SCENARIO-BASED OPTIMIZATION AND CLIMATE RESILIENCE OF URBAN STORMWATER DRAINAGE SYSTEMS IN ASABA, NIGERIA

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ABSTRACT

Urban drainage systems in growing cities tend to experience capacity deficiencies and intensified runoff in the face of a changing climate. The resilience of urban drainage corridors in Asaba, Delta State, Nigeria, was investigated through scenario-based hydrologic and hydraulic modelling of five drainage corridors: Okpanam Road, DLA Road, Summit Road, Nnebisi Road, and Cable Point. Each corridor was assessed using EPA SWMM, GIS-based spatial analysis, the Rational Method, and Manning's equation under four intervention scenarios—increased rainfall, low-impact development (LID), smart operational improvement, and drainage upsizing—in addition to a baseline scenario. The study found that the existing drainage systems have deficient conveyance capacity, with FoS values ranging from 0.20 to 0.59 across the five corridors under baseline conditions. Under a 1.5× rainfall scenario, a 50% increase in rainfall produced an approximately 50% increase in peak runoff, reducing hydraulic adequacy. LID measures reduced peak runoff by approximately 20%, while smart operational improvements produced a modest increase in full-flow capacity. Drainage upsizing provided the largest individual increase in reported capacity, reaching approximately 62.6% at the best-performing corridor under the assessed scenario. No single intervention achieved uniformly adequate outcomes across all corridors. The combined 40% LID and 40% channel-upsizing scenario reported zero hydraulic shortfall at all five corridors. The study therefore demonstrates a scenario-based approach for assessing urban drainage resilience and comparing alternative runoff-reduction and conveyance-improvement measures in Asaba.

Keywords: Urban drainage resilience; EPA SWMM; Scenario analysis; Low-impact development; Drainage capacity; Climate resilience; Asaba

1.0 INTRODUCTION

Urbanization refers to the expansion and increasing complexity of urban areas associated with population growth, economic activity, and spatial development (World Bank, 2015). Although urban areas serve as centres of economic and social development, rapid urbanization can also create significant challenges for stormwater management, particularly where drainage infrastructure does not expand at a rate commensurate with urban growth. In Asaba, as in many Nigerian cities, increasing development has resulted in a greater proportion of impervious surfaces such as roads, rooftops, and paved areas. These surfaces reduce natural infiltration and increase the volume and rate of stormwater runoff. Consequently, inadequate drainage capacity can contribute to urban flooding, waterlogging, infrastructure damage, traffic disruption, and other socioeconomic impacts.

Rapid urban expansion without a corresponding increase in drainage infrastructure has been identified as an important contributor to flooding in southern Nigerian cities (Ibe & Ndulibe, 2023). Effective urban stormwater management therefore requires carefully designed drainage systems capable of managing runoff quantity and quality while reducing erosion and pollution (Agbo & Chukwu, 2021). Failure of stormwater management systems can result in waterlogging, property damage, traffic congestion, and deterioration of the urban environment (Okonkwo & Ibe, 2023).

Flash floods and rainfall-related damage have been reported in several Nigerian urban centres, including Asaba (Eze & Uzochukwu, 2021). The city's low-lying areas, increasing built-up surfaces, and rainfall intensity contribute to its vulnerability to flooding, particularly during the rainy season (Eze & Uzochukwu, 2021). Modelling urban rainfall-runoff processes therefore requires appropriate hydrologic and hydraulic tools. The U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM) provides a framework for simulating urban runoff and drainage-system performance (Rossman, 2015). EPA SWMM can support the diagnosis of drainage deficiencies, evaluation of stormwater management alternatives, and assessment of potential improvement measures.

Rapid land-use development, blockage of drainage channels, and inadequate planning can increase flood vulnerability (Onwudinjo & Eboh, 2020). Intense rainfall associated with changing climatic conditions can further increase pressure on urban drainage systems (Idogho & Alabi, 2021). In parts of Asaba, including Okpanam, Summit Road, and Cable Point, urban development has not always been accompanied by adequate stormwater infrastructure. This mismatch between urban expansion and drainage provision can increase susceptibility to flooding, particularly in densely developed areas (Omodanisi & Nwakamma, 2022). Traditional drainage assessment methods based on simplified or static assumptions may not adequately represent the dynamic response of urban catchments. Integrated modelling approaches such as EPA SWMM can therefore provide a more systematic basis for assessing drainage performance and evaluating alternative interventions (Agbo & Chukwu, 2021).

2.0 MATERIALS AND METHODS

2.1 Study Area and Data Collection

The study was carried out in Asaba, the capital of Delta State, Nigeria, between approximately latitude 6°11′54″N and longitude 6°43′55″E (Fig. 1.1). The terrain consists of a moderately steep area between the Asaba–Okpanam ridge and the lower floodplain of the River Niger. Annual precipitation is approximately 1,800–2,400 mm. Five drainage corridors were selected to represent different urban land-use and drainage conditions: DLA Road, Okpanam Road, Summit Road, Nnebisi Road, and Cable Point. These corridors include residential, commercial, and mixed-use areas.

2.2 Data Sources

Rainfall data were obtained from the Nigerian Meteorological Agency (NiMet), while hydrological information was obtained from the Nigeria Hydrological Services Agency (NIHSA). Additional information on drainage planning, layout, and existing conditions was obtained from relevant Delta State authorities, supported by drainage-layout surveys, GPS observations, and other surveying data. GIS and remotely sensed data were used to delineate catchments, identify surface-runoff areas, and estimate catchment parameters. Key variables included catchment area, topography, land cover, imperviousness, flow-path width, depression storage, and surface roughness. Drainage flow lines and conduits were represented using dimensional parameters such as length, flow area, width, direction, roughness, and velocity characteristics.

2.3 Hydrological and Hydraulic Modelling

EPA SWMM was used as the principal hydrologic and hydraulic modelling platform. The model represents rainfall-runoff transformation and hydraulic routing through the drainage system. The Rational Method was also applied independently to estimate peak runoff:

$$Q_{peak}=0.00278CIA \quad (1)$$

where:

- Qpeak = peak runoff discharge (m^3/s);
- C = runoff coefficient;
- i = rainfall intensity (mm/hr); and
- A = catchment area (ha).

Drainage capacity was evaluated using Manning's equation:

$$Q_{full}=n1AR2/3S1/2 \quad (2)$$

where:

- Qfull = full-flow discharge capacity;
- n = Manning's roughness coefficient;
- A = flow area;
- R = hydraulic radius; and
- S = channel slope.

EPA SWMM uses hydraulic routing based on the Saint-Venant equations and is capable of representing conditions such as surcharging, backwater effects and flow reversal.

2.4 Factor of Safety

Hydraulic adequacy was represented using the Factor of Safety:

$$FoS = Q\_{full}/Q\_{peak} \quad (3)$$

A value of:

- $FoS \geq 1.0$ indicates that available full-flow capacity is at least equal to estimated peak runoff;
- $FoS < 1.0$ indicates a hydraulic capacity deficit.

This indicator was selected because it allows drainage corridors with different runoff and channel capacities to be compared on a common basis.

2.5 Scenario Development

Four principal scenarios were considered:

Scenario 1: Rainfall Stress

Rainfall was amplified by a factor of 1.5. This represents a 50% increase above the baseline rainfall condition and was used to assess the sensitivity of the drainage systems to increased rainfall intensity.

Scenario 2: Low-Impact Development

The effective runoff coefficient was reduced by 20% to simulate source-control and low-impact development (LID) practices, such as vegetated infiltration trenches and permeable pavements.

Scenario 3: Smart Operational Improvement

The 10% increase in effective operation of drainage was employed to symbolize measures like enhanced control, debris removal and operational effectiveness.

Scenario 4: Channel Upsizing

Drainage channel capacity was increased by 20% to represent structural expansion or upsizing of the channels. A combined scenario involving 40% LID and a 40% increase in channel capacity was also assessed to examine the potential effect of combined runoff-reduction and conveyance-improvement measures.

2.6 Assessment of Scenarios

The assessment focused on comparing the baseline drainage condition with the rainfall-stress, low-impact development (LID), smart operational improvement, and channel-upsizing scenarios. The results are presented as a scenario-based hydraulic assessment rather than as statistically calibrated or independently validated model results. Table 1 presents the baseline hydraulic capacity of the drainage channels at the five selected locations in Asaba. The comparison uses estimated peak runoff and the full-flow capacity of each existing drainage channel. The Factor of Safety (FoS) was calculated as the ratio of full-flow capacity to peak runoff. An FoS value below 1.0 indicates that the channel capacity is insufficient to convey the estimated peak runoff.

Table 1: Baseline Hydraulic Adequacy of Drains at Key Asaba Locations

(FoS = Q_full / Q_peak; values < 1 indicate capacity deficit)

Location	**Land Use**	**Area (ha)**	**C_eff**	**i (mm/hr)**	**Q_peak (m^3/s)**	**Q_full (m^3/s)**	**FoS**	**Capacity Flag**
Okpanam Road	Residential	20	0.55	122.5	3.74	1.62	0.433	Undersized (FoS < 1)
DLA Road	Commercial	20	0.8	134.8	5.99	2.56	0.427	Undersized (FoS < 1)
Summit Road	Mixed Use	20	0.65	119	4.30	0.868	0.201	Undersized (FoS < 1)
Nnebisi Road	Commercial	20	0.8	142.3	6 .32	3.76	0.59	Undersized (FoS < 1)

Cable Point	Residential	20	0.55	128.6	3.93	1.52	0.39	Undersized (FoS < 1

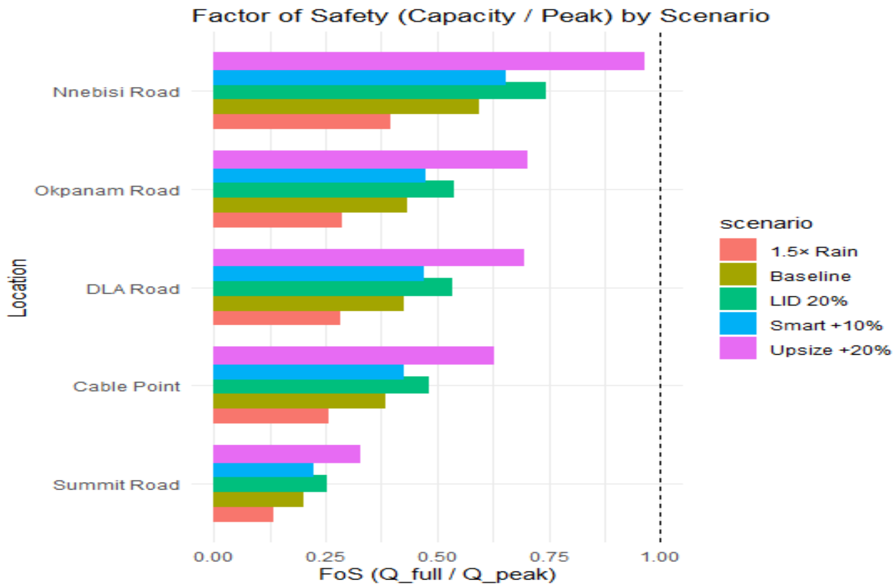

Figure 1.1: Scenario-Based Factor of Safety (FoS) Analysis for Urban Drainage Performance under Variable Rainfall and Intervention Strategies. latitude 6°11′54″N and longitude 6°43′55″E

3.0 DISCUSSION

The results presented in Figure 1.1 show the Factor of Safety (FoS = Q_{full}/Q_{peak}) for the five selected locations under baseline and intervention scenarios. The baseline results indicate that all five locations have FoS values below 1, confirming inadequate hydraulic capacity relative to estimated peak runoff. Nnebisi Road recorded the highest baseline FoS (0.59), followed by Okpanam Road and DLA Road (0.43 each), Cable Point (0.39), and Summit Road (0.20). Thus, Summit Road recorded the greatest hydraulic deficiency, while Nnebisi Road had the highest relative capacity among the assessed corridors. The peak runoff values were highest at Nnebisi Road (6.32 m^3/s), followed by DLA Road (5.99 m^3/s), Summit Road (4.30 m^3/s), Cable Point (3.93 m^3/s), and Okpanam Road (3.74 m^3/s). However, Q_{full} remained lower than Q_{peak} at all locations, confirming existing capacity deficits. Under the 1.5× rainfall scenario, increased rainfall intensity increases peak runoff and reduces the FoS across the assessed locations. The intervention scenarios improve hydraulic performance either by reducing runoff or by increasing conveyance capacity.

Table 2 presents the sensitivity of drainage performance to a 1.5× rainfall condition and the effects of alternative mitigation measures. The assessed strategies included a 50% increase in rainfall, a 20% reduction in the effective runoff coefficient through LID measures, a 10% improvement in operational control, and a 20% increase in channel capacity through upsizing.

Table 2: Effects of Rainfall Stress and Mitigation Measures on Drainage Performance

Location	Scenario	Note	Q_peak	Q_full	FoS
Cable Point	1.5× Rain	Stress test	5.9	1.52	0.26
Cable Point	LID 20%	C reduced by 20%	3.15	1.52	0.48
Cable Point	Smart +10%	Ops/control gain	3.93	1.67	0.42
Cable Point	Upsize +20%	Bigger channel	3.93	2.46	0.63
DLA Road	1.5× Rain	Stress test	8.99	2.56	0.28
DLA Road	LID 20%	C reduced by 20%	4.8	2.56	0.53
DLA Road	Smart +10%	Ops/control gain	6	2.82	0.47
DLA Road	Upsize +20%	Bigger channel	6	4.16	0.69
Nnebisi Road	1.5× Rain	Stress test	9.49	3.76	0.4
Nnebisi Road	LID 20%	C reduced by 20%	5.06	3.76	0.74
Nnebisi Road	Smart +10%	Ops/control gain	6.33	4.14	0.65
Nnebisi Road	Upsize +20%	Bigger channel	6.33	6.12	0.97
Okpanam Road	1.5× Rain	Stress test	5.62	1.62	0.29
Okpanam Road	LID 20%	C reduced by 20%	3	1.62	0.54
Okpanam Road	Smart +10%	Ops/control gain	3.75	1.78	0.48
Okpanam Road	Upsize +20%	Bigger channel	3.75	2.63	0.7
Summit Road	1.5× Rain	Stress test	6.45	0.87	0.13
Summit Road	LID 20%	C reduced by 20%	3.44	0.87	0.25
Summit Road	Smart +10%	Ops/control gain	4.3	0.96	0.22
Summit Road	Upsize +20%	Bigger channel	4.3	1.41	0.33

The results in Table 2 show that the 1.5× rainfall scenario substantially reduced hydraulic adequacy at all locations, with FoS values ranging from 0.13 to 0.40. Summit Road recorded the lowest FoS under the rainfall-stress scenario. The 20% LID scenario reduced peak runoff and improved FoS at all locations, with the greatest FoS under LID occurring at Nnebisi Road (0.74). The smart-operational scenario produced moderate improvements, although none of the locations achieved an FoS of 1.0 or greater. Channel upsizing produced the largest improvement among the individual interventions, increasing FoS to 0.97 at Nnebisi Road and 0.70 at Okpanam Road. However, Summit Road remained substantially deficient under the 20% upsizing scenario.

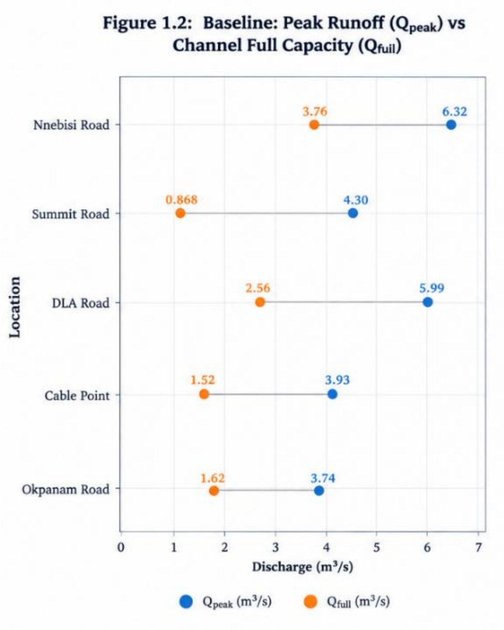

Figure 1.2: Baseline Peak Runoff (Q_{peak}) vs. Channel Full-Flow Capacity ($Q_{x(full)}$) at Key Asaba Locations

Figure 1.2 compares baseline peak runoff (Q_peak) with channel full-flow capacity (Q_full) at five key Asaba locations. Okpanam Road has a Q_peak of 3.74 m³/s compared with a Q_full of 1.62 m³/s; DLA Road has 5.99 m³/s compared with 2.56 m³/s; Summit Road has 4.30 m³/s compared with 0.87 m³/s; Nnebisi Road has 6.32 m³/s compared with 3.76 m³/s; and Cable Point has 3.93 m³/s compared with 1.52 m³/s. Thus, Q_peak exceeds Q_full at all locations, indicating inadequate baseline drainage capacity, with the largest relative deficits occurring at Summit Road and Cable Point.

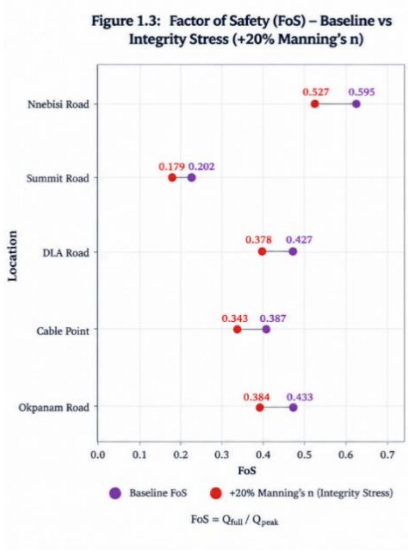

Figure 1.3: Factor of Safety (FoS) Under Baseline and +20% Roughness Stress Test

Figure 1.3 presents the Factor of Safety (FoS), calculated as Q_{full}/Q_{peak}, under the baseline condition and a +20% Manning's roughness stress test representing possible effects of debris, vegetation, sediment accumulation, and rough channel surfaces. The results show that the FoS remains below 1 at the assessed locations, confirming that channel capacity is insufficient to accommodate the estimated peak runoff, while the increased roughness condition further reduces hydraulic capacity and increases flood vulnerability. This highlights the importance of regular desilting, vegetation and debris removal, and maintenance of channel surfaces, alongside structural capacity improvements and LID retrofits to reduce runoff and strengthen the resilience of the drainage system under adverse conditions.

Table 3 presents the results of the combined mitigation strategy involving 40% LID and 40% channel upsizing.

Table 3: Combined LID and Drainage Upsizing Scenario

Location	Land use	LID (%)	Upsize (%)	FoS shortfall	Relative cost
Cable Point	Residential	40%	40%	0	1.6
DLA Road	Commercial	40%	40%	0	1.6
Nnebisi Road	Commercial	40%	40%	0	1.6
Okpanam Road	Residential	40%	40%	0	1.6
Summit Road	Mixed Use	40%	40%	0	1

As shown in Table 3, the combined LID and drainage-upsizing scenario reports zero hydraulic shortfall at all five sites. The relative cost index is reported as 1.6 for Cable Point, DLA Road, Nnebisi Road, and Okpanam Road, and 1.0 for Summit Road. However, the basis used to derive the relative cost index is not described in the methodology and should be defined before publication.

Table 4 presents the physical characteristics and full-flow capacities of the existing drainage channels.

Table 4: Existing Drain Dimensions and Full-Flow Capacity

Location	Rainfall (mm)	Runoff (mm)	Drain Width (m)	Drain Depth (m)	Land Use	Full-Flow Capacity, Q_full (m³/s)
Okpanam Road	122.5	2.1	1.2	0.8	Residential	1.62
DLA Road	134.8	2.5	1.5	0.9	Commercial	2.56
Summit Road	119	1.9	1	0.6	Mixed Use	1.06
Nnebisi Road	142.3	2.7	1.8	1	Commercial	3.76
Cable Point	128.6	2.2	1.3	0.7	Residential	1.86

Table 4 reports the physical characteristics and full-flow capacities of the existing drainage channels. Nnebisi Road has the highest reported full-flow capacity (3.76 m^3/s), followed by DLA Road (2.56 m^3/s), while Summit Road has the lowest reported capacity (0.87 m^3/s). The results indicate that smaller or hydraulically less capable channels are more susceptible to surcharge when runoff increases. The capacity values in Table 4 should be checked against the Manning's equation inputs and the roughness coefficient used in the calculations before final submission.

Table 5 summarizes the baseline comparison between peak runoff and existing drainage capacity.

Location	Q_peak (m³/s)	Q_full (m³/s)	FoS	Capacity Flag
Nnebisi Road	6.33	3.76	0.59	Undersized
DLA Road	6.00	2.56	0.43	Undersized
Okpanam Road	3.75	1.62	0.43	Undersized
Cable Point	3.95	1.52	0.39	Undersized
Summit	4.30	0.87	0.20	Undersized

The results show that all five drainage corridors have hydraulic capacity deficits relative to the design storm. The FoS values indicate that the existing channels provide approximately 20% to 59% of the estimated peak-flow requirement, with the highest relative capacity at Nnebisi Road (59%) and the lowest at Summit Road (20%). The results indicate that Summit Road and Cable Point require particular attention in drainage improvement planning. The scenario analysis also shows that increased rainfall raises peak runoff without improving channel conveyance, whereas LID reduces runoff and channel upsizing increases conveyance capacity. Combining runoff-reduction measures with structural improvements can therefore provide a more comprehensive drainage-improvement strategy. The spatial assessment further indicates that flood susceptibility is associated with relatively flat, low-lying areas near drainage discharge points and the River Niger corridor. Combining elevation, surface flatness, and distance from drainage channels can provide useful spatial information for flood-risk assessment.

Table 6 shows that Hydraulic design analysis was undertaken for the undersized drainage corridors and dimensions were developed for each. The design peak discharge was calculated using the Rational method, and using Manning's equation the full flow capacity for the design channels was determined. For Okpanam road and Cable Point, a 1.20 m by 0.90 m rectangular channel with a cross-sectional area of 1.08 m2 and a gradient of 1%, and a full flow capacity of approximately 4.20 m3/sec was found to be adequate against the design peak discharge of 3.74 m3/sec yielding a FoS of 1.12. For DLA Road, Nnebisi Road and Summit Road, a 1.50m by 1.00m rectangular channel with a cross-sectional area of 1.50 m2 and a gradient of 1%, provided a full flow capacity of approximately 6.55m3/sec compared to a design peak discharge of 5.99 m3/sec and yielded a FoS of 1.09.

Table 6: Proposed Drainage Dimensions and Hydraulic Adequacy

Location	**Land Use**	**Q_peak (m^3/s)**	**Proposed Drain Size (m)**	**Q_full (m^3/s)**	**FoS**	**Capacity Flag**
Okpanam Road	Residential	3.74	1.20 × 0.90	4.20	1.12	Adequate
Cable Point Road	Residential	3.93	1.20 × 0.90	4.20	1.07	Adequate
DLA Road	Commercial	5.99	1.50 × 1.00	6.55	1.09	Adequate
Nnebisi Road	Commercial	6.32	1.50 × 1.00	6.55	1.04	Adequate
Summit Road	Mixed Use	4.30	1.50 × 1.00	6.55	1.52	Adequate

Table 6 indicates that the proposed channel designs provide FoS values greater than 1.0 at all five locations. Using the Q_{peak} and Q_{full} values presented in the table, the calculated FoS values are 1.12 for Okpanam Road, 1.07 for Cable Point, 1.09 for DLA Road, 1.04 for Nnebisi Road, and 1.52 for Summit Road. These values indicate that the proposed channel dimensions provide sufficient full-flow capacity for the stated design peak discharges, subject to verification of the underlying Manning's roughness coefficient, channel slope, and design assumptions.

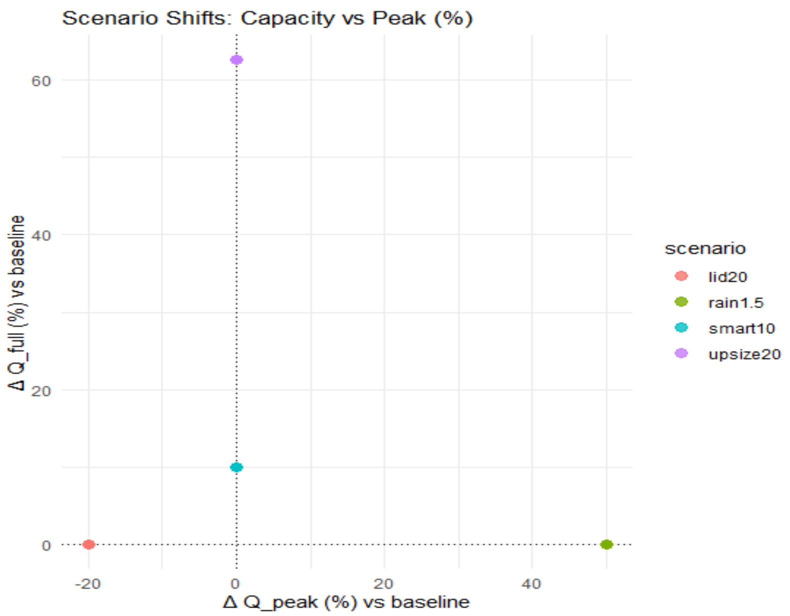

Figure 1.4: Comparative Percentage Change Analysis of Scenario Shifts in Drainage System Capacity and Peak Runoff

Figure 1.4 shows the percentage changes in peak runoff and channel capacity under the assessed scenarios. The LID20 scenario reduces peak runoff by approximately 20%, while the smart10 scenario increases capacity by approximately 10% without materially changing peak runoff. The upsize20 scenario increases channel capacity by approximately 63% based on the reported scenario values, while the 1.5× rainfall scenario increases peak runoff by approximately 50% and reduces hydraulic adequacy. These results indicate that combining runoff-mitigation measures such as LID with structural conveyance improvements can provide a more comprehensive strategy for managing urban flood risk.

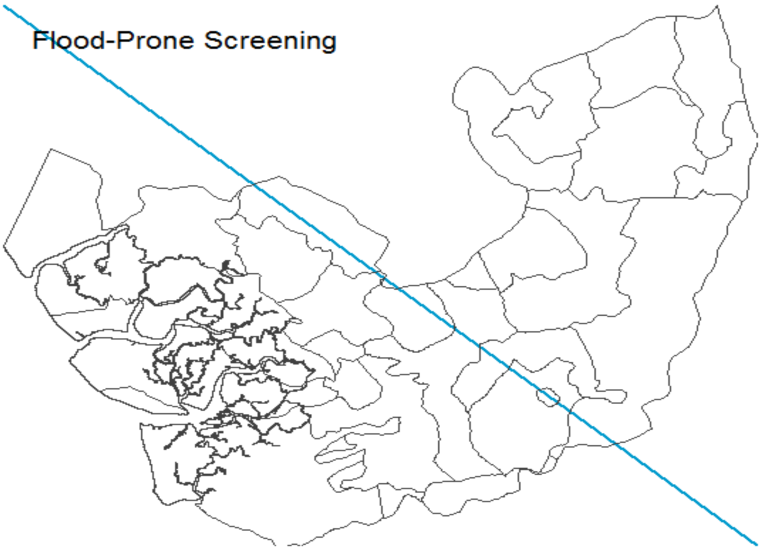

Figure 1.5: Flood-Prone Screening of Asaba and Surrounding LGAs Using DEM and Drain Proximity

Figure 1.5 presents a first-level screening of flood proneness across Asaba and surrounding areas using a combination of a digital elevation model (DEM), runoff-accumulation indicators, and drainage proximity. The figure provides a spatial basis for identifying locations that may warrant further investigation. Areas showing low elevation and close proximity to drainage pathways appear more susceptible within the screening framework. Because this is a screening analysis, the mapped patterns should be interpreted as indicators of relative susceptibility rather than as independently validated flood-hazard boundaries.

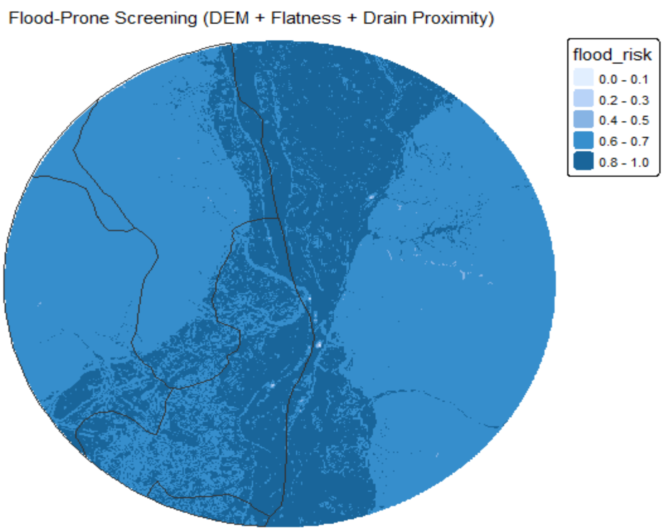

Figure 1.6: Flood Risk Screening in Asaba Metropolis Using DEM, Flatness, and Drainage Proximity

Figure 1.6 displays a composite flood-risk index for Asaba based on altitude (DEM), planform flatness, and proximity of roads and rivers to drainage channels. Higher index values represent areas classified by the study as having greater flood susceptibility, while lower values represent relatively elevated or better-drained areas. The spatial pattern indicates greater susceptibility in low-lying areas near the Niger River and drainage corridors. The results support consideration of drainage upgrades, flood-resilient land-use practices, and green infrastructure in areas identified as relatively high risk. Because the index is a screening product, further field validation and hydrologic-hydraulic analysis would be required before using it for detailed planning or zoning decisions.

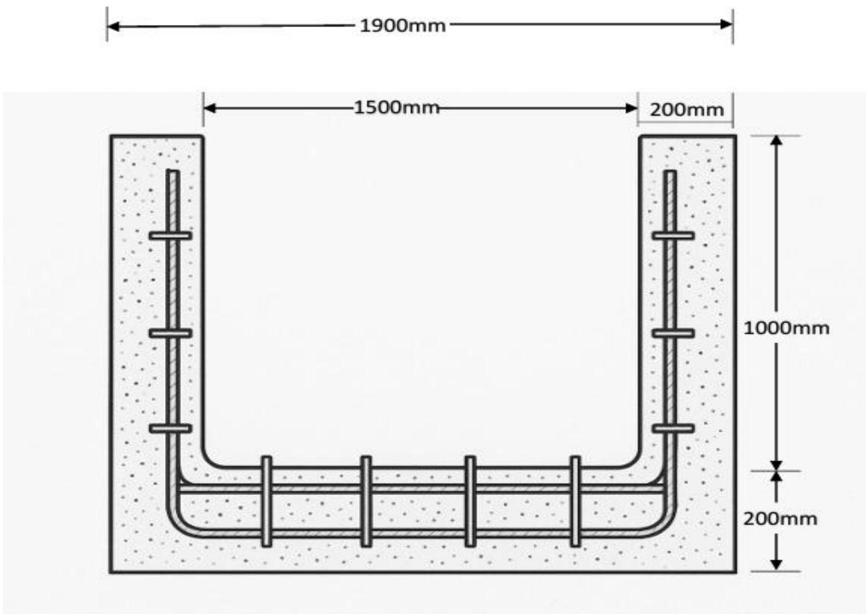

Figure 1.7: Cross-sectional view of recommended drainage design for Okpanam and Cable Point roads

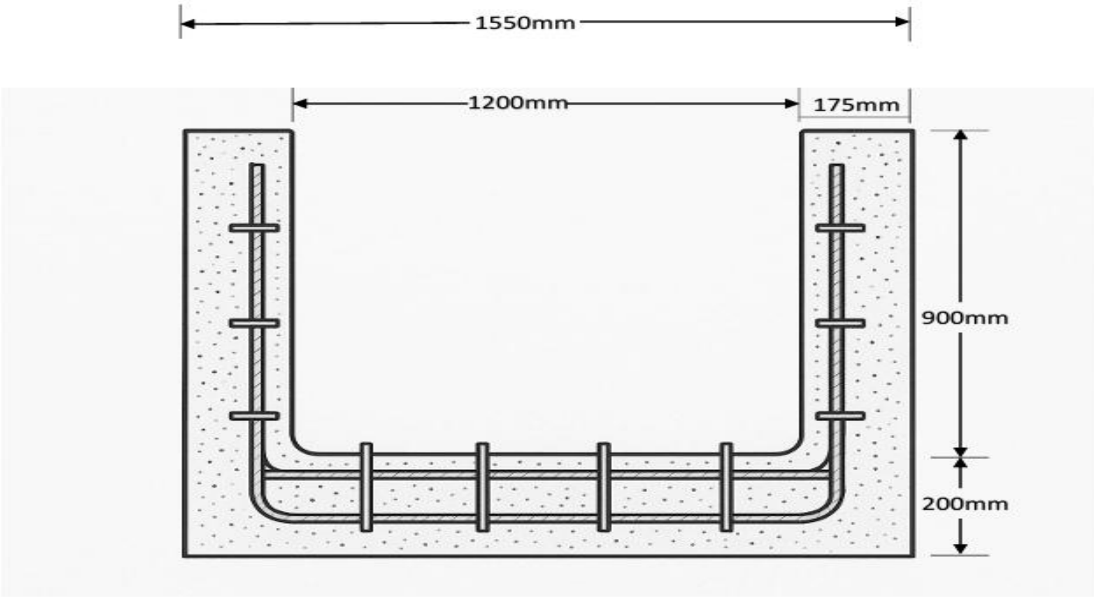

Figure 1.8: Cross-sectional view of recommended drainage design for Nnebisi, DLA and Summit roads

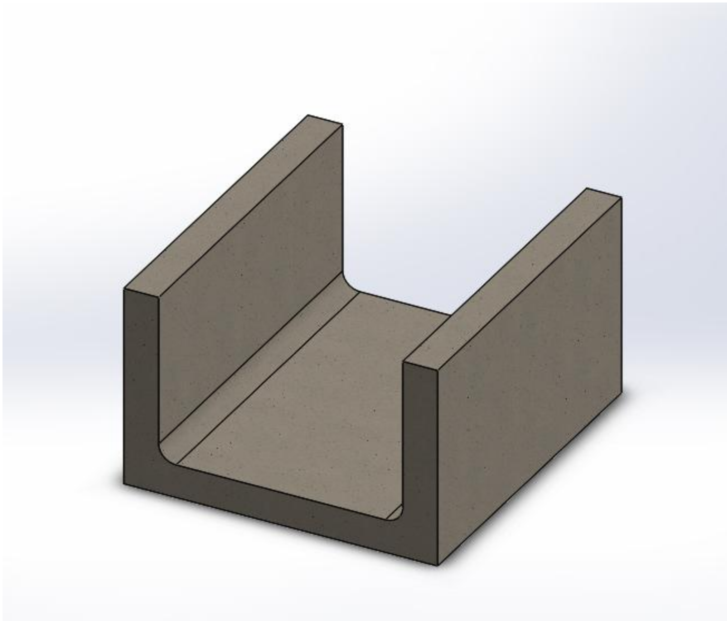

Figure 1.9: 3D design of recommended drainage system

4.0 CONCLUSION

This study evaluated the effects of climate stress and alternative mitigation measures on selected urban stormwater drainage corridors in Asaba. At baseline conditions, all five assessed corridors exhibited inadequate hydraulic capacity, with FoS values ranging from 0.20 at Summit Road to 0.59 at Nnebisi Road. Under the 1.5× rainfall scenario, peak runoff increased by approximately 50%, while FoS declined to values between 0.13 and 0.40. LID measures reduced peak runoff by approximately 20%, while the smart-operational scenario produced a smaller improvement in drainage capacity. Channel upsizing produced the largest individual increase in reported full-flow capacity, reaching approximately 62.6% at the best-performing location under the assessed scenario. However, no single intervention achieved hydraulic adequacy at all five locations. The combined 40% LID and 40% channel-upsizing scenario reported zero hydraulic shortfall at all five locations. These findings indicate that a resilience strategy combining runoff reduction, improved conveyance capacity, maintenance, and climate-sensitive drainage design can provide a broader response to increasing stormwater risk in Asaba. The EPA SWMM scenario-analysis framework also provides a basis for comparing alternative drainage-management strategies and supporting infrastructure planning decisions.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest associated with this study. The research was conducted independently, and no financial, commercial, or personal relationships influenced the study design, analysis, interpretation of results, or preparation of the manuscript.

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