical Information System (GIS) v4.X, a hydrologic data software for data, visualization, editing, and integration with other modeling tools to simulate the impact of various Low Impact Developments (LIDs) on mitigating stormwater in the study area. The study area was divided into six sub-basins within the GIS environment and imported into SWMM to assess the effects of selected LIDs, including green roofs, rain gardens, vegetative swales, and permeable pavements. The SWAT model was used to predict water flow in the Malete watershed and surface runoff. The study identified areas susceptible to erosion and categorized them as low, moderate, severe, and extreme. The results showed that permeable pavements exhibited the highest reduction rate, reducing stormwater by approximately 50% across all sub-basins, while green roofs showed the lowest reduction rate of only 0.003%. Regional calibration was implemented, revealing a significant correlation of 71% between simulated and observed flows in the study area. The findings of this study can serve as a valuable decision-support tool for stakeholders and authorities when selecting appropriate LID practices to mitigate the urban impact of stormwater generation.

Keywords: ***Low Impact Development (LIDs), Malete, MapWindow GIS, MWSWAT,*** **Soil** ***Erosion, Stormwater, SWMM***

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Corresponding author- ***Adeniyi Ganiyu***

I. INTRODUCTION

Stormwater refers to precipitation originating from rain, sleet, or melting snow. In natural environments, only a small portion of this precipitation becomes surface runoff. Runoff typically flows into nearby streams, creeks, rivers, lakes, or wetlands. However, owing to rapid global urbanization, the characteristics of natural land cover are transforming into impermeable surfaces, leading to the degradation of natural surroundings. These negative impacts include increased runoff, heightened peak flows that result in flash floods, degradation of water quality, and other water-related challenges [1].

As reported in several works of literature [2-5], climate change exacerbates these issues, making urban areas susceptible to erosion and recurrent flooding which has led to various climate change impact studies in urban catchments. The combination of climate change and urban growth has disrupted hydrological patterns, elevated runoff volumes, and caused erosion, floods, and ecosystem deterioration. In recent times, the use of Low-impact development (LID) strategies has advocated for decentralized stormwater management systems distributed across the catchment area, as opposed to centralized approaches. LIDs offer benefits such as curbing storm runoff volume [6], enhancing stormwater quality and river conditions, reducing flood peaks, boosting infiltration rates and base flow, restoring the water cycle equilibrium, and disrupting urbanization [7, 8]. Traditionally, urban flood control methods have focused on constructing drainage channels to convey the generated runoff [9, 10]. However, such drainage systems yield only short-term effects and fail to address the root problems.

In recent times, Low Impact Development (LID) practices have come to the forefront as a viable approach to mitigate the negative effects of urbanization and restore natural water cycles in urban areas, promoting a more sustainable future. Various hydrological models, such as the Storm Water Management Model (SWMM), can simulate the impact of diverse LIDs and replicate natural hydrological conditions to a great extent [11, 12]. Numerous studies have been published on modeling Low Impact Developments (LIDs) to sustainably manage runoff across various catchment scales. For instance, researchers in a study [13] developed models for detention ponds and infiltration trenches to assess their impact on runoff volume. The results showed that Low

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Impact Development (LID) practices significantly reduce stormwater runoff for small rainfall events but have limited effectiveness during flood events. Similarly, another study [14] investigated the effectiveness of green roofs in mitigating runoff using the Storm Water Management Model (SWMM). The simulation revealed that green roofs are an excellent solution for reducing runoff. A study [13] integrated detention ponds and infiltration trenches into an existing hydrological model to evaluate their effect on runoff volume. The findings confirmed that LID practices effectively control stormwater during small rainfall events but have limited influence during flood events. This approach is widely adopted to mitigate the adverse effects of urban stormwater runoff.

However, very few of these studies could be found in the literature to address the issue of stormwater reduction in Africa or sub-Saharan African watersheds. A notable study [15] investigated the impact of Low Impact Developments (LIDs) on runoff generation in Eldoret, Kenya, using the Storm Water Management Model (SWMM). The study findings revealed that infiltrating 100% of impervious areas with infiltration trenches led to a 25% reduction in average runoff flow and a 19.6% decrease in total runoff volume. Additionally, bio-retention ponds were found to reduce average runoff flow and volume by 1.6% and 4.4%, respectively. Another African application of LIDs was explored by a study [16], which discovered that combining Permeable Pavement and Rain Barrels offered the most effective runoff control, achieving a remarkable 57% removal rate

The choice of Malete, a town situated in Kwara State, Nigeria is because the town is experiencing rapid growth, largely attributed to the establishment of Kwara State University. Over the past decade, the University has witnessed a significant rise in student enrollment and staff numbers, leading to the extensive construction of student hostels within the town. This urban expansion has amplified the generation of stormwater runoff, potentially causing issues such as waterlogging, traffic congestion, the submergence of infrastructure, and disruptions to utility pipelines such as gas and electricity. Urban waterlogged areas severely affect human safety and properties. This study aimed to assess the impact of selected Low Impact Development (LID) techniques on managing stormwater generation in the study area. The outcomes of this study could provide

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valuable insights and a decision-making criterion for local authorities and developers in the implementation of the most effective LID alternatives for stormwater management in the region.

II. METHODOLOGY

A. *Description of the Study Area*

The study site is situated in Malete town, located between latitudes 8^{0}36' and 8^{0}24' North and longitudes 4^{0}36' and 4^{0}10' East. It covers a total area of 1,230.0 square kilometers and is a small town within the Moro Local Government Area of Kwara State of Nigeria. The administrative center of this locality is in Bode Saadu, a town located along Jebba Road. The Moro Local Government comprises five districts: Lanwa, Ejidongari, Olooru, Malete, and Ipaye. The terrain of the area closely resembles the surrounding plains, which are characterized by gently undulating slopes. The town employs a combination of open stormwater drainage systems and earthen drains to manage the stormwater flow generated within the vicinity. Malete town is home to Kwara State University, which was established in 2009. The primary occupations of Malete residents are farming and trading. It is a predominantly Yoruba-populated agrarian community. In addition to agriculture, the residents of Malete also participate in hunting and fishing activities. Nevertheless, its fertile soil renders it particularly favorable for extensive farming and agro-industries. Fig. 1 shows the location of Malete Town in Kwara State.

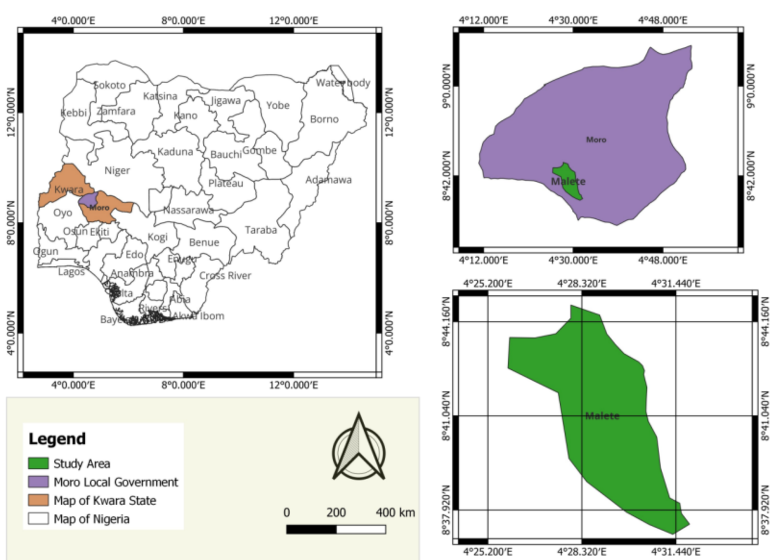

Fig. 1. Map of Nigeria showing the location of the study area

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B. Data Collection and Description

This study utilized a range of data for its analysis. This includes 90 m resolution topography data from the Shuttle Radar Topography Mission's (SRTM) final version, which employed radar technology to generate a detailed digital elevation model of the Earth's surface. Land use and land cover (LULC) data was obtained from the Global Land Cover Characterization (GLCC) database, with a spatial resolution of 1 kilometer and 24 classes of land-use representation, used to estimate vegetation and other parameters representing the watershed area [17,18] [19]. The land use map of the study area is shown in Fig. 2. Digital soil data was extracted from the harmonized digital soil map of the world (HWSD v1.1), produced by the Food and Agriculture Organization of the United Nations, providing information on 16,000 different soil mapping units, with data available for two layers (0-30 cm and 30-100 cm depth), and complemented with additional soil data collected and analyzed from various locations within the watershed area [20]. Finally, weather data was obtained from the Nigeria Meteorological Agency (NIMET), covering a period of 30 hydrological years, including daily precipitation, maximum and minimum temperatures, solar radiation, relative humidity, and wind speed, with 19 years of data (from 2001-2019) used specifically for the SWMM Model.

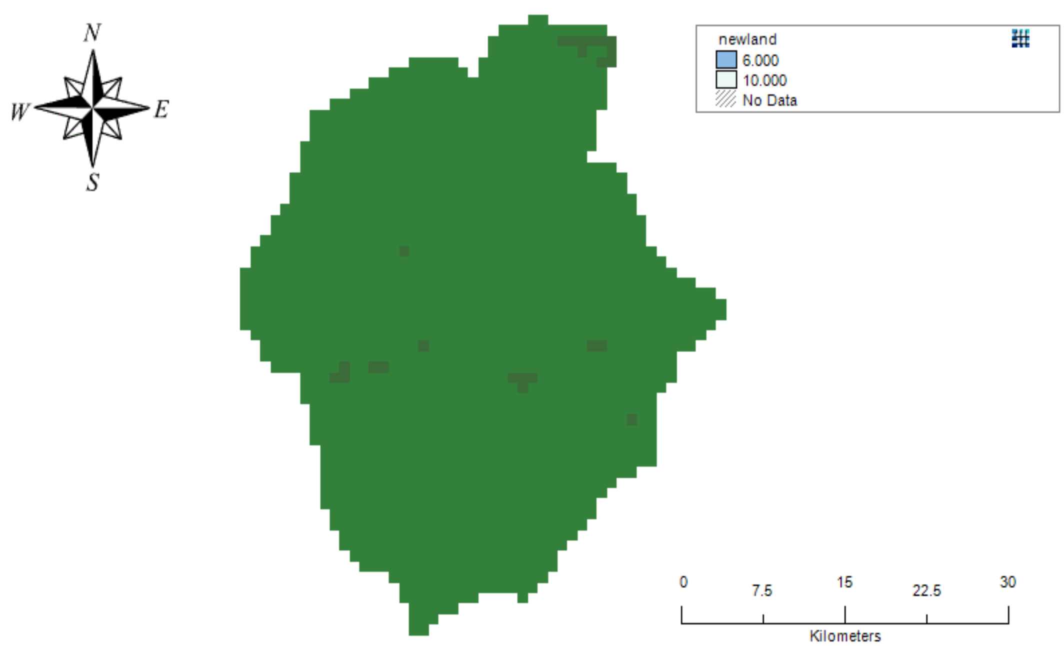

Fig. 2. Land use map of the study area

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C. Geo-Processing of Data and SWAT Model Setup

The physical model used in this study for the prediction of sediment yield and identification of erosion-prone areas is the Soil and Water Assessment Tool, SWAT [21, 22]. SWAT has been used by many researchers and its availability and efficacy in the prediction of different hydrological processes has also been reported in many studies [23-27]. The primary spatial data needed for the modeling of the study area is the Digital Elevation Model (DEM) which was geo-processed using the Automatic Watershed Delineation (AWD) tool embedded in the MapWindow GIS interface. This involved configuring the elevation units, and threshold size, and defining an outlet for the watershed. Additional spatial data, such as land use and soil maps, played a pivotal role in delineating the watershed into sub-basins. The land use map served as a basis for estimating parameters such as vegetation within the study area. Using the GIS component of the MWSWAT, the study area was subdivided into six subbasins and 11 hydrologic response units (HRUs). Notably, the HRU represents the smallest spatial unit within the model.

In this study, the SWAT analysis was conducted utilizing the Runoff Curve Number approach to assess surface runoff resulting from precipitation. The SCS curve number method, serving as a rainfall-runoff model designed for computing excess rainfall or direct runoff, assumes an initial abstraction related to the curve number before ponding occurs. The rationale for employing this method in the study lies in its widespread application across many countries attributed to its perceived simplicity, predictability, stability, and reliance on a single parameter, as noted by a study [28]. Additionally, [29] demonstrated that the curve number method exhibits superior predictive performance in SWAT applications compared to the Green-Ampt method. For the estimation of potential evapotranspiration, the Hargreaves method was adopted due to its simplified equation, which relies only on two climatic parameters: temperature and incident radiation. This method is particularly recommended in situations where reliable data are lacking, as highlighted by [30]. In the simulation of channel water routing, the variable-storage routing method was chosen. This method links the outflow volume to both the storage coefficient and the volume stored, providing a comprehensive approach to simulate the dynamics of water routing in channels.

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D. Modeling in SWMM

This study adopted a Storm Water Management Model (SWMM), which is a comprehensive simulation model for hydrology and water quality. This model is used to simulate runoff events in urban areas, either for event-based or continuous simulations [31]. The fundamental input parameters required to simulate hydrographs encompass the rainfall hyetograph and physical attributes of the sub-catchments. The infiltration loss on pervious surfaces was determined using the Horton equation by leveraging available soil data. The EPASWMM is a deterministic physically based model designed to replicate the movement of water inflows, outflows, and storage within sub-catchments. Fig. 3 shows the schematic diagram of SWAT and SWMM modeling processes for the simulation of flow and performance evaluation of LIDs of the study area. The entire catchment was composed of six sub-catchments, ten junctions, ten conduit links, one outfall, and one rain gauge station as shown in Fig. 4. SWMM software was utilized to calculate the quantity of runoff generated within each sub-catchment and to determine flow rates and depths within conduits during the simulation period, which involved multiple time steps.

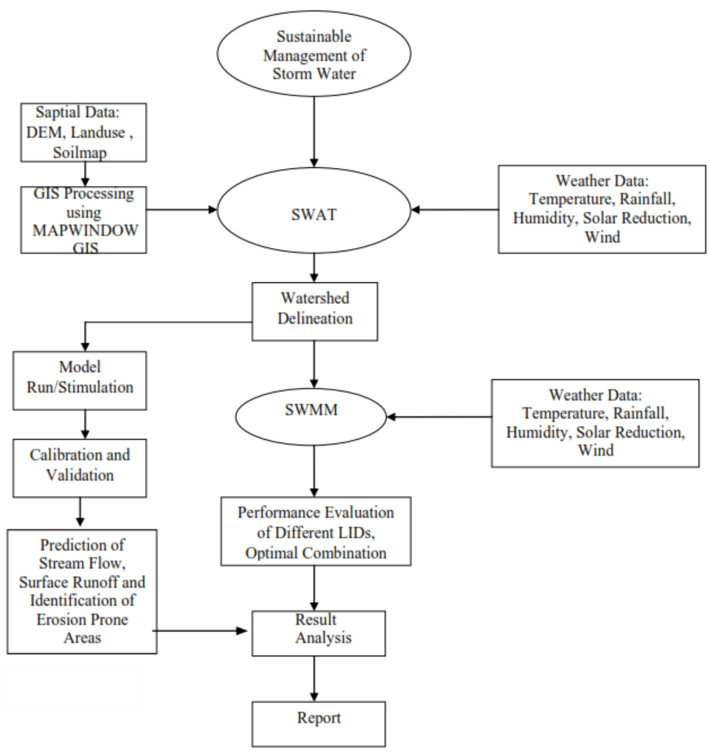

Fig. 3. Graphical representation of processes involved in the methodology.

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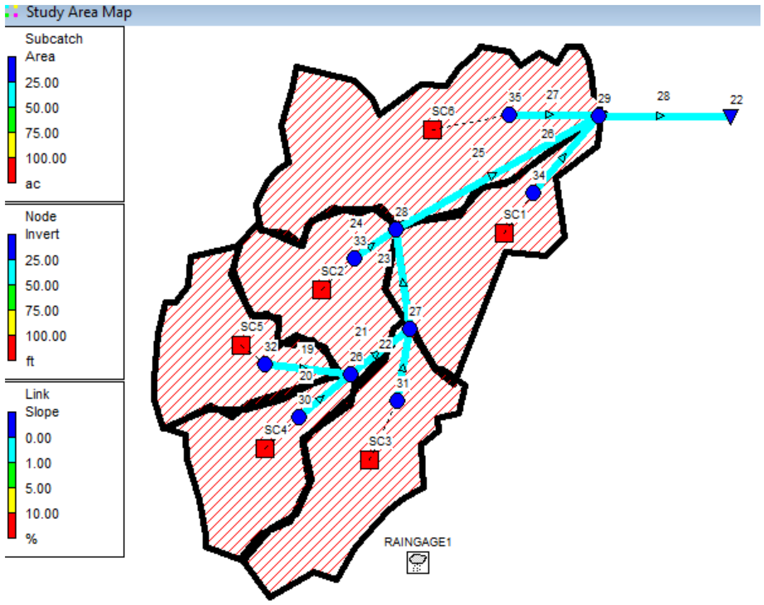

Fig. 4. Watershed delineation of the study area

E. Implementation of Low Impact Development (LID) for Runoff Reduction

Selected LIDs were modeled in the study area to study their effectiveness in the reduction of runoff generated. These techniques have been shown to effectively reduce stormwater pollutants, with Rain Gardens capable of removing solids, organics, nutrients, and heavy metals [32]. Green Roofs, consisting of a vegetative covering on a water-resistant material, have also been proven to be effective [33-36]. To evaluate the efficiency of these LID practices in mitigating runoff, the Storm Water Management Model (SWMM) was employed as an analytical tool. The selected LID controls were integrated into the model for each sub-catchment, allowing for a detailed analysis of their impact on runoff reduction. The core methodology of this study involved using SWMM as a modeling tool to explore the impact of LID practices on stormwater reduction. The results of the study are presented in the following section, highlighting the effectiveness of the selected LIDs in reducing stormwater runoff.

III. RESULTS AND DISCUSSION

A. Prediction of Total Stream Flow in the Sub-Basin

Fig. 5 displays the predicted streamflow data for each sub-basin. Sub-basin 4 had the highest streamflow rate at 216.67 m^3/s, while sub-basin 2 had the lowest at 65.56 m^3/s. This significant

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difference is due to the unique geological formations and land cover characteristics of sub-basin 4, which result in a high streamflow rate and increased susceptibility to erosion and flooding. In contrast, sub-basin 2's more permeable layer allows for greater groundwater infiltration, leading to reduced streamflow, erosion, and flooding risks. Overall, the total streamflow at the study area's outlet is predicted to be 451.91 m^3/s during the simulation period.

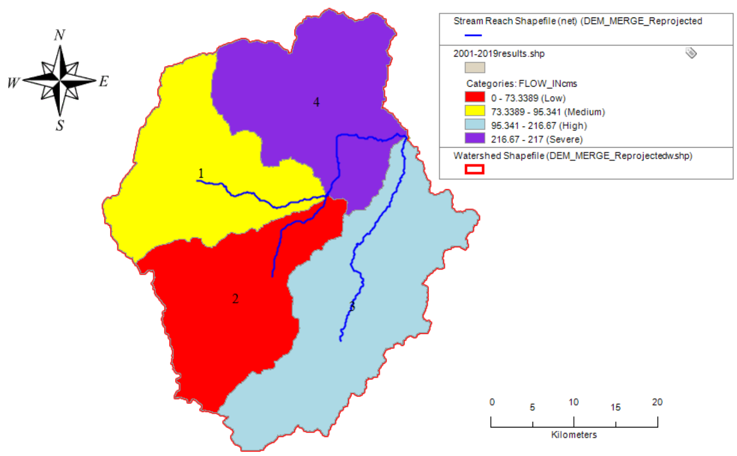

Fig. 5. Spatial variation in stream flow in the study area

B. Prediction of Total Surface Runoff in the Sub-basin

The model predictions revealed significant variations in total surface runoff across the sub-basins during the simulation period. Sub-basin 1 exhibited the highest predicted surface runoff, with a value of 313.09 mm, while sub-basin 2 experienced the lowest, at 292.59 mm. The geological formations and land cover characteristics of sub-basin 1 likely contributed to its high surface runoff rate, making it prone to erosion and flooding. This high runoff may be attributed to impermeable soil, steep terrain, or land cover types that hinder effective water absorption, resulting in excess water flowing over the surface and leading to erosion and potential flooding.

In contrast, the sub-basin 2 low surface runoff rate is attributed to its relatively permeable layer, which facilitates higher infiltration rates and allows water to recharge groundwater. This results in less surface runoff, reduced erosion, and a lower risk of flooding. Fig. 6 provides a visual representation of the predicted surface runoff distribution across the study area, while Table I provides a detailed breakdown of the predicted total flow and total surface runoff in each sub-basin.

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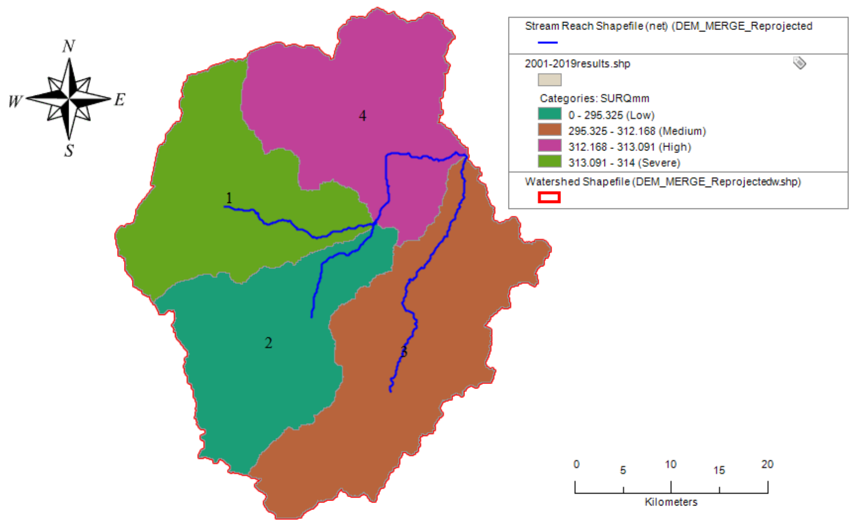

Fig. 6. Variability in surface runoff across the study area

Table I: Sub-basin-specific predictions of total flow and total surface runoff

Basins Number	Area (km^2)	Flow (m^3/s)	Surface runoff (mm)
1	324.94	73.34	313.09
2	318.53	66.56	292.59
3	447.96	95.34	295.32
4	349.13	216.67	312.17
	Total	451.91	1213.17

C. Identification of Erosion Prone Area

The areas vulnerable to erosion were classified into four categories: low, moderate, severe, and extreme. This categorization helps understand the erosion risk across the watershed. The results show that sub-basin 4 has a high proportion of areas at severe risk of erosion, while sub-basin 3 has a significant presence of erosion-prone areas. In contrast, sub-basin 2 is largely composed of areas with low erosion risk. In sub-basin 4, the significant presence of severe erosion is likely attributed to the steep slope gradient, which increases water runoff velocity and contributes to more pronounced erosion. Additionally, poor vegetative cover exposes the soil to erosion, diminishing its protection against the impact of rainfall. The soil characteristics, such as low cohesion or high erodibility, could further exacerbate vulnerability. Unsustainable land use practices, such as

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improper agricultural methods or construction activities, may also play a role in enhancing erosion risk in this sub-basin.

Sub-basin 3 exhibits a high occurrence of erosion-prone areas, possibly due to intensive agricultural practices. Extensive plowing and the absence of cover crops contribute to soil erosion. Urbanization in this sub-basin may lead to impervious surfaces, altered drainage patterns, and increased erosion risk. Furthermore, changes in the hydrological cycle, such as altered precipitation patterns or heightened storm intensity, could elevate the overall vulnerability to erosion in sub-basin 3. Contrastingly, sub-basin 2 is primarily characterized by low erosion-prone areas. This might be attributed to the presence of sufficient vegetative cover, either through natural vegetation or well-managed land cover, contributing to soil stabilization and reduced erosion. The gentle slopes in this sub-basin may also play a role in minimizing erosion risk. Effective conservation practices, such as contour plowing or afforestation, could be implemented, further reducing the susceptibility to erosion in sub-basin 2. The spatial map of the erosion-prone areas is shown in Fig. 7.

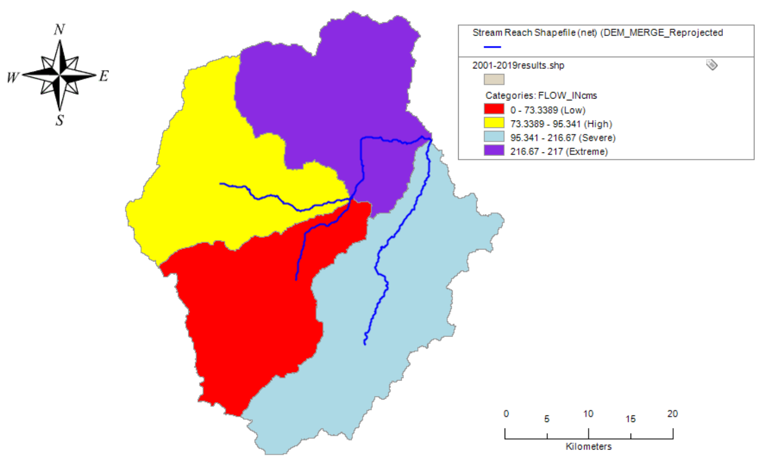

Fig. 7. Classification of erosion-prone areas

D. Model Calibration, Validation, and Performance Evaluation

Due to a lack of observed data for the study area, regional calibration was adopted to calibrate and validate the model. Regional calibration of hydrological models is a process used to enhance the accuracy and reliability of hydrological simulations over a larger geographic area by adjusting

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model parameters to better reflect the specific characteristics and behaviors of different sub-regions within the area. This process is crucial for understanding water resources, predicting floods, and managing water systems effectively. It involved using observed data from nearby Asa River located between latitude 8^0 36’ and 8^0 24’ North and longitudes 4^0 36’ and $4^0$10’ East with the predicted flow values in the watershed to establish a calibration for the model. Fig. 8 shows the correlations between the observed and simulated flow with a correlation coefficient of 0.7099 indicating a good correlation between the observed and simulated flow. In other words, the strength of the relationship between these two variables is constrained to approximately 71 %. It is imperative to state that this approach may have its limitations; however, it is supported by various relevant literature sources that reported similar levels of correlation between [11, 37-40]

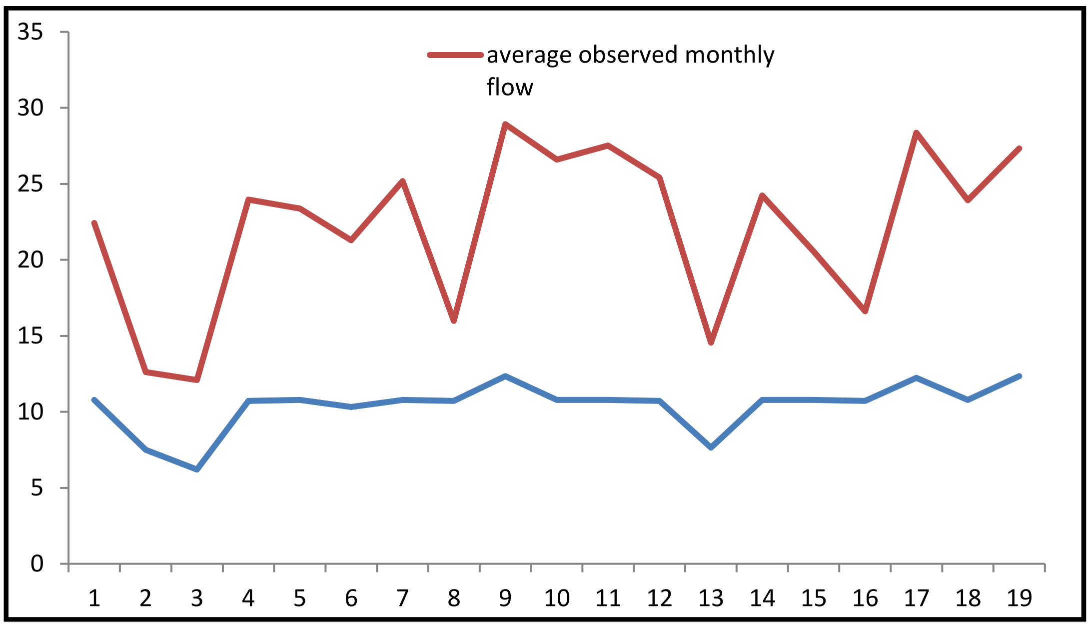

Fig. 8. Graphical representation of the predicted flow and observed flow for the calibration period.

E. Effect of Application of Permeable Pavement on Stormwater Reduction

The findings of the study as presented in Fig. 8 revealed a significant insight into the effectiveness of various LID models in reducing stormwater generation across the sub-basins within the study area. Notably, all LID models demonstrated the capacity to reduce stormwater generation to varying degrees. However, the permeable pavement was identified as the most performing among the LID techniques in the reduction of surface runoff, flood peaks, and delaying peak flow. On

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average, an impressive stormwater reduction of approximately 50% was achieved. This result indicated that permeable pavement can be used effectively and efficiently in the reduction of stormwater generated in the study area. The result obtained in this study also aligned with the results that were obtained in the literature [41-43]. The consistency in findings can be attributed to factors such as the high rainfall intensity in the study area and the presence of substantial vegetative cover. These factors contributed to the efficacy of permeable pavement, rendering it a reliable option for stormwater management in regions with analogous environmental conditions. In conclusion, the results of this study highlight the efficacy of Low Impact Development (LID) techniques in mitigating stormwater generation, emphasizing their potential as effective strategies for managing urban runoff, and promoting sustainable water management practices

F. Impact of Vegetative Swale Implementation on Stormwater Mitigation

The implementation of vegetative swales in the study area yielded a runoff reduction percentage ranging from 13.95 % to 15.56 %, making it the second most effective Low Impact Development (LID) technique. While this reduction is substantial, it falls short of the results reported in previous studies [44-45]. The inconsistencies in outcomes may be attributed to regional factors unique to the study area. A plausible explanation for the relatively lower runoff reduction achieved by vegetative swales is the climatic conditions, which differed from those in the regions where studies [44] and [45] conducted their research experiments. Specifically, the study area may have experienced a lower frequency of rainfall events, lower rainfall intensity, and shorter rainfall durations, which could have impacted the effectiveness of vegetative swales in reducing runoff. This highlights the importance of considering local climatic conditions when implementing and evaluating the effectiveness of Low Impact Development (LID) techniques. The reduced rainfall frequency, intensity, and duration may have limited the swales' ability to capture and filter stormwater, resulting in a lower runoff reduction percentage.

G. Impact of Rain Garden Implementation on Stormwater Mitigation

The rain gardens in the study area demonstrated a negligible runoff reduction, with values ranging from 0.0003% to 0.31%. These findings are consistent with the results reported by a study [46] but diverge from those obtained by [47]. The inconsistencies in these findings can be attributed to

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various factors, including the unique rainfall patterns and land use characteristics of the study areas. Notably, the effectiveness of rain gardens in reducing runoff appears to be limited in this context. Reduction in the runoff generation is an indication that rain gardens may not be a suitable strategy for mitigating stormwater runoff in this region, potentially due to the high rainfall intensity or land use practices that impede the performance of rain gardens.

H. Impact of Green Roofs on Stormwater Reduction

Application of Green roofs in the management of stormwater in the study area has the least impact as a management strategy with a negligible 0.0003% reduction observed in the study area. This finding aligns with the results of a previous study [14]. The limited effectiveness of green roofs in reducing stormwater runoff in this study can be attributed to various factors. The capacity of green roofs to capture, retain, and release rainwater is heavily dependent on the vegetation and soil substrate used. Factors such as vegetation type, soil composition, and substrate depth can significantly influence green roof performance. The consistency of these results with the study [14] suggests that both studies share commonalities in terms of climate, vegetation type, and green roof design, leading to similar outcomes.

I. Effects of Combination of LIDs on Stormwater Reduction

The study of various Low Impact Development (LID) technique combinations on stormwater reduction in the study area yielded insightful results, as illustrated in Fig. 9. The outcome of this study showed that the combination of permeable pavement and vegetative swale may reduce the stormwater generation up to about 65.09 percent in the study area, showcasing exceptional efficiency in mitigating stormwater runoff. However, these results diverge from those reported by the study [14], suggesting that the performance of LID techniques can be significantly influenced by local conditions, including rainfall patterns, soil characteristics, and the built environment. In contrast, the combination of Green Roof and Rain Garden yielded the lowest stormwater reduction percentage of 0.19 %, indicating limited effectiveness in stormwater management. It is essential to acknowledge that the combined performance of LID techniques can vary substantially depending on the specific attributes of the study area, including climate, land use, and soil composition.

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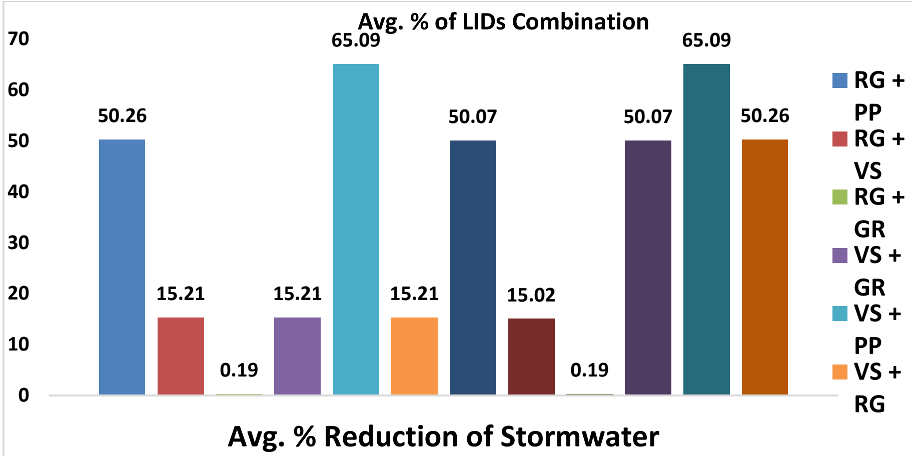

Fig. 9. Average percentage reduction of stormwater generation using varieties of LID combination.

IV. CONCLUSION

The study and experimental analysis revealed that annual stream flow and surface runoff values showed significant variation, with stream flow ranging from 1264.66 m^3/s to 4116.74 m^3/s and surface runoff varying from 1264.66 mm to 5931.9 mm. The study identified areas prone to erosion and categorized them into four levels of susceptibility: low, moderate, severe, and extreme. This identification is crucial for targeted mitigation efforts. The simulation results demonstrated the effectiveness of Low Impact Development (LID) techniques in reducing the environmental and water quality impacts of stormwater. All examined LID techniques showed positive results.

Among the LID techniques, permeable pavement showed the highest percentage reduction in runoff, while green roofs had the lowest percentage reduction. Combining LID techniques resulted in varying levels of effectiveness, with the combination of permeable pavement and vegetative swale achieving the highest percentage reduction in stormwater. In contrast, the combination of green roofs and rain gardens showed the lowest percentage reduction. The regional calibration of the model revealed a strong correlation of 71 % between predicted and observed flow data, indicating a significant relationship between the two datasets. This calibration enhances the reliability of the model's predictions.

Therefore, it was concluded that the integration of SWAT and SWMM models can provide a robust decision-support framework for stakeholders and authorities in the region. By leveraging these models, policymakers and practitioners can make informed decisions about effective stormwater

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management practices, ultimately contributing to the sustainability and resilience of urban water systems. The use of these models can also help identify areas with high stormwater generation potential and prioritize interventions aimed at reducing runoff and improving water quality.

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Conflict of interests

The authors declare that there is no conflict of interest

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