Journal of Geomatics Engineering, Technology, and Science (GETS)
ISSN p:2830-1811 e:2988-532X, 2026, Vol. 4, No. 2, 8-14
https://doi.org/10.51967/gets.v4i2.67

Hydrological Modeling and GIS-Based Drainage Design for Urban Flood Management in Edaiken, Benin City, Nigeria

Stephen Olushola Oladosu[a], Esther Charlie Joshua[a], & Bright Odion Akenbor[b]

[a] Department of Geomatics Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Edo State, Nigeria
[b] Department of Geology, Federal University Otuoke, PMB 126 Yenagoa, Bayelsa State, Nigeria

ABSTRACT

Urban flooding remains a persistent challenge in rapidly urbanizing regions of developing countries, largely due to inadequate drainage infrastructure and increasing surface runoff. This study presents a data-driven approach to flood mitigation through the integration of hydrological modeling, field surveys, and Geographic Information System (GIS)-based spatial analysis in Edaiken, Benin City, Nigeria. The study area was delineated into five sub-catchments (SC1–SC5) using Digital Elevation Models (DEMs) to analyze runoff patterns and flow accumulation. Hydrological parameters, including time of concentration (0.284–0.583 hours), rainfall intensity (137.034–175.972 mm/hr), and peak discharge (0.49–2.78 m³/s), were computed using the Rational Method, while hydraulic capacities were evaluated using Manning's equation. Results indicate that sub-catchments SC3 and SC4 contribute the highest runoff volumes due to low elevation and high flow convergence. The cumulative discharge increased downstream to approximately 7.00 m³/s, necessitating drainage dimensions ranging from 0.9 × 0.9 m to 1.0 × 1.0 m. The findings reveal that flooding in the study area is primarily driven by undersized drainage systems, poor maintenance, and rapid urbanization. The proposed drainage redesign provides a technically sound framework for improving urban drainage capacity and supporting flood risk management. This study provides a scalable framework for sustainable urban drainage planning in flood-prone cities across sub-Saharan Africa.

ARTICLE HISTORY

Received: March 20th, 2026
Accepted: April 21st, 2026
Published: April 22nd, 2026

KEYWORDS

Urban Flooding; Drainage Design; GIS; Hydrological Modeling; Rational Method; Benin City.

CORRESPONDING AUTHOR

Stephen Olushola Oladosu
Email: olushola.oladosu@uniben.edu

How to cite: Oladosu, S. O., Joshua, E. C., & Akenbor, B. O. (2026). Hydrological Modeling and GIS-Based Drainage Design for Urban Flood Management in Edaiken, Benin City, Nigeria. *Journal of Geomatics Engineering, Technology, and Science*, *4*(2), 8-14. https://doi.org/10.51967/gets.v4i2.67

1. INTRODUCTION

Urban flooding has emerged as one of the most significant environmental challenges affecting rapidly growing cities worldwide, particularly in developing countries where urban expansion often outpaces infrastructure development. Globally, floods account for approximately 43% of all natural disasters and result in substantial economic losses exceeding $50–60 billion annually (United Nations Office for Disaster Risk Reduction, 2018; World Bank, 2022). These impacts are disproportionately severe in low- and middle-income countries due to weak planning systems, inadequate drainage infrastructure, and limited disaster preparedness.

In sub-Saharan Africa, urban flooding has intensified due to a combination of climate variability and rapid, unregulated urbanization. Increasing rainfall

CONTACT Stephen Olushola Oladosu ✉ olushola.oladosu@uniben.edu

intensity linked to climate change has been identified as a major driver of flood risk, with projections indicating a rise in extreme precipitation events across tropical regions (Yoshihide Hirabayashi et al., 2022; Intergovernmental Panel on Climate Change, 2021). At the same time, the expansion of impervious surfaces such as roads, rooftops, and pavements significantly reduces infiltration capacity, thereby increasing surface runoff and overwhelming existing drainage systems (Ahiablame & Shakya, 2016; Monachese et al., 2025).

Nigeria has experienced recurrent and increasingly severe flood events over the past decades, highlighting systemic weaknesses in urban planning and water management. The 2022 nationwide flood disaster affected over three million people and displaced more than 1.4 million, making it one of the most devastating flood events in the country's history (National Emergency Management Agency, 2022; United Nations Office for the Coordination of Humanitarian Affairs, 2022).

These events underscore the urgent need for sustainable flood mitigation strategies that integrate engineering design with environmental and spatial analysis. Urban flooding in cities such as Benin City is primarily attributed to inadequate drainage infrastructure, poor maintenance practices, and unregulated land-use development.

Blocked drainage channels due to improper waste disposal and encroachment on natural waterways further exacerbate the problem, leading to frequent waterlogging and infrastructure damage (World Bank, 2022; Ologunorisa & Abawua, 2005).

In many cases, existing drainage systems were designed using outdated rainfall data and are no longer capable of accommodating current hydrological conditions. Recent advances in hydrological modeling and Geographic Information Systems (GIS) have provided powerful tools for analyzing flood dynamics and designing efficient drainage systems.

The integration of Digital Elevation Models (DEMs), runoff estimation methods such as the Rational Method, and hydraulic modeling techniques enables a more accurate assessment of flood-prone areas and infrastructure requirements (Kumar, 20236 Alam et al., 2023). These data-driven approaches have proven effective in improving urban flood resilience in both developed and developing contexts.

Despite these advancements, many urban flood mitigation efforts in Nigeria remain reactive and lack a comprehensive analytical framework. There is therefore a need for studies that combine field observations, hydrological analysis, and geospatial techniques to develop practical and scalable drainage solutions tailored to local conditions. This study addresses this gap by applying GIS-based catchment analysis and hydrological modeling to design an efficient urban drainage system for flood mitigation along Edaiken Primary School Road in Benin City. The research aims to identify flood-prone zones, evaluate runoff characteristics, and propose a drainage design capable of managing peak stormwater discharge under current urban conditions.

2. METHOD

2.1. Description of the Study Area

The study area is located along Edaiken Primary School Road and its surrounding environment within the Ugbowo district of Benin City, Edo State, Nigeria. Geographically, the area lies approximately between latitudes 6.370°N and 6.376°N, and longitudes 5.617°E and 5.624°E. It is situated within a rapidly urbanizing part of Benin City characterized by mixed land use, including residential developments, small-scale commercial activities, and institutional facilities such as Edaiken Primary School.

Topographically, the terrain is relatively flat, with elevations ranging from approximately 80 to 90 meters above mean sea level. This low-relief landscape limits natural drainage gradients, thereby reducing the efficiency of surface runoff conveyance. Consequently, the area is highly susceptible to water accumulation, particularly during periods of intense rainfall. The region experiences a tropical climate with a distinct wet season extending from April to October and a dry season from November to March. Annual rainfall ranges between 1,800 mm and 2,100 mm, contributing significantly torunoff generation and flood occurrence within the area. Figure 1 shows the map of the study area.

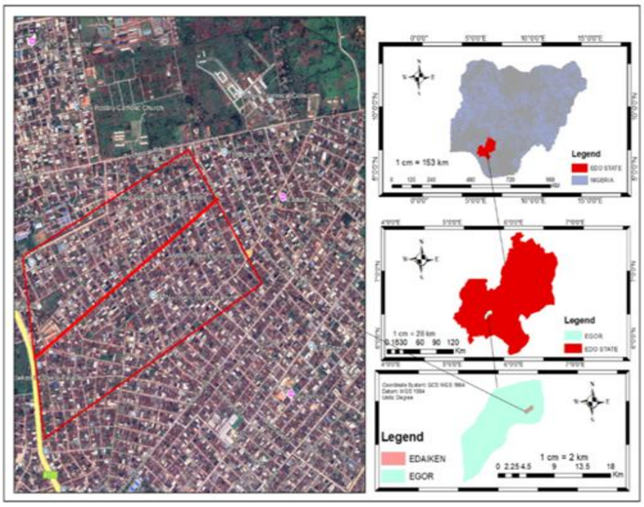

Figure 1. Map of the Study Area

2.2. Research Workflow

The methodological framework adopted in this study integrates field data collection, geospatial analysis, hydrological modeling, and hydraulic design to develop an efficient drainage system for flood mitigation. The workflow follows a sequential process: The data acquisition, catchment analysis, hydrological modelling, hydraulic analysis, as well as drainage design and optimization. Figure 2 shows the flow diagram for the processes involved in the workflow.

Figure 2. Research workflow diagram

2.3. Integrated Approach

An integrated methodology combining field data acquisition, geospatial analysis, hydrological modeling, and hydraulic evaluation was adopted to assess and redesign the drainage system within the study area.

Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model provided by the NASA, with a spatial resolution of 30 m and an estimated vertical accuracy of ±10–16 m (Farr et al., 2007; USGS, 2020). The DEM formed the basis for terrain analysis, including watershed delineation, flow direction, and flood susceptibility assessment.

To enhance positional reliability, selected ground control points were acquired using a dual frequency GNSS receiver during field reconnaissance. These observations provided horizontal accuracy in the range of ±3–5 m and were used for spatial validation of the DEM (Hofmann-Wellenhof et al., 2001). Additional field observations included visual inspection and limited measurement of drainage channels to identify flow paths, blockages, and structural conditions, as well as approximate channel geometry (width, depth, and slope) for hydraulic evaluation (Chow, 1959; Akan & Houghtalen, 2003).

Rainfall data were sourced from the Nigerian Meteorological Agency, consisting of a 25-year historical record for the study area. These data were used to derive rainfall intensity values through Intensity–Duration–Frequency (IDF) relationships, with typical measurement uncertainty ranging between ±5–10% (Chow et al., 1988; NiMet, 2020).

All datasets were processed and integrated within a Geographic Information System (GIS) environment, including Global Mapper in order to ensure consistency in coordinate systems, scale, and analytical procedures. The integration of these datasets provided a reliable foundation for terrain analysis, hydrological modelling, and drainage system evaluation, consistent with established GIS-based methodologies (Burrough & McDonnell, 1998).

Based on terrain characteristics, the study area was subdivided into five sub-catchments (SC1–SC5) to represent runoff generation and routing.

Hydrological analysis was carried out to estimate runoff characteristics. The time of concentration (T_c) was computed using the Kerby–Hathaway equation (Chow et al., 1988):

$$T_c = 0.828\left(\frac{(L \cdot r)^{0.467}}{S^{0.235}}\right) \qquad (1)$$

Where Tc is the time of concentration (hours), L is the flow length (km), r is the surface roughness coefficient, and S is the slope (m/m). The computed Tc was used to determine the corresponding rainfall intensity for each sub-catchment.

Peak runoff was estimated using the Rational Method (Kuichling, 1889; Chow et al., 1988):

$$Q = CIA \qquad (2)$$

Where Q is the peak discharge (m^3/s), C is the runoff coefficient, I is the rainfall intensity (mm/hr), and A is the catchment area (km²). Equation (2) is widely applied in urban hydrology due to its suitability for small catchments with relatively uniform rainfall distribution.

Hydraulic capacity of the drainage channels was evaluated using Manning's equation (Manning, 1891):

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (3)$$

Where n is Manning's roughness coefficient, A is the cross-sectional area (m²), R is the hydraulic radius (m), and S is the channel slope (m/m). The hydraulic radius was computed as:

$$R = \frac{A}{P} \qquad (4)$$

Where P is the wetted perimeter (m). The discharge capacity obtained from Equation (3) was compared with the peak runoff estimated using equation (2) to assess the adequacy of existing drainage structures.

Flow regime conditions were evaluated using the Froude number (Chow, 1959):

$$Fr = \frac{V}{\sqrt{gD}} \qquad (5)$$

Where Fr is the Froude number, V is flow velocity (m/s), g is gravitational acceleration (9.81 m/s²), and D is hydraulic depth (m). Flow conditions were classified as subcritical ($Fr < 1$), critical ($Fr = 1$), or supercritical ($Fr > 1$), providing insight into flow stability and erosion potential.

The Intensity–Duration–Frequency (IDF) relationship was computed using a commonly adopted empirical equation 6:

$$i = \frac{a}{(t + b)c} \qquad (6)$$

Where: i is the rainfall intensity (mm/hr), t signifies rainfall duration (hours) in our case, Tc (0.2–0.4 hrs), and **a**, **b**, **c** are empirical constants (from NiMet IDF data for Zone II)

Table 1 shows the summary of the characteristics of the existing versus proposed drainage system.

Table 1. Existing Versus Proposed Drainage System

Section	Existing Size (m)	Existing Capacity (m³/s)	Proposed Size (m)	Proposed Capacity (m³/s)	Froude No.	Flow Regime
Left-hand Side						
SC1	0.6×0.6	0.728	0.9×0.9	2.00	1.054	Supercritical
SC2	0.7×0.8	1.518	0.9×0.9	2.31	1.223	Supercritical
SC3	1.2×1.4	4.196	0.9×0.9	4.196	0.852	Subcritical
SC4	1.5×1.6	6.818	1.0×1.0	6.818	0.906	Subcritical
SC5	1.5×1.7	7.348	1.0×1.0	7.348	0.892	Subcritical

Based on the results obtained from equations (2)–(5), drainage channels were redesigned to accommodate cumulative discharge along the flow path. Channel dimensions were progressively increased downstream to match increasing runoff contributions from multiple sub-catchments. The final design was guided by hydraulic efficiency, self-cleansing velocity, structural feasibility, and maintenance considerations, ensuring an effective and sustainable drainage system for flood mitigation.

3. RESULTS AND DISCUSSION

3.1. Spatial Delineation of Flood-Prone Catchments

The GIS-based terrain analysis enabled the delineation of five sub-catchments (SC1–SC5), revealing that flood susceptibility is strongly influenced by topography and flow accumulation patterns. Figure 3 shows the sub-catchment delineation.

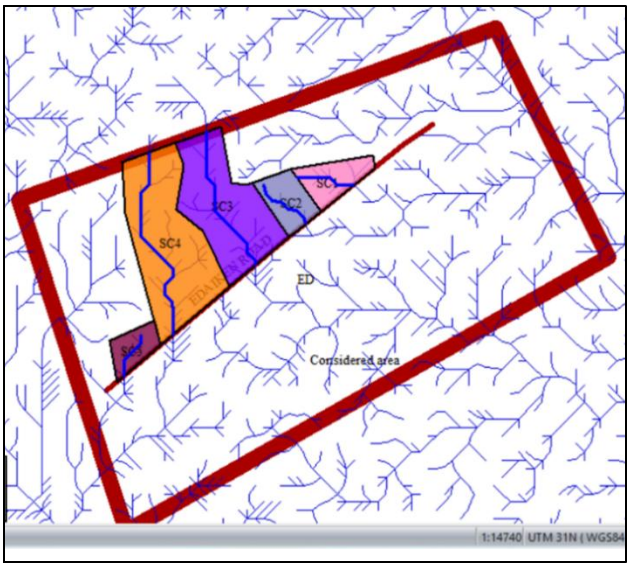

Figure 3. Catchment Delineation

Sub-catchments SC3 and SC4 were identified as the most critical flood-contributing zones due to their lower elevations and higher flow convergence. Areas described as having lower elevations were quantified using DEM-derived statistics. The sub-catchments exhibited elevation ranges between 120 m and 315 m, with mean elevations of SC1 = 135 m, SC2 = 160 m, SC3 = 180 m, SC4 = 210 m, SC5 = 250 m. Sub-catchments with mean elevations below the overall study area average of 187 m were classified as low-lying and therefore more susceptible to surface runoff accumulation.

Similarly, the areas with higher flow convergence was evaluated using flow accumulation values derived from the DEM.. Flow accumulation ranged from 150 to 4,200 cells, with peak values observed in SC2 (4,200 cells) and SC3 (3,800 cells), indicating major drainage pathways. Sub-catchments with flow accumulation values exceeding 3,000 cells were classified as high-convergence zones, reflecting greater potential for runoff concentration and flood risk.

Comparative analysis showed that SC2, characterized by both relatively low mean elevation (160 m) and high flow accumulation (4,200 cells), represents the most hydraulically vulnerable sub-catchment within the study area. This observation is consistent with findings by Kumaru, (2026), who demonstrated that areas with high flow accumulation and low elevation are more prone to urban flooding due to runoff concentration effects.

Similarly, Alam et al. (2023) reported that poorly drained low-lying zones in urban environments act as natural sinks for stormwater, significantly increasing flood risk.

3.2. Hydrological Characteristics of Sub-Catchments

The hydrological analysis shows short times of concentration (0.284–0.583 hours), indicating rapid runoff response typical of urban catchments. Table 2 shows the proposed drain design characteristics for the left-hand side. There was no significant contribution from the right-hand side drain, hence it was not presented.

Table 2. Left-Hand Side Drain Characteristics

Sub-Catchment	Time of Concentration, Tc (hrs)	Rainfall Intensity, I (mm/hr)	Peak Discharge, Q (m^3/s)	Cross-sectional Area, A (m^2)	Hydraulic Radius, R (m)	Velocity, V (m/s)	Drain Capacity, DC (m^3/s)	Froude Number, Fr
SC1	0.28	175.97	0.73	0.31	0.19	2.92	0.89	1.29
SC2	0.29	175.06	0.72	0.31	0.19	2.38	0.73	1.05
SC3	0.49	144.34	2.29	0.31	0.19	2.79	0.85	1.23
SC4	0.58	137.03	2.78	0.31	0.19	1.26	0.39	0.56
SC5	0.32	169.14	0.49	0.31	0.19	2.29	0.70	1.01

Note: Tc = Time of Concentration; I = Rainfall Intensity; Q = Peak Discharge; A = Cross-sectional Area; R = Hydraulic Radius; V = Flow Velocity; DC = Drain Capacity; Fr = Froude Number.

This aligns with studies by Chow et al. (1988), which established that urbanized catchments with high impervious surface coverage exhibit reduced lag time and faster peak flow generation.

The high rainfall intensities (137–176 mm/hr) further amplify runoff generation. Comparable results were reported by Hirabayashi et al. (2013), who linked increasing rainfall intensity in tropical regions to rising urban flood risks.

Sub-catchments SC3 and SC4 recorded the highest discharges (2.30 m^3/s and 2.78 m^3/s), confirming that runoff magnitude is strongly controlled by both rainfall intensity and catchment characteristics. This supports findings by Ahiablame and Shakya (2016), who noted that peak discharge in urban basins is primarily influenced by land use and drainage efficiency.

Sensitivity analysis was performed to evaluate the robustness of high-convergence classifications, different flow accumulation thresholds varying between 2,500–4,000 cells. SC2 remained the most hydraulically vulnerable sub-catchment across all threshold scenarios, indicating consistent flood risk patterns despite variations in parameter selection.

3.3. Drainage Design Response and System Optimization

The redesigned drainage system incorporates increasing channel dimensions downstream to accommodate cumulative discharge. The proposed drainage design is as shown in Figures 4.- 8.

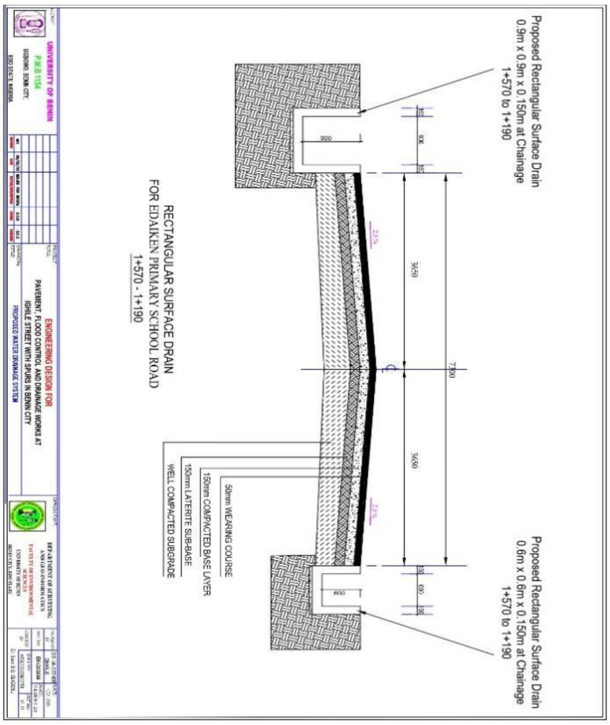

Figure 4. Drainage Design Cross-Section One

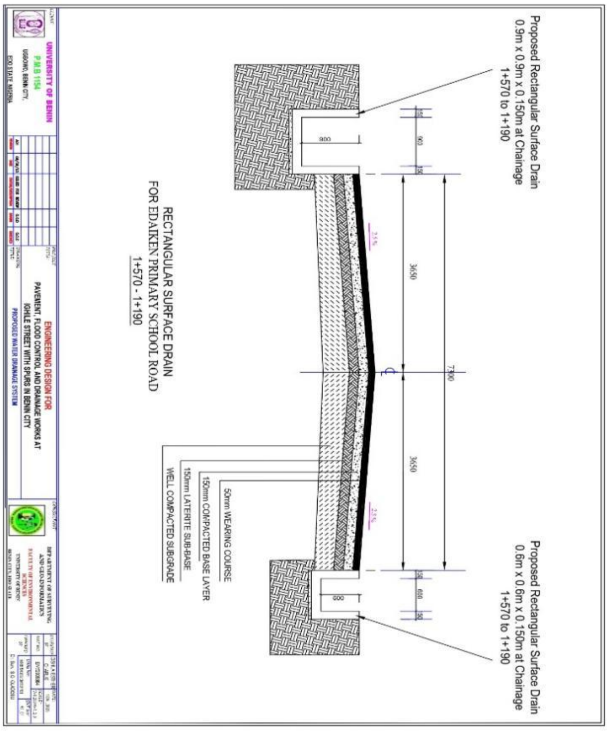

Figure 5. Drainage Design Cross-Section Two

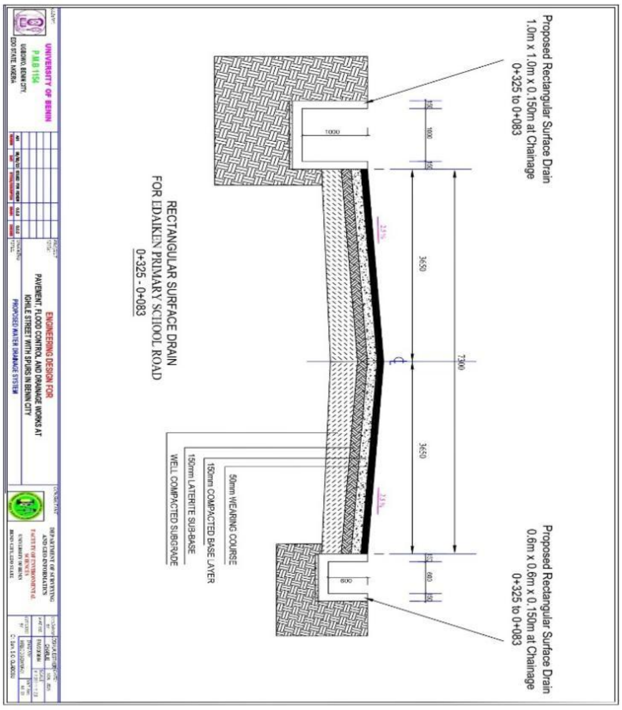

Figure 6. Drainage Design Cross-Section Three

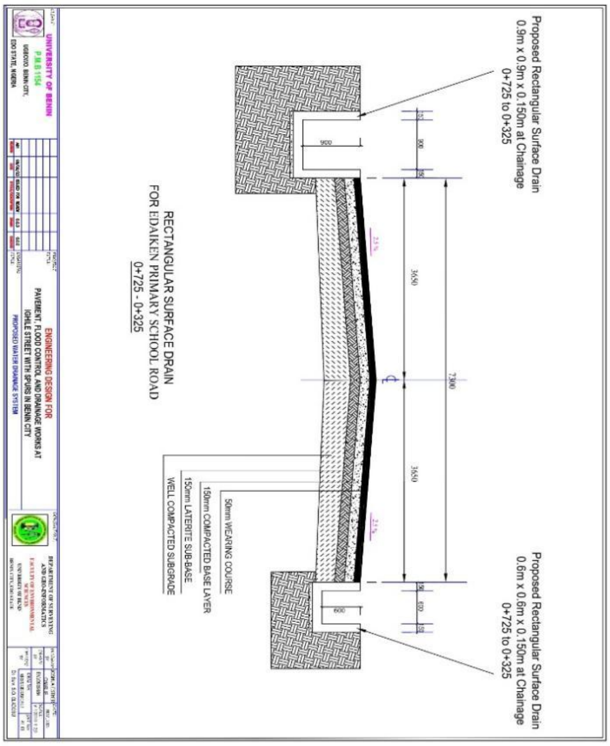

Figure 7. Drainage Design Cross-Section Four

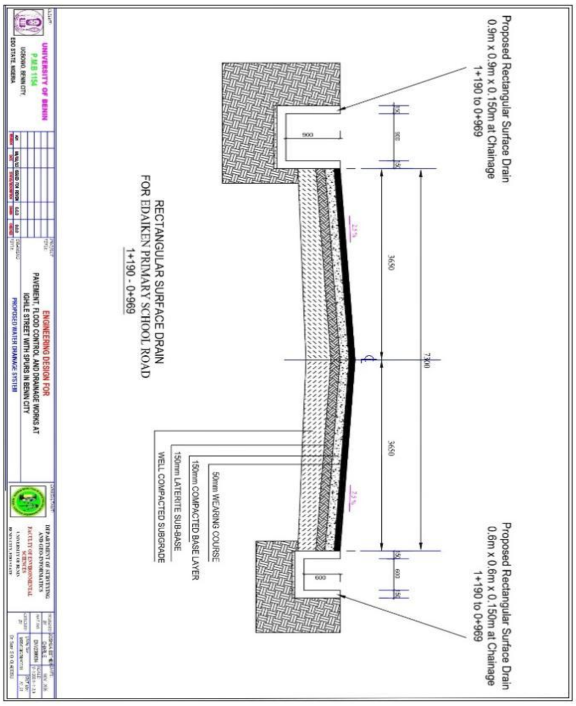

Figure 8. Drainage Design Cross-Section Five

The required sizes (0.9 × 0.9 m to 1.0 × 1.0 m) ensure that the drainage capacity exceeds peak runoff, thereby preventing overtopping. This design approach aligns with recommendations by the FMW, (2013) which emphasize capacity-based drainage design for urban roads.

The dominance of flow contribution from the left-hand side of the catchment reflects terrain-controlled runoff patterns.

Table 3. Right-Hand Side Drain Characteristics

Chainage (From)	Chainage (To)	Contributing Catchment	Cumulative Discharge, Qt (m^3/s)	Distance (m)	Calculated Drain Size (m)	Adopted Drain Size (m)
1+570	1+190	–	–	373	0.6 × 0.6	0.9 × 0.9
1+190	00+969	Minor runoff	~0.10	224	0.6 × 0.6	0.9 × 0.9
00+969	00+725	Minor runoff	~0.15	245	0.6 × 0.6	0.9 × 0.9
00+725	00+325	Negligible	~0.20	400	0.6 × 0.6	0.9 × 0.9
00+325	00+083	Negligible	~0.25	242	0.6 × 0.6	0.9 × 0.9
00+083	00+000	Negligible	~0.30	83	0.6 × 0.6	0.9 × 0.9

Similar asymmetric drainage behavior was observed by Sobowale et al. (2024), who reported that topography significantly influences flow distribution in urban drainage systems.

4. CONCLUSION

This study evaluated flood occurrence along Edaiken Primary School Road in Benin City using an integrated approach combining field observations, GIS-based analysis, and hydrological and hydraulic modeling. The results revealed that flooding in the area is primarily driven by topographic control of runoff, high rainfall intensity, and inadequate drainage capacity. The delineation of five sub-catchments identified SC3 and SC4 as the major contributors to peak discharge, while the existing drainage system was found to be insufficient to convey the cumulative flow.

The redesigned drainage network, with appropriately sized channels and improved hydraulic capacity, was developed to accommodate the estimated peak runoff derived from the hydrological analysis. The design indicates that the proposed system can enhance stormwater conveyance and reduce the likelihood of channel overtopping under the evaluated conditions. However, it is important to note that the study does not include scenario-based simulations or quantitative validation of flood reduction. Therefore, the results should be interpreted as a design-based assessment. Future work should validate DEM-based flow accumulation results using hydrological models such as HEC-HMS or SWMM to simulate runoff under different rainfall intensities and sub-catchment responses.

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