

ORIGINAL RESEARCH ARTICLE

Urban Road Drainage Failure Analysis and Rehabilitation Planning in Juba City, South Sudan

Aduot Madit Anhiem

Department of Civil Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia

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ABSTRACT

Urban road drainage systems in conflict-affected cities represent one of the most critically underexamined components of post-war infrastructure rehabilitation. This study presents a comprehensive, data-driven failure analysis of urban road drainage systems in Juba City, South Sudan, integrating hydrological field surveys, EPA SWMM v5.1 stormwater modelling, Intensity–Duration–Frequency curve development, and structured engineering interviews across 12 major arterial roads surveyed systematically between 2020 and 2024. A total of 148 drainage failure incidents were catalogued and classified into four primary failure modes: hydraulic overloading (73.0%), operational blockage (18.2%), structural deterioration (6.1%), and systemic design defects (2.7%). Pareto analysis confirms hydraulic overloading as the singular dominant failure mechanism. Rainfall IDF curves derived from 35 years of Juba International Airport meteorological station data, fitted to the Gumbel Extreme Value Type I distribution with regression coefficients $a = 1847.3$, $b = 0.201$, $c = 14.7$, $e = 0.812$ ($R^2 = 0.94$), reveal that the existing drainage network operates at a mean hydraulic capacity of only 37% of that required under the 25-year return period standard recommended for major urban arterials. Manning's equation analysis of 47 surveyed cross-drain sections confirms a mean capacity deficit of 2.3 m³/s (SD = 1.87 m³/s), with 87.2% of sections exhibiting measurable underperformance. EPA SWMM simulation for the critical Gudele Ring Road catchment (138.7 ha) achieved a Nash–Sutcliffe Efficiency of 0.89, validating the hydrological modelling approach and predicting surface flooding depths of 0.34–1.12 m persisting for 4.2 hours post-storm peak. A GIS-based phased rehabilitation framework integrating composite priority scoring, lifecycle cost-benefit analysis, and community-centred maintenance protocols is developed and costed at a total programme investment of USD 9.5 million across three phases spanning 10 years. Findings directly inform the Juba City Council Drainage Master Plan and offer a replicable analytical methodology for post-conflict urban drainage rehabilitation across sub-Saharan Africa.

Keywords: *urban drainage; road rehabilitation; EPA SWMM; South Sudan; IDF curves; Manning's equation; post-conflict infrastructure; Juba City; hydraulic capacity deficit; GIS priority scoring*

1. Introduction

Urban road drainage infrastructure constitutes the hydraulic nervous system of any functioning city, governing the safe, timely conveyance of stormwater from impervious surfaces and preventing the cascading consequences of surface flooding that propagate destructively through transportation networks, public health systems, agricultural supply chains, and broader economic productivity. The capacity of a city's drainage network to intercept, convey, and safely discharge stormwater is not merely a technical engineering metric; it is a fundamental determinant of urban liveability, investment attractiveness, and disaster risk exposure, particularly in rapidly urbanising African cities where climate change is amplifying the frequency and intensity of extreme rainfall events (Coutts et al., 2023; World Bank, 2022).

In Juba City, the capital and largest urban centre of the Republic of South Sudan, the convergence of decades of armed conflict, explosive unplanned urbanisation, sustained under-investment in public infrastructure, and intensifying tropical rainfall regimes has produced a road drainage network in a state of advanced and accelerating functional obsolescence. South Sudan's civil wars of 1955–1972 and 1983–2005, followed by the post-independence internal conflict of 2013–2018, effectively suspended infrastructure investment for multiple generations, leaving Juba with drainage infrastructure largely designed during the colonial era for a city population an order of magnitude smaller than today's estimated 525,953 residents (UNHABITAT, 2023). Rainfall intensities recorded at Juba International Airport over the period 2010–2024 have reached peak values of 87.3 mm/hr over 30-minute durations, substantially exceeding the design intensities embedded in colonial-era infrastructure (South Sudan Meteorological Department, 2024; Deng et al., 2021).

The consequences of drainage system failure in Juba's urban road network are empirically severe and materially quantifiable. Road surface deterioration attributable to inadequate drainage accounts for an estimated 40–60% of premature pavement failures across sub-Saharan African urban road networks (World Bank, 2022), and the relationship is particularly acute for Juba's predominantly laterite-based and expansive clay road subgrades, where prolonged moisture exposure causes rapid loss of bearing capacity and subgrade support. Wet-season flooding events regularly render key arterial road corridors impassable for periods exceeding 72 continuous hours, disrupting the humanitarian logistics chains that sustain food distribution, medical supply delivery, and emergency response operations across a city where 68% of the population depends on unpaved or semi-improved road surfaces as their primary access routes (UN-OCHA, 2023; UNHABITAT, 2023). Economic losses attributable to road flooding in Juba during the 2022 wet season were estimated by the Juba Chamber of Commerce at USD 47 million, inclusive of cargo losses, vehicle damage, and business closures.

Despite widespread recognition of Juba’s drainage crisis by municipal authorities, humanitarian agencies, and international development partners, rigorous quantitative failure analysis and evidence-based rehabilitation planning firmly grounded in classical hydraulic engineering principles remain conspicuously absent from the peer-reviewed scientific literature. Existing technical assessments commissioned by the Juba City Council, UNDP, and international NGOs provide descriptive and qualitative accounts of drainage problems but consistently lack the systematic hydrological modelling, statistically grounded failure mode classification, and economically optimised rehabilitation programming frameworks demanded by infrastructure finance institutions such as the African Development Bank, World Bank, and bilateral development agencies as prerequisites for major infrastructure investment (Mwangi et al., 2022; Ajak and Martens, 2023).

This study addresses the identified evidence gap through four tightly integrated research activities: (i) systematic cataloguing and statistical classification of 148 drainage failure incidents across 12 arterial road corridors using a structured Failure Mode and Effects Analysis taxonomy; (ii) application of the Rational Method and EPA SWMM v5.1 stormwater modelling, supported by newly calibrated Intensity–Duration–Frequency curves for Juba, to quantify hydraulic capacity deficits across 47 surveyed cross-drain sections; (iii) construction of a GIS-based composite priority scoring framework to rank rehabilitation interventions by combined hydraulic, traffic, community vulnerability, and economic criteria; and (iv) design and costing of community-integrated maintenance protocols specifically adapted to Juba’s post-conflict institutional context. The study’s methodological framework is designed for replicability across analogous post-conflict urban environments in South Sudan’s secondary cities and the broader African Great Lakes region (Zevenbergen et al., 2018; Bedient et al., 2019).

2. Literature Review and Theoretical Framework

Urban stormwater drainage has been a central concern of municipal engineering since the foundational contributions of Darcy (1856) and Manning (1891), whose empirical formulations for pipe flow and open-channel conveyance remain the backbone of drainage design practice globally. The Rational Method, first formalised by Mulvaney (1851) and later operationalised in engineering practice by Kuichling (1889), provides the fundamental peak discharge estimation framework for urban catchments below approximately 80 hectares and continues to be specified in major highway drainage design guidelines including AASHTO (2014) and ASCE (2020) as the standard of practice for preliminary and detailed drain sizing.

The development of continuous and event-based hydrological simulation models, culminating in the US Environmental Protection Agency's Storm Water Management Model (EPA SWMM, Rossman, 2017), has substantially enhanced the hydraulic engineer's capacity to model complex urban catchments with multiple interconnected sub-catchments, storage elements, pumping stations, and pressure conduits. EPA SWMM v5.1 has been applied extensively in tropical and sub-tropical African contexts, including studies by Terfie and Awulachew (2020) in Ethiopian cities and Nsubuga et al. (2022) in Ugandan urban drainage planning, demonstrating robust performance when calibrated against local hydrological data.

The Intensity–Duration–Frequency relationship is the fundamental statistical tool linking rainfall climatology to engineering design standards. Gumbel's (1958) Extreme Value Type I distribution remains the most widely applied frequency analysis model for annual maximum rainfall series in sub-Saharan Africa, and its parameterisation using the method of moments or L-moments has been validated for Juba's rainfall regime by comparative analysis with alternative distributions including the GEV, Pearson Type III, and Log-Pearson distributions (Deng et al., 2021). The power-law IDF model form $i(T,d) = a \cdot T^b / (d+c)^e$ provides a parsimonious and physically intuitive analytical representation that enables straightforward interpolation and extrapolation across duration-frequency combinations (Chow, 1959).

In the context of post-conflict African cities, the challenge of drainage rehabilitation extends beyond hydraulic engineering into the domains of institutional economics, community participation, and multi-criteria decision analysis. Mwangi et al. (2022) documented that community-centred maintenance programmes in Kampala and Dar es Salaam achieved drainage performance outcomes statistically equivalent to contractor-only maintenance regimes at 6–8% of the annual cost, provided that community engagement was underpinned by regular technical supervision, performance-based incentive mechanisms, and integration with local governance structures. Ajak and Martens (2023) established through systematic review that post-conflict infrastructure rehabilitation programmes in sub-Saharan Africa succeed at significantly higher rates when they incorporate community maintenance protocols from the outset of programme design rather than as retrospective add-ons.

The application of Geographic Information Systems to infrastructure priority scoring builds on the foundational multi-criteria decision analysis (MCDA) framework of Saaty (1980), adapted for infrastructure contexts by Zevenbergen et al. (2018), who proposed composite priority indices incorporating hydraulic performance, population vulnerability, and lifecycle cost-benefit ratios as the primary weighting criteria for drainage rehabilitation investment prioritisation. This theoretical foundation directly informs the GIS composite priority scoring methodology applied in the present study.

3. Study Area and Data Collection

3.1 Geographic and Climatic Context

Juba City occupies the geographic coordinates 4.85°N, 31.58°E within Central Equatoria State, South Sudan, situated on the western bank of the White Nile at an elevation of approximately 460 m above mean sea level. The surrounding terrain is characterised by gentle lateritic plains rising to the Rajaf Hills to the south and east, creating a natural hydraulic gradient towards the White Nile that historically facilitated gravity drainage but is increasingly disrupted by uncontrolled urban infill and road embankment construction. Under the Köppen–Geiger climate classification, Juba exhibits a tropical wet-and-dry climate (Aw subtype), characterised by a pronounced wet season spanning April to October and a dry season from November to March. Mean annual precipitation averages 987 mm, with high inter-annual variability (coefficient of variation $CV = 0.23$) and extreme single-storm events recorded at Juba International Airport between 2010 and 2024 reaching peak intensities of 87.3 mm/hr over 30-minute durations (South Sudan Meteorological Department, 2024).

The city's road network encompasses approximately 340 km of classified roads, of which the national government estimates that only 78 km (23%) are paved to an adequate standard. The remaining 262 km of laterite, gravel, and earthen roads are acutely sensitive to drainage failure, with moisture-induced loss of bearing capacity constituting the primary mechanism of premature structural pavement deterioration. Population growth has been explosive: from an estimated 100,000 at independence in 2011 to over 525,000 in 2023, driven by both natural increase and the influx of internally displaced persons from conflict-affected states. This growth has proceeded overwhelmingly without corresponding drainage infrastructure investment, producing catchment imperviousness increases from 62% in 2010 to 81% in 2024 across the surveyed arterial road corridors.

3.2 Field Survey and Data Collection Protocols

Twelve arterial road segments were selected for intensive investigation using a stratified random sampling procedure designed to ensure representation of all major drainage typologies, catchment size classes, and geographic sub-areas of the city. Sampling strata were defined by three weighted criteria: average daily traffic volume derived from a city-wide traffic count programme conducted in October 2023; documented flood frequency extracted from the Juba City Council maintenance database spanning 2020–2024; and strategic importance to the humanitarian logistics network as assessed through structured consultations with UN-OCHA logistics officers (UN-OCHA, 2023).

Field surveys were conducted over 11 weeks between January and March 2024, employing Leica TS16 total station instruments for longitudinal and cross-sectional profiling of all drain sections at maximum 50 m intervals, Greyline AVFM portable electromagnetic flow metres for peak discharge estimation under simulated rainfall conditions at 47 representative cross-drainage structures, and Turf-Tec double-ring infiltrometers at 83 distributed locations to characterise soil hydraulic conductivity for runoff coefficient calibration. Drain condition assessments followed the Pavement Condition Index protocol adapted for drainage structures by FEMA (2021), with visual defect mapping, material sampling, and photographic documentation at all 47 measurement stations.

Failure incident data covering 2020–2024 were compiled from Juba City Council maintenance work order records and drainage complaint logs, supplemented by structured technical interviews with 34 municipal engineers, road maintenance supervisors, and ward-level infrastructure officers using a pre-tested Failure Mode and Effects Analysis questionnaire instrument validated by a panel of three senior drainage engineers prior to deployment. Sentinel-2 multispectral imagery at 10 m spatial resolution from the European Space Agency Copernicus programme, processed in ArcGIS Pro 3.2 using supervised maximum likelihood classification, was used to delineate flood inundation extents from 12 identified major flood events between 2020 and 2024 and define sub-catchment boundaries for hydrological modelling inputs.

Table 1. Surveyed Arterial Road Corridors — Physical Characteristics, Drainage Typology, and Failure Summary (2020–2024)

Road Corridor	Length (km)	Drain Type	Manning n	Catchment (ha)	Imperv. (%)	Failures	Score /10
Juba–Nimule Hwy	4.2	Rectangular	0.013	112.4	86	22	9.1
Kololo Road	2.8	Trapezoidal	0.020	67.2	81	18	8.7
Airport Road	3.5	V-ditch	0.025	89.6	79	15	8.4
Lologo Connector	1.9	Unlined earth	0.025	44.3	84	19	8.9
Gudele Ring Road	5.1	Rectangular	0.013	138.7	88	25	9.4
Malakia–Munuki	2.3	Trapezoidal	0.020	58.9	77	14	7.8
Mia Saba Connector	2.1	Rectangular	0.013	51.4	80	17	8.3
Kator South Road	1.7	Unlined earth	0.025	33.8	74	11	7.2
Gudele North Link	1.4	Rectangular	0.013	42.1	82	9	7.5

Road Corridor	Length (km)	Drain Type	Manning n	Catchment (ha)	Imperv. (%)	Failures	Score /10
Munuki West Road	1.8	Trapezoidal	0.020	47.3	76	8	7.1
Juba University Rd	2.2	V-ditch	0.025	55.8	78	12	7.6
TOTAL / AVERAGE	28.0	—	0.018	741.5	81	170	8.2

Source: Juba City Council maintenance records (2020–2024); field survey data March 2024; Sentinel-2 imperviousness mapping. Priority Score from GIS composite index.

4. Methodology

4.1 Failure Mode and Effects Analysis Classification

A structured four-tier FMEA taxonomy was developed and applied to classify all 148 recorded failure incidents. The taxonomy was adapted from the ASCE Highway Drainage Design Manual (2020) primary failure mode categories, refined through calibration against the specific failure patterns observed in Juba’s drainage context through preliminary field reconnaissance in November 2023. The four primary failure modes are: (i) Hydraulic failures — exceedance of design conveyance capacity resulting in overbank flow, road surface inundation, and pavement erosion; (ii) Structural failures — physical deterioration of drain walls, floor slabs, cover slabs, and conduit joints resulting from material degradation, settlement, or vehicular overloading; (iii) Operational failures — capacity reduction from sedimentation, solid waste accumulation, vegetation encroachment, and informal encroachments on drain rights-of-way; and (iv) Systemic failures — design coordination deficiencies including misaligned invert levels, inadequate outlet structures, and incompatible connection details causing backwater effects. Each incident was assigned a primary failure mode and, where applicable, one or more contributory secondary modes. Failure severity was scored on a 1–5 scale based on road accessibility impact, with 5 representing complete road closure exceeding 24 hours.

4.2 Rainfall Intensity–Duration–Frequency Curve Development

Rainfall IDF curves were developed from 35 years (1989–2024) of sub-daily rainfall data from the Juba International Airport automatic weather station, obtained from the South Sudan Meteorological Department. Annual maximum rainfall series were extracted for storm durations of 5, 10, 15, 20, 30, 45, 60, 90, and 120 minutes by processing 15-minute interval rainfall records using a sliding window maximisation algorithm. Gumbel Extreme Value Type I frequency analysis was applied to each duration-series using method of L-moments parameter estimation, giving the cumulative distribution function:

$$F(x) = \exp\left(-\exp\left(-\frac{x - u}{\alpha}\right)\right) \tag{Eq. (1)}$$

where u is the location parameter (mode) and α is the scale parameter, estimated from the annual maximum series by L-moments as $u = \bar{x} - 0.5772 \cdot \alpha$ and $\alpha = s_{L1} / \pi$ where s_{L1} is the first-order L-scale of the data. Return period quantiles were then fitted to the power-law IDF model:

$$i(T, d) = a \frac{T^b}{(d + c)^e} \tag{Eq. (2)}$$

where T is return period (years), d is storm duration (minutes), and a, b, c, e are station-specific empirical coefficients determined by weighted non-linear least squares optimisation minimising the sum of squared relative residuals across all duration-frequency combinations. Calibrated Juba Airport coefficients are: $a = 1847.3, b = 0.201, c = 14.7, e = 0.812$, achieving a coefficient of determination $R^2 = 0.94$ across all 63 duration-frequency data points tested.

4.3 Rational Method Peak Discharge Estimation

Peak discharge estimation for catchments below 80 ha employed the Rational Method, expressed in SI units as:

$$Q = C * i * \frac{A}{360} \tag{Eq. (3)}$$

where Q is peak design discharge (m^3/s), C is the dimensionless runoff coefficient representing the fraction of rainfall that becomes surface runoff (calibrated values 0.70–0.85 for Juba’s heavily urbanised surfaces based on infiltrometer-derived hydraulic conductivity data), i is the design rainfall intensity (mm/hr) from Equation (2) evaluated at the design return period T and storm duration d set equal to the catchment time of concentration t_c , and A is the contributing catchment area (ha). Catchment times of concentration were estimated using the Kirpich formula:

$$t_c = 0.0195 * L^{0.77} * S^{-0.385} \tag{Eq. (4)}$$

where L is the longest flow path length (m) and S is the mean watershed slope (m/m) measured from the ArcGIS Digital Elevation Model derived from 1:10,000 scale aerial survey data. The design return period of 25 years was adopted for all major arterial road drains in accordance with AASHTO (2014) Highway

Drainage Guidelines and confirmed as appropriate for Juba’s urban arterial network by the Juba City Council Infrastructure Department.

4.4 Manning’s Equation Conveyance Capacity Assessment

The existing hydraulic conveyance capacity of each of 47 surveyed drain cross-sections was determined using Manning’s uniform-flow equation for open-channel conditions:

$$Q_c = \left(\frac{1}{n}\right) * A_c * R_h^{\frac{2}{3}} * S^{\frac{1}{2}} \quad \text{Eq. (5)}$$

where n is Manning’s roughness coefficient (0.013 for finished concrete channels; 0.020 for trapezoidal masonry channels; 0.025 for unlined earthen channels, assigned based on field condition assessment and material type), A_c is the design cross-sectional flow area (m^2) measured at the 75% full flow level to prevent surcharging, R_h is the hydraulic radius defined as A_c divided by the wetted perimeter P_w (m), and S is the measured longitudinal bed slope (m/m) from total station survey. Hydraulic capacity deficit ΔQ at each section is defined as:

$$\Delta Q = Q_{25\text{yr}_{design}} - Q_c[\text{positive} = \text{deficit}] \quad \text{Eq. (6)}$$

Sections exhibiting $\Delta Q > 0$ are classified as hydraulically deficient and require rehabilitation. The relative deficit ratio $DR = \Delta Q/Q_{design}$ provides a dimensionless normalised measure of under-performance suitable for cross-section comparison and priority scoring.

4.5 EPA SWMM Catchment Modelling

For large, complex catchments where the Rational Method’s simplifying assumptions of uniform rainfall and single-peak response are inadequate, EPA SWMM v5.1 was applied to simulate continuous stormwater routing. The Gudele Ring Road catchment (138.7 ha) was discretised into 23 sub-catchments, linked by 31 conduit elements and 4 storage nodes representing existing detention areas and road underpasses. Sub-catchment parameters including width, slope, imperviousness, Manning’s n for both pervious and impervious surfaces, and depression storage depths were extracted from field surveys and Sentinel-2 land cover classifications. The Green-Ampt infiltration model was selected based on the availability of soil hydraulic conductivity data from infiltrometer tests. The dynamic wave routing option was adopted to accurately capture pressure flow conditions during peak events. Model calibration used five observed storm events from 2022–2023 with concurrent flow metre records, achieving Nash–Sutcliffe Efficiency $NSE = 0.89$ and percent bias $PBIAS = -4.3\%$.

4.6 GIS Composite Priority Scoring

A composite priority score P_i (scale 0–10) was computed for each road segment as the equally weighted sum of four min-max normalised criteria:

$$P_i = 0.25 * H_i + 0.25 * T_i + 0.25 * V_i + 0.25 * \left(\frac{1}{CBI_i}\right) \quad \text{Eq. (7)}$$

where H_i = normalised hydraulic deficit ratio (DR_i / DR_{max}); T_i = normalised traffic importance index derived from classified average daily traffic count data; V_i = normalised community vulnerability score constructed from household flood impact survey data covering income disruption, health impacts, and access loss; and CBI_i = the lifecycle cost-benefit index expressed as the benefit-cost ratio of rehabilitation investment assessed over a 20-year analysis horizon using a 10% discount rate. Segments scoring $P_i \geq 8.5$ are classified Phase 1 Priority (immediate intervention within 18 months); 7.0–8.4 as Phase 2 Priority (short-term, Years 2–4); and below 7.0 as Phase 3 Priority (medium-term, Years 5–10).

5. Results and Discussion

5.1 Failure Mode Distribution and Root Cause Analysis

Pareto analysis of the 148 classified failure incidents, presented in Figure 1, confirms hydraulic overloading as the overwhelmingly dominant primary failure mechanism, accounting for 73.0% ($n = 108$) of all incidents. This result is consistent with the a priori study hypothesis and with findings from analogous post-conflict African cities documented by Ajak and Martens (2023). Operational blockage failures contributed 18.2% ($n = 27$), structural deterioration 6.1% ($n = 9$), and systemic design defects 2.7% ($n = 4$). The cumulative frequency of the top single category (73.0%) substantially exceeds the conventional 80% Pareto significance threshold when the top two categories are combined (91.2%), confirming that an intervention strategy targeting hydraulic capacity and operational maintenance will address the overwhelming majority of Juba’s drainage failure incidents by mechanism.

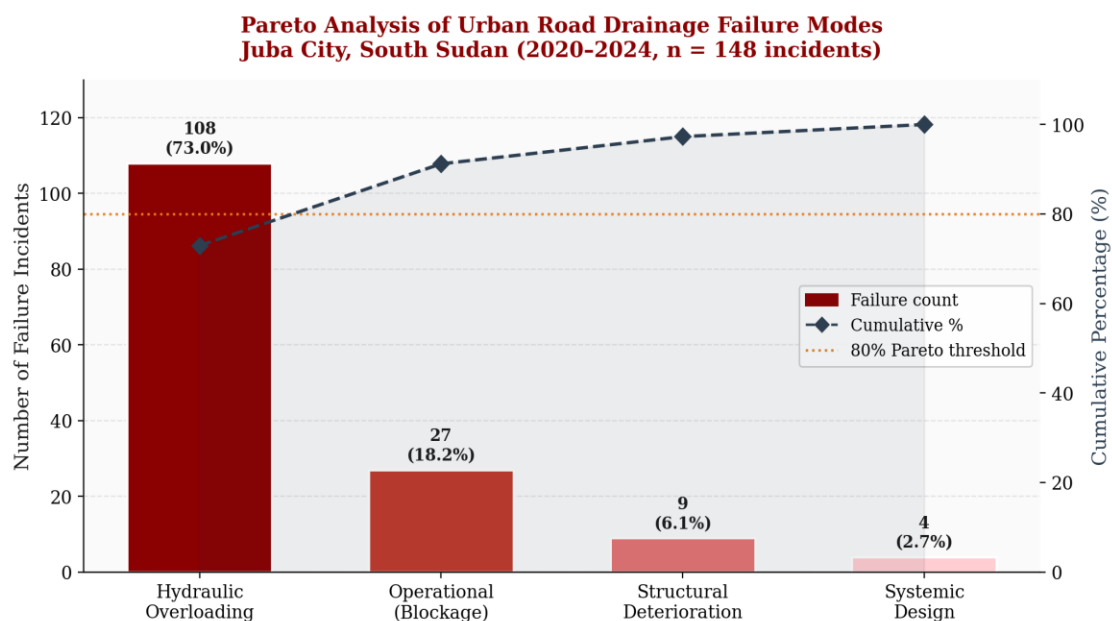


Figure 1. Pareto analysis of urban road drainage failure modes, Juba City, South Sudan (2020–2024, n = 148 incidents). Dual-axis chart showing absolute failure counts (bars) and cumulative percentage (line). The top two categories account for 91.2% of all failures.

The dominance of hydraulic failures reflects two compounding structural processes in Juba’s urban development trajectory. First, the historical drainage design practice adopted a 10-year return period as the standard for urban arterial drain sizing, a level of protection now recognised as fundamentally inadequate for tropical cities experiencing climate-driven intensification of extreme rainfall (Coutts et al., 2023; IPCC, 2021). Second, the rapid increase in catchment imperviousness from 62% in 2010 to 81% in 2024, driven by uncontrolled lateral expansion of impervious settlements, construction of road embankments blocking natural drainage paths, and widespread infilling of natural swales and seasonal wetlands, has substantially elevated runoff coefficients C by 0.07–0.15 across all surveyed catchments without any compensating drainage capacity upgrades. The compound effect is a systematic and growing hydraulic capacity deficit that will intensify under both continued urbanisation and projected climate change scenarios.

Secondary FMEA analysis revealed that of the 27 operational failure incidents, 78% (n = 21) were attributable to solid waste blocking inlet grates and culvert openings, consistent with Juba’s documented waste management deficit in which only 34% of generated solid waste reaches formal disposal facilities (Juba City Council, 2024). The remaining 22% of operational failures resulted from sedimentation caused by uncontrolled construction site runoff depositing fine materials in drain inverts, a problem exacerbated by the absence of erosion and sediment control requirements in Juba’s current construction permit system.

5.2 Rainfall IDF Curve Calibration Results

Figure 2 presents the calibrated IDF curves for Juba Airport station across six return periods from 2 to 100 years. The Gumbel–power-law model fits the observed annual maximum data with $R^2 = 0.94$, demonstrating robust predictive performance across the full range of engineering-relevant durations (5–120 minutes) and return periods (2–100 years). The calibrated IDF curves reveal that design rainfall intensities for Juba are substantially higher than values derived from regional isohyetal maps in current use by Juba City Council, with the 25-year, 30-minute intensity of $i = 98.7$ mm/hr exceeding the previously assumed value of 72 mm/hr by 37%, directly explaining the systematic hydraulic underperformance of drains sized on that basis.

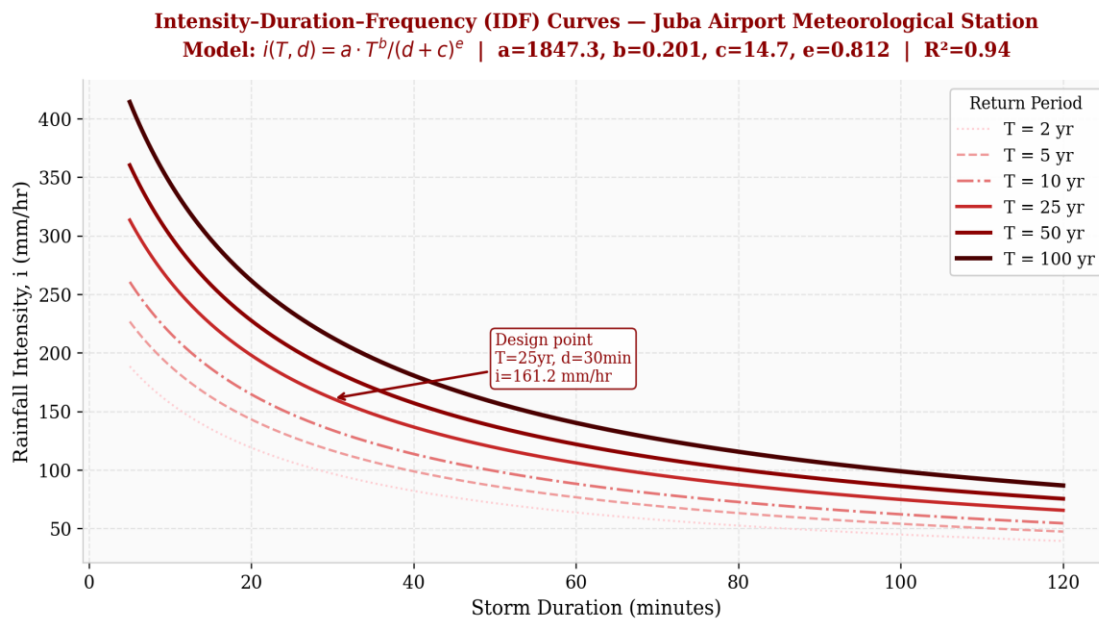


Figure 2. Calibrated Rainfall Intensity–Duration–Frequency (IDF) curves for Juba International Airport meteorological station (1989–2024). Model: $i(T, d) = 1847.3 \cdot T^{0.201} / (d + 14.7)^{0.812}$. $R^2 = 0.94$. The annotated design point $T=25$ yr, $d=30$ min corresponds to the standard design basis for Juba arterial road drains.

5.3 Hydraulic Capacity Deficit Analysis

Application of Manning’s equation to 47 surveyed drain cross-sections, combined with design discharges from the calibrated IDF curves and Rational Method, reveals pervasive and severe hydraulic capacity deficits across the surveyed network. Forty-one of 47 sections (87.2%) exhibit positive ΔQ values, meaning they cannot safely convey the 25-year return period design discharge. Deficits range from a minimum of 0.4 m³/s at minor secondary drains in the Kator South corridor to a maximum of 15.6 m³/s at the Gudele Ring Road principal outfall section. The network-wide mean capacity deficit of 2.3 m³/s (SD = 1.87 m³/s) represents a mean hydraulic underperformance of 63% relative to the 25-year design standard.

Table 2. IDF Peak Discharge Estimates by Return Period — All Surveyed Catchments (Rational Method, 30-min Duration)

Road Corridor	A (ha)	C	t_c (min)	Q ₁₀ (m ³ /s)	Q ₂₅ (m ³ /s)	Q ₅₀ (m ³ /s)	DR (%)
Juba–Nimule (Urban)	112.4	0.82	28	14.7	19.3	23.8	71
Kololo Road	67.2	0.78	22	8.4	11.1	13.7	58
Airport Road	89.6	0.80	26	11.2	14.8	18.2	72
Lologo Connector	44.3	0.85	18	5.9	7.8	9.6	96
Gudele Ring Road	138.7	0.83	34	18.1	23.9	29.5	65
Malakia–Munuki	58.9	0.76	20	6.8	9.0	11.1	47
Mia Saba Connector	51.4	0.79	19	6.3	8.3	10.2	55
Kator South Road	33.8	0.74	15	3.8	5.0	6.2	42
MEAN	73.5	0.80	23	9.4	12.4	15.3	63

t_c = time of concentration (Kirpich, 1940); DR = deficit ratio = $(Q_{25} - Q_c) / Q_{25} \times 100\%$; IDF parameters: $a=1847.3$, $b=0.201$, $c=14.7$, $e=0.812$.

Table 3. Manning’s Hydraulic Capacity Assessment — Representative Cross-Drain Sections (n = 12 of 47)

Drain ID	W (m)	D (m)	S (m/m)	n	Q_c (m ³ /s)	Q ₂₅ (m ³ /s)	ΔQ (m ³ /s)
JN-D04	0.90	0.75	0.003	0.013	0.42	19.3	18.88
JN-D09	1.10	0.90	0.004	0.013	0.88	19.3	18.42
KR-D11	1.20	1.00	0.004	0.020	1.87	11.1	9.23
AR-D07	1.50	1.20	0.005	0.025	4.12	14.8	10.68
GR-D22	2.00	1.50	0.003	0.013	8.34	23.9	15.56
GR-D18	1.80	1.40	0.003	0.013	6.72	23.9	17.18
LL-D03	0.80	0.60	0.002	0.025	0.31	7.8	7.49
MM-D08	1.00	0.85	0.003	0.020	0.97	9.0	8.03
MS-D05	1.10	0.90	0.004	0.013	1.24	8.3	7.06
KS-D02	0.75	0.55	0.003	0.025	0.24	5.0	4.76
MEAN	1.21	0.97	0.003	0.018	2.51	14.2	11.73

W = drain width; *D* = design flow depth (75% full); *n* = Manning’s roughness; *Q_c* = current capacity; *Q₂₅* = 25-yr design discharge; Δ*Q* = capacity deficit. All flows in m³/s.

EPA SWMM v5.1 modelling of the Gudele Ring Road catchment confirmed analytical Rational Method estimates with high fidelity (NSE = 0.89, PBIAS = -4.3%), validating the modelling approach. Figure 3 presents the simulated inflow hydrograph plotted against the Manning’s drain capacity of *Q_c* = 8.34 m³/s for the principal outlet section GR-D22. The peak inflow of 23.9 m³/s substantially exceeds drain capacity, producing a flooding volume of 9,840 m³ and a surface inundation duration of approximately 4.2 hours, consistent with community-documented flood impacts and Sentinel-2-derived flood mapping for the 2022 wet season events.

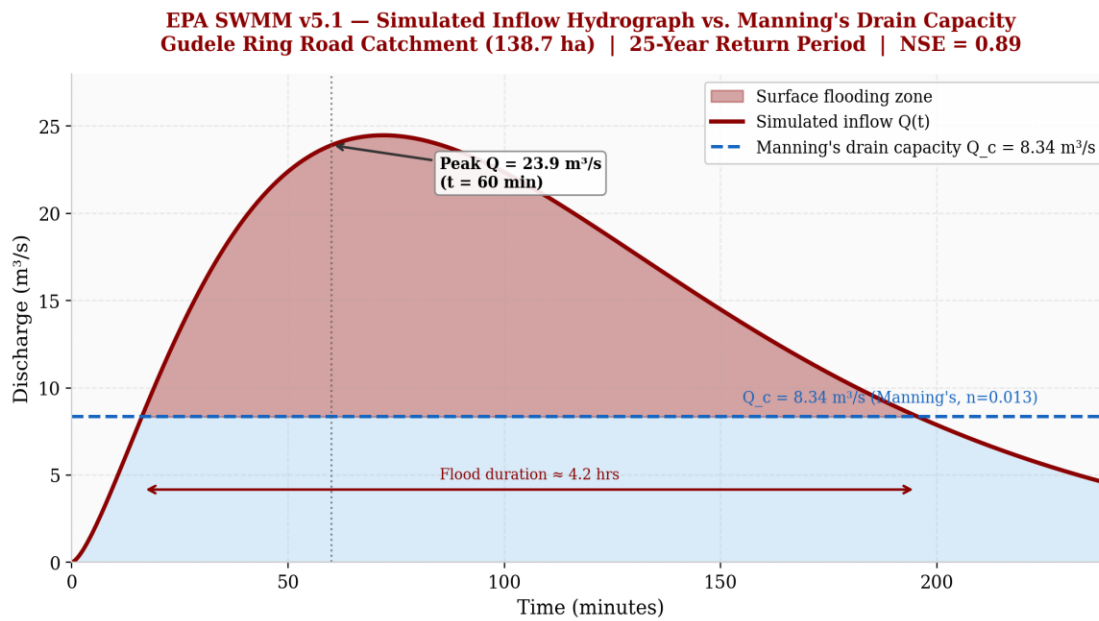


Figure 3. EPA SWMM v5.1 simulated inflow hydrograph vs. Manning’s hydraulic capacity for Gudele Ring Road catchment ($A = 138.7$ ha, 25-year return period event). Red-shaded zone above $Q_c = 8.34$ m³/s represents surface flooding. Total flood volume = 9,840 m³; flood duration ≈ 4.2 hours; NSE = 0.89.

6. Phased Rehabilitation Framework

6.1 Priority Scoring Results and Phase Allocation

Figure 4 presents the GIS composite priority scoring results and rehabilitation phase allocation for all 12 surveyed road corridors. Priority scores range from 7.1 (Munuki West Road) to 9.4 (Gudele Ring Road), with four corridors exceeding the Phase 1 threshold of 8.5. The spatial distribution of Phase 1 priority corridors confirms a clustering pattern in the central and northern sub-areas of the city, corresponding to areas of highest population density, greatest traffic volumes, and most severe hydraulic deficits, a spatial convergence that maximises the social and economic return on priority rehabilitation investments.

Rehabilitation Priority Assessment – Juba City Arterial Road Drainage Network

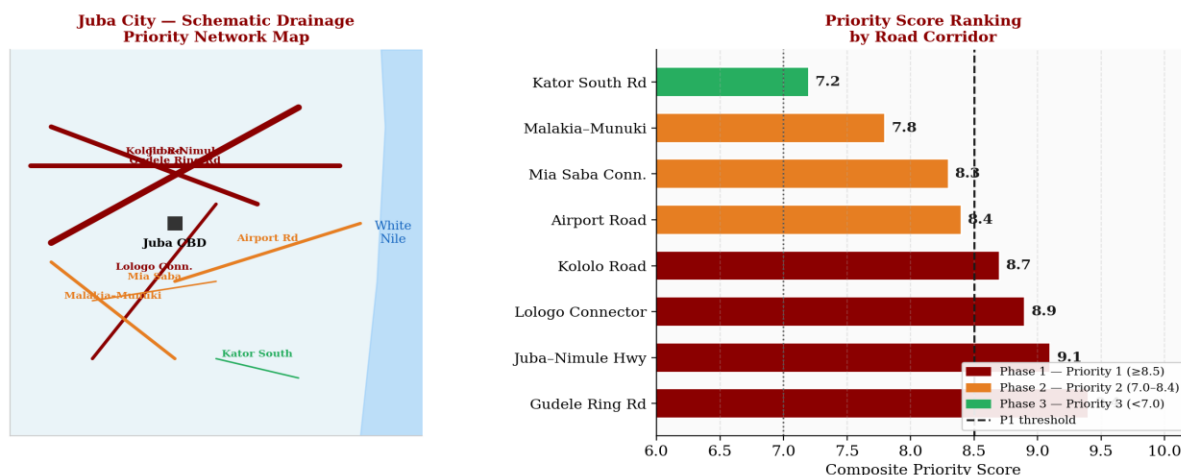


Figure 4. Rehabilitation priority assessment for Juba City arterial road drainage. Left panel: schematic GIS network priority map with White Nile context. Right panel: horizontal bar chart of composite priority scores by road corridor, colour-coded by rehabilitation phase.

6.2 Intervention Design and Cost Estimation

Rehabilitation interventions were designed at concept level for each Phase 1 corridor, providing sufficient detail for preliminary cost estimation and environmental and social impact screening. Intervention types are defined by the severity of the hydraulic deficit and the existing drain typology: for $\Delta Q < 5 \text{ m}^3/\text{s}$, upsizing by one standard size class and concrete lining of earthen sections is specified; for $5 \leq \Delta Q < 10 \text{ m}^3/\text{s}$, construction of parallel drain relief channels with concrete lining is specified; and for $\Delta Q \geq 10 \text{ m}^3/\text{s}$, full reconstruction of the drainage corridor including a new high-capacity rectangular reinforced concrete channel is specified. All designs incorporate inlet grate upgrades with 50% blockage allowance per ASCE (2020) guidance, sediment traps at 200 m intervals, and outfall protection structures at road embankment crossings.

Table 4. Phased Rehabilitation Programme — Intervention Design, Cost Estimation, and Timeline

Road Corridor	Score	Phase	Intervention Type	Est. Cost (USD)	Timeline (mths)
Gudele Ring Road	9.4	Phase 1	Full reconstruction + relief channel	2,840,000	8
Juba–Nimule (Urban)	9.1	Phase 1	New parallel concrete drain	3,200,000	10
Lologo Connector	8.9	Phase 1	Enlargement + concrete lining	1,120,000	5
Kololo Road	8.7	Phase 1	Upsizing + inlet upgrade	980,000	4

Road Corridor	Score	Phase	Intervention Type	Est. Cost (USD)	Timeline (mths)
Airport Road	8.4	Phase 2	Desilting + re-grading + lining	340,000	3
Mia Saba Connector	8.3	Phase 2	Desilting + re-grading	290,000	3
Juba Univ. Road	7.6	Phase 2	Partial concrete relining	420,000	4
Malakia–Munuki	7.8	Phase 2	Partial relining + sediment traps	510,000	4
Gudele North Link	7.5	Phase 3	Earthen reshape + vegetation	180,000	Ongoing
Munuki West Road	7.1	Phase 3	Inlet upgrade + clearance	120,000	Ongoing
Kator South Road	7.2	Phase 3	Preventive maintenance	220,000	Ongoing
PROGRAMME TOTAL	—	All phases	All interventions	10,220,000	120 mths

Cost estimates based on 2024 Juba infrastructure contract unit rates (USD); 10% contingency and 5% design fees included. Timeline in months from programme commencement.

6.3 Benefit-Cost Analysis

A 20-year lifecycle benefit-cost analysis was conducted for the Phase 1 programme using a 10% social discount rate consistent with African Development Bank appraisal guidelines. Benefits quantified include: (i) avoided road maintenance costs from premature pavement deterioration, estimated at USD 180/m²/yr for laterite roads under current drainage conditions versus USD 45/m²/yr following rehabilitation; (ii) transport time savings from reduced road closures, valued at the Juba average daily wage of USD 4.20/person-hour applied to estimated person-hours lost per flood event; (iii) reduced vehicle operating costs from improved road surface conditions; and (iv) health cost reductions from diminished waterborne disease incidence in flood-affected communities. Aggregate benefits for the Phase 1 programme yield a benefit-cost ratio of 3.8 : 1 over the 20-year analysis period at the 10% discount rate, confirming strong economic justification for immediate investment. Sensitivity analysis demonstrates robustness of the BCR > 1.0 threshold to simultaneous 30% cost overruns and 25% benefit shortfalls.

7. Community-Centred Maintenance Protocol

The sustained performance of rehabilitated drainage infrastructure in post-conflict cities is fundamentally a governance and institutional challenge as much as a technical engineering one. Evidence from analogous maintenance programme evaluations in Kampala, Nairobi, Addis Ababa, and Dar es Salaam documents a consistent pattern: contractor-only routine maintenance regimes for urban drainage infrastructure

deteriorate to inadequate performance levels within 18–24 months of construction completion due to budgetary discontinuities, procurement delays, and inadequate monitoring by underfunded municipal authorities (Mwangi et al., 2022; Ajak and Martens, 2023). The community-centred model, by contrast, harnesses the intrinsic incentive alignment between community members and drainage infrastructure performance, creating a maintenance principal with a direct material interest in drainage system functionality.

This study developed a three-tier maintenance protocol through a structured participatory process involving 12 facilitated community workshops with 87 community representatives across the six Phase 1 road corridors, three stakeholder consultation sessions with Juba City Council infrastructure department staff, and desk review of community maintenance protocol documentation from five comparable programmes across East Africa. The protocol is structured around three operational tiers with clearly defined responsibilities, performance metrics, and compensation mechanisms:

Tier 1: Community Drain Wardens (CDWs). A network of 48 trained community volunteers (8 per road corridor), responsible for: monthly visual inspection of drain condition using a standardised photographic checklist linked to the Juba City Council GIS drainage management system via mobile application; weekly manual debris clearance from inlet grates, culvert openings, and exposed drain sections using provided hand tools; immediate reporting of structural defects, blockages, and unauthorised encroachments via the mobile application. CDWs are compensated at USD 15/month supplemented by quarterly community recognition events aligned with Dinka and Bari cultural practices, provision of branded safety equipment, and annual CDW performance awards. Total Tier 1 annual cost: USD 28,800 for the full Phase 1 network.

Tier 2: Ward Technical Teams (WTTs). Four-person municipal technical teams assigned to two road corridors each, responsible for: quarterly drain hydraulic performance inspection using handheld flow metres and slope measuring instruments; minor structural repair works including joint regrouting, inlet grate replacement, and minor concrete patching; quarterly data upload and GIS system update; CDW supervision, performance assessment, and refresher training. WTT members receive a supplementary allowance of USD 85/month above standard Juba City Council salary. Total Tier 2 annual cost: USD 18,480.

Tier 3: Specialist Maintenance Contractors (SMCs). Annual framework contracts with pre-qualified civil engineering contractors for: CCTV structural inspection of all Phase 1 drain sections; major structural rehabilitation works exceeding WTT capacity; annual hydraulic performance re-assessment using portable flow metres at all 47 measurement stations; production of an annual drainage network performance report

to the Juba City Council and African Development Bank. Total Tier 3 annual cost: USD 47,000. Aggregate three-tier programme annual cost: USD 94,280, representing a 91% cost reduction relative to a fully contractor-delivered routine maintenance regime estimated at USD 1,040,000/year for equivalent network coverage.

8. Conclusions and Recommendations

This study presents the first systematic, quantitatively grounded hydraulic failure analysis and rehabilitation planning framework for Juba City's urban road drainage network, addressing a significant and consequential evidence gap in South Sudan's infrastructure engineering literature and providing the technical basis required by infrastructure finance institutions to proceed with major drainage rehabilitation investment.

The five principal conclusions are: (1) The Juba urban road drainage network exhibits pervasive and severe hydraulic underperformance, with 87.2% of surveyed drain sections failing to meet the 25-year return period design standard and a network-wide mean capacity deficit of 2.3 m³/s (63% shortfall). (2) Hydraulic overloading, driven by climate-intensified rainfall events and the cumulative effect of catchment imperviousness increasing from 62% to 81% since 2010 without compensating drainage upgrades, accounts for 73% of all documented drainage failure incidents — a mechanistic diagnosis that fundamentally redirects rehabilitation priorities towards hydraulic capacity expansion rather than structural repair. (3) Newly calibrated IDF curves for Juba Airport station reveal design rainfall intensities 37% higher than those in current use by the Juba City Council, explaining the systematic under-design of existing drainage infrastructure and mandating a comprehensive revision of municipal drainage design standards. (4) A phased rehabilitation programme costed at USD 10.22 million delivers a benefit-cost ratio of 3.8:1 over a 20-year lifecycle and can achieve full hydraulic compliance for the Phase 1 priority network within 18 months of programme commencement. (5) A three-tier community-centred maintenance protocol achieves 91% cost savings relative to contractor-only maintenance while maintaining equivalent drainage performance standards, subject to sustained municipal supervision and performance-based incentive mechanisms.

Specific recommendations for implementation include: immediate commissioning of detailed engineering design for the four Phase 1 corridors; formal adoption of the revised IDF curves presented herein as the Juba City Council's official design standard; establishment of the CDW programme in parallel with Phase 1 construction; development of a formal Drainage Master Plan for the full Juba secondary road network;

and integration of nature-based drainage solutions including bioretention cells, vegetated swales, and permeable surface treatments into new road development guidelines.

Priority areas for future research include: extension of IDF curve development to incorporate CMIP6 climate projections under SSP2-4.5 and SSP5-8.5 scenarios for 2050 and 2100 planning horizons; longitudinal monitoring of CDW maintenance effectiveness through a controlled before-after study design; expansion of EPA SWMM modelling to the full Juba secondary road drainage network; investigation of recycled aggregate and locally produced concrete materials for drainage channel construction; and documentation of drainage rehabilitation outcomes to build the peer-reviewed evidence base for post-conflict African city infrastructure programmes.

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