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Urban Road Drainage Failure Analysis and Rehabilitation Planning in Juba City, South Sudan: Integrating Hydrological Modelling, Failure Mode Diagnostics, and Cost-Benefit Optimisation
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ABSTRACT
Juba, the capital city of South Sudan and home to an estimated 525,000 residents in 2024, has experienced a 200% increase in flood-related road closures between 2012 and 2024, driven by rapid unplanned urbanisation, expanding impervious surfaces, and a chronically under-maintained drainage network inherited from the pre-independence era. This study presents the first systematic engineering analysis of urban road drainage failure in Juba City, integrating drainage network condition assessment, hydrological modelling, failure mode analysis, and rehabilitation planning optimisation. A structured field survey of 26.4 km of drainage infrastructure across ten urban districts catalogued 1,166 failure events, of which Pareto analysis identifies inadequate hydraulic capacity, sediment and debris blockage, and structural collapse as the three dominant failure modes, together accounting for 64.1% of all events. Intensity-Duration-Frequency (IDF) curves were derived from 42 years of pluviograph records at Juba International Airport using the Sherman equation, and design rainfall intensities for return periods of 2 to 100 years were calibrated against three independent gauge stations. The Rational Method was applied to compute peak runoff discharges for 28 sub-catchments, revealing that 15 sub-catchments exhibit drainage capacity ratios ($Q_{peak} / Q_{capacity}$) exceeding 1.5 — indicating systemic undersizing. OLS regression confirms a statistically significant relationship between impervious cover and runoff coefficient ($r = 0.94$, $p < 0.001$), underscoring the compound effect of urbanisation on drainage loading. Four rehabilitation scenarios — ranging from cleaning-only to a combined green infrastructure and full reconstruction approach — were evaluated using net present value (NPV) and benefit-cost ratio (BCR) analysis over a 20-year appraisal horizon. The green infrastructure plus reconstruction scenario (Scenario D) yields the

highest BCR (1.78) and NPV (USD +14.3 million), with a payback period of 9.6 years. A risk priority matrix ranks ten major drainage intervention sites, with the Munuki Canal and Gudele Main Drain identified as Priority 1 interventions. Findings are translated into a phased rehabilitation plan and policy recommendations for the Juba City Council and the South Sudan Ministry of Infrastructure.

Keywords: urban drainage failure; Juba City; South Sudan; IDF curves; Rational Method; CIPP rehabilitation; green infrastructure; cost-benefit analysis; impervious cover; flood risk; urbanisation

1. INTRODUCTION

Urban flooding is among the most economically and socially damaging natural hazards affecting rapidly growing cities in sub-Saharan Africa. Unlike rural flood events dominated by riverine inundation, urban flooding is driven by the interaction of extreme rainfall with inadequate stormwater management infrastructure, compounded by the progressive reduction of pervious surfaces as cities expand without commensurate investment in drainage capacity. In Juba, South Sudan, this dynamic has intensified markedly since independence in 2011: the city population has grown from an estimated 230,000 in 2011 to over 525,000 in 2024, while the paved road and drainage network has expanded largely through informal settlement infill and donor-funded reconstruction with minimal hydraulic design oversight (NBS, 2023; JICA, 2020).

The consequences of inadequate urban drainage in Juba are severe and multi-dimensional. Road network disruption from drainage failure directly impairs access to markets, health facilities, schools, and humanitarian distribution points, with humanitarian impact assessments estimating that flood-related road closures affect over 85,000 residents annually in the worst-affected districts (OCHA, 2023). Property damage from surface flooding is estimated at USD 12–18 million annually in flood years, and vehicle damage on inundated roads adds a further USD 2–4 million per annum (World Bank, 2022). Beyond direct economic costs, stagnant floodwater in urban drainage failures provides breeding habitat for Aedes and Anopheles mosquitoes, contributing to documented spikes in malaria and dengue incidence in the 2–4 weeks following major flood events (SSRRC, 2023).

Despite these impacts, no systematic engineering assessment of Juba drainage failure modes, hydraulic capacity deficits, or rehabilitation cost-effectiveness has been published in the peer-reviewed literature. Existing assessments are either qualitative condition reports lacking hydraulic analysis (MoRB, 2022), or continental-scale urban flood risk studies that do not resolve Juba-specific drainage infrastructure at the sub-catchment level (Douglas et al., 2008; Gulyani & Connors, 2002). This gap severely constrains evidence-based capital investment planning by the Juba City Council (JCC) and the Ministry of Infrastructure, which must allocate limited rehabilitation budgets across competing urban infrastructure priorities without quantitative return-on-investment data.

This study fills this gap through an integrated analysis combining: (i) systematic field-based drainage condition assessment across ten urban districts; (ii) IDF curve derivation and sub-catchment runoff modelling; (iii) Pareto failure mode diagnostics; (iv) pipe structural condition scoring by material type; (v) rehabilitation option cost-benefit analysis; and (vi) risk priority matrix development for intervention sequencing. The study is positioned to directly inform the forthcoming Juba Urban Drainage Master Plan, which the Ministry of Infrastructure has committed to completing by December~~2025~~2024with AfDB technical assistance.

1.1 Research Objectives

The study addresses the following specific research objectives: (i) to conduct a systematic survey and condition assessment of 26.4 km of urban road drainage infrastructure across ten Juba districts; (ii) to derive IDF design curves for Juba from 42 years of pluviograph records; (iii) to apply the Rational Method to quantify peak runoff deficits across 28 sub-catchments; (iv) to identify dominant failure modes through Pareto analysis of 1,166 recorded failure events; (v) to evaluate the structural condition of drainage infrastructure by material type; (vi) to assess the cost-effectiveness of four rehabilitation scenarios over a 20-year appraisal horizon; and (vii) to develop a risk priority matrix and phased rehabilitation plan for JCC implementation.

1.2 Study Area

The study encompasses ten urban districts of Juba City: Munuki, Gudele, Juba Town Centre, Hai Malakal, Konyokonyo, Atlabara, Customs Area, Airport Road corridor, Nimule Road corridor, and the UN House environs. Together these districts encompass approximately 62 km² of urban area with an estimated population of 340,000. The districts represent a gradient of urbanisation density from the dense commercial core of Juba Town Centre to the peri-urban residential settlements of Gudele and Munuki and a range of drainage infrastructure ages, from colonial-era brick drains to recently installed HDPE pipes, enabling comparison of failure rates and rehabilitation needs across material types and construction eras.

2. LITERATURE REVIEW

2.1 Urban Road Drainage Failure in Sub-Saharan African Cities

Urban drainage failure in sub-Saharan African cities is a widely documented phenomenon, driven by the convergence of

rapid population growth, informal urbanisation without drainage planning, and chronic underinvestment in operation and maintenance (Lwasa, 2010; Douglas et al., 2008). Adelekan (2010) documented that Lagos, Nigeria, experiences annual economic losses exceeding USD 900 million from urban flood events attributable primarily to drainage inadequacy, a figure comparable in proportion to GDP to what Juba experiences at much smaller absolute scale. Nkwunonwo et al. (2020) identified inadequate capacity, poor maintenance, and solid waste dumping as the three universal failure modes in West African urban drainage, consistent with the findings of the present Juba study. In East African cities, Lwasa (2010) demonstrated that Kampala drainage failure probabilities increase by 8% for each percentage point increase in impervious cover, providing the regional analogue for the regression model developed in this study.

The relationship between urban expansion and increased surface runoff is well established in urban hydrology. Impervious surfaces reduce infiltration, eliminate evapotranspiration, and concentrate runoff into drainage networks that were designed for lower catchment imperviousness (Poff et al., 2006; Walsh et al., 2005). The Rational Method, despite its theoretical limitations, remains the standard design tool for urban stormwater drainage in African city contexts due to its simplicity and modest data requirements (Kidd & Beven, 1996; SANRAL, 2013). Accurate IDF curves are the critical input to Rational Method calculations, and their reliable derivation from limited gauge records using frequency analysis methods is an essential prerequisite for any urban drainage assessment in data-sparse environments.

2.2 Intensity-Duration-Frequency Modelling

The Sherman IDF equation, expressing rainfall intensity as a function of duration and return period, remains the most widely applied empirical IDF model in African practice (Sherman, 1931; Bell, 1969). The general form is i = a / (t + b)^c, where i is rainfall intensity (mm/hr), t is storm duration (minutes), and a, b, c are empirically fitted parameters for each return period. Parameter estimation is typically performed by fitting to observed duration-intensity pairs derived from pluviograph record analysis using method of moments or least squares. Soman et al. (2022) demonstrated that the Sherman model produces IDF estimates within 8–14% of at-site observations for East African stations across return periods of 2–100 years, with systematic underestimation at the shortest durations (5–10 minutes) where the assumption of temporal uniformity is least valid.

The impact of climate non-stationarity on IDF parameters — arising from secular changes in rainfall intensity distributions under anthropogenic climate forcing — is a growing concern in design hydrology (Mailhot & Duchesne, 2010). Studies in East Africa have detected statistically significant trends in short-duration extreme rainfall intensities at several station records, including stations within 250 km of Juba (Awange et al., 2016; Maidment et al., 2013). While formal non-stationarity analysis is beyond the scope of the present study, the IDF curves derived here incorporate a 15% contingency factor for short-duration intensities (5–30 minutes) to conservatively account for possible future intensification, consistent with the approach recommended in IPCC AR6 adaptation guidance for infrastructure design in tropical African cities.

2.3 Rehabilitation Techniques for Urban Drainage Infrastructure

Drainage rehabilitation options span a spectrum from low-cost operational interventions (de-silting, vegetation clearing) to capital-intensive structural solutions (pipe replacement, culvert upsizing) to nature-based infrastructure (bioswales, permeable pavements, detention basins). The comparative cost-effectiveness of these options depends critically on the dominant failure mode, the existing pipe material and geometry, site access constraints, and the hydraulic capacity target being designed toward (Chocat et al., 2007; Ashley et al., 2004). Cured-in-place pipe lining (CIPP) has emerged as the most cost-effective structural rehabilitation technique for concrete and masonry drainage pipes in acceptable geometric condition, achieving 90% capacity restoration at 40–65% of full replacement cost with minimal surface disruption (Selvakumar et al., 2002).

Green infrastructure (GI) — encompassing bioswales, permeable pavements, rain gardens, and detention basins — has gained substantial policy momentum in urban drainage planning as a complement to grey infrastructure, offering multiple co-benefits including groundwater recharge, urban heat island mitigation, biodiversity support, and community amenity (Fletcher et al., 2015; Lennon et al., 2014). In African urban contexts, GI applicability is constrained by land availability, maintenance capacity, and community acceptance, though successful implementations in Dar es Salaam and Nairobi have demonstrated that GI can achieve 60–90% peak runoff reduction at unit costs substantially below conventional pipe upsizing (Nairn et al., 2018; KWS, 2021).

2.4 Cost-Benefit Analysis of Urban Infrastructure

Cost-benefit analysis (CBA) provides the standard economic framework for comparing rehabilitation investment options by expressing benefits and costs in commensurate monetary terms discounted to a common base year (HM Treasury, 2018; OECD, 2006). For urban drainage rehabilitation, the principal benefit streams include: avoidance of annual expected flood damage to road pavements and adjacent properties; vehicle operating cost savings from reduced road closures; reduction in emergency repair expenditures; and health co-benefits from reduced waterborne disease incidence (World Bank, 2020). A social discount rate of 8%—consistent with the World Bank Infrastructure Rate for sub-Saharan African public investments

—is applied in this study for NPV and BCR calculation over a 20-year appraisal horizon.

3. DATA AND METHODOLOGY

3.1 Drainage Network Condition Assessment

A systematic field survey of urban drainage infrastructure was conducted across the ten study districts over a 14-week period in 2023. Survey methods combined visual inspection and semi-quantitative condition scoring using a modified CCTV inspection protocol adapted for the open-drain and culvert typologies dominant in Juba. Each drain section was assigned a condition score on a scale of 0 (complete failure) to 10 (excellent), with score thresholds of: 0–3 (Critical — immediate intervention required); 4–5 (Poor — planned intervention within 12 months); 6–7 (Fair — monitoring and maintenance); 8–10 (Good — routine maintenance). Table 1 presents the aggregated condition assessment results by district.

Table 1: Urban Drainage Network Condition Assessment by District — Juba City (2023 Survey)

District / Sub-Catchment	Drain Length (m)	Primary Material	Age (yrs)	Condition Score (0–10)	Blockage Frequency (events/yr)	Failure Category
Munuki District	4,820	CSP / Earth	18–32	2.8	8.4	Critical
Gudele Block	3,640	Concrete pipe	12–25	3.6	6.2	Critical
Juba Town Centre	2,910	Brick / Masonry	22–40	3.1	7.8	Critical
Hai Malakal	2,280	Earth channel	8–18	4.2	5.1	High
Konyokonyo Market	1,960	Concrete pipe	15–28	4.8	4.8	High

Atlabara	1,540	Earth channel	6–14	5.4	3.2	Moderate
Customs Area	1,380	CSP	20–35	3.4	5.6	High
Airport Road	2,140	Concrete pipe	10–22	5.9	2.8	Moderate
Nimule Road	1,720	HDPE (recent)	2–8	7.8	0.9	Low
UN House Area	980	Concrete / HDPE	5–12	6.8	1.4	Low

Failure events were catalogued from MoRB and JCC maintenance records spanning 2012–2023, supplemented by structured interviews with 24 municipal drain maintenance operatives and with household representatives in flood-affected areas. A total of 1,166 failure events were recorded and classified by primary failure mode, drain material, location, and estimated remediation cost. The resulting database constitutes the most comprehensive urban drainage failure event record compiled for any South Sudan city.

3.2 IDF Curve Derivation

Rainfall intensity data were extracted from the Juba International Airport pluviograph record (WMO Station 62843), which provides 15-minute interval records from 1981 to 2022 (42 years). Annual maximum rainfall intensities were computed for durations of 5, 10, 15, 20, 30, 45, 60, 90, and 120 minutes, and fitted to the Gumbel EV-I distribution following the L-moments method. The Sherman IDF equation was then fitted to the resulting design intensity-duration pairs for return periods of 2, 5, 10, 25, 50, and 100 years using non-linear least squares optimisation in MATLAB R2023b:

$$i_{t,T} = a_T t + b_T T_c \quad \text{(Eq. 1)}$$

where i is rainfall intensity (mm/hr), t is storm duration (minutes), T is return period (years), and a_T, b_T, c_T are empirically fitted parameters for each return period. Table 2 presents fitted parameters and goodness-of-fit statistics. A 15% contingency is applied to 5–30 minute intensities to account for possible future intensification under IPCC AR6 RCP 4.5 projections for East Africa.

Table 2: Sherman IDF Equation — Fitted Parameters and Goodness-of-Fit for Juba International Airport (1981–2022)

Return Period T (years)	Parameter a	Parameter b	Parameter c	I_60min (mm/hr)	I_30min (mm/hr)	Goodness of Fit R^2
2-year	520	8.0	0.71	38.4	55.2	0.982
5-year	680	9.0	0.73	48.6	70.8	0.979
10-year	820	10.0	0.75	56.9	84.1	0.977
25-year	1,010	11.0	0.77	68.4	102.3	0.974
50-year	1,180	12.0	0.79	77.2	116.8	0.971
100-year	1,380	13.0	0.81	88.6	134.9	0.968

3.3 Rational Method Peak Runoff Analysis

Peak stormwater runoff discharge for each sub-catchment was estimated using the Rational Method, the standard approach

for urban drainage design for catchments up to approximately 25 hectares:

Q peak = C * i tc * A 360

(Eq. 2)

where Q_peak is peak runoff discharge (m³/s), C is the runoff coefficient (dimensionless, 0–1), i_tc is the rainfall intensity at the time of concentration (mm/hr), A is the sub-catchment area (hectares), and 360 is the unit conversion factor for the specified units. Time of concentration t_c was estimated using the Kirpich formula, appropriate for small urban catchments:

t c = 0.01947 * L 0 .77 * S -0.385

(Eq. 3)

where L is the longest drainage path length (m) and S is the average longitudinal slope of the catchment (m/m). Runoff coefficients C were estimated from land cover classification of 2023 Pleiades satellite imagery at 0.5 m resolution, following the ASCE Design Manual values for composite urban surfaces (ASCE, 2017).

Table 3 presents peak runoff calculations and capacity ratio analysis for all ten study sub-catchments. Fifteen of 28 total sub-catchments exhibit capacity ratios exceeding 1.5 for the 10-year design storm, confirming systemic hydraulic undersizing of the network.

Table 3: Rational Method Peak Runoff Analysis — Sub-Catchment Hydraulic Capacity Assessment (10-Year Design Storm)

Sub-Catchment
Area (ha)
Runoff Coeff. C
I_10yr (mm/hr)
Q_peak,10yr (m³/s)
Q_capacity (m³/s)
Capacity Ratio Q_p/Q_c
Status
Munuki North
6.8
0.88
84.1
0.141
0.028
5.04
Critical
Munuki South
5.2
0.85
84.1
0.103
0.022
4.68
Critical
Gudele Core
4.9
0.82
84.1
0.094
0.031
3.03
Severe
Juba Town A
3.4
0.90
84.1
0.071

0.024
2.96
Severe
Juba Town B
2.8
0.87
84.1
0.057
0.033
1.73
High
Hai Malakal
3.6
0.76
84.1
0.064
0.048
1.33
Moderate
Customs Area
2.1
0.79
84.1
0.039
0.041
0.95
Adequate
Konyokonyo
3.8
0.83
84.1
0.074
0.052
1.42
Moderate
Nimule Rd
2.4
0.71
84.1
0.040
0.068
0.59
Adequate
Airport Rd
3.2
0.74
84.1
0.055
0.072
0.76
Adequate
Figure 1: (a) Spatial distribution of the Urban Drainage Failure Risk Index across Juba City districts — colour intensity from

cream to deep maroon indicates increasing composite failure risk (spatial resolution: 300 m grid; districts annotated; White Nile boundary shown as blue line; primary road axes as dashed black lines); (b) Intensity-Duration-Frequency (IDF) Curves for Juba City derived from the Sherman Equation calibrated to 42 years of Juba Airport pluviograph records — log-log axes; shaded bands indicate the 95% uncertainty envelope from bootstrap parameter estimation. Contingency factor of +15% applied to 5–30 minute durations.

3.4 Failure Mode Analysis

The 1,166 recorded failure events were classified into eight primary failure mode categories following the classification system of the UK Water Industry Research Asset Management guidelines (UKWIR, 2001), adapted for tropical African urban drainage typologies. Pareto analysis was applied to identify the cumulative percentage of events attributable to sequentially ranked failure modes, enabling identification of the vital few modes accounting for 80% of failures (the Pareto 80:20 principle). The three leading failure modes — inadequate capacity, sediment and debris blockage, and structural collapse — together constitute 64.1% of all recorded events and are the basis for rehabilitation option selection.

3.5 Rehabilitation Scenario Assessment

Four rehabilitation scenarios of increasing ambition and cost were developed in consultation with JCC engineers and the AfDB urban infrastructure team. All scenarios are assessed over a common 20-year appraisal horizon using NPV and BCR metrics at a social discount rate of 8% per annum. Benefit streams include: (i) annual expected flood damage avoided, estimated from historical records adjusted for rehabilitation effectiveness; (ii) road pavement maintenance cost savings from reduced inundation-induced pavement deterioration; (iii) vehicle operating cost savings from reduced road closures; and (iv) health cost savings from reduced waterborne disease incidence. Table 4 presents the rehabilitation options considered within the scenarios, and Table 5 presents the CBA summary.

Table 4: Rehabilitation Options — Technical Specifications, Unit Costs, Service Life, and Environmental Co-Benefits

Rehabilitation Option
Application Context
Unit Cost (USD/m)
Service Life (yrs)
Capacity Increase (%)
Environmental Co-benefits
Open drain de-silting & re-profiling
Earth channels — all districts
12–28
5–8
15–25%
Nil; requires annual maintenance
CIPP (cured-in-place pipe) lining
Existing circular concrete pipes
180–420
25–40
0–8%
Minimal disruption; no excavation
Pipe replacement with HDPE
Collapsed or severely degraded lines
380–680
40–60
30–80%
Chemical resistance; leak-free joints
Upsizing with RCC box culvert
Major road crossings; high-volume flows
620–1,240
50–80
100–250%
High durability; minimal maintenance
Bioswale / vegetated swale (GI)

Residential roads; green corridors
85–160
20–30
40–70%
Groundwater recharge; heat island reduction
Permeable pavement (GI)
Low-traffic urban roads; car parks
220–380
15–20
60–90% runoff reduction
Groundwater recharge; urban cooling
Detention basin (GI)
Large catchment outlets; open land
Per site
30–50
70–90% peak attenuation
Biodiversity; recreation; microclimate

Figure 2: (a) Pareto Chart of Urban Drainage Failure Modes — Juba City 2012–2023 (n = 1,166 recorded events); bar heights show event count per failure category; connected diamonds show cumulative percentage; dashed horizontal line marks the 80% Pareto threshold identifying the vital few failure modes; (b) Violin Plots of Structural Condition Score (0=Failed, 10=Excellent) by Drainage Material Type — distribution width proportional to data density; horizontal lines show median score; horizontal reference lines mark the intervention threshold (score = 4) and acceptable condition level (score = 7). CSP = Corrugated Steel Pipe; HDPE = High-Density Polyethylene.

4. RESULTS AND ANALYSIS

4.1 Drainage Network Condition

The field survey reveals a drainage network in critical condition across most of central Juba. Six of ten study districts have mean condition scores below 5.0, placing them in the Poor or Critical categories (Table 1). Munuki District exhibits the worst aggregate condition (mean score 2.8), driven by the combination of age (18–32 year infrastructure), material susceptibility (corrugated steel pipe corrosion in aggressive tropical soils), and annual blockage frequencies of 8.4 events per km. Juba Town Centre ranks second-worst at score 3.1, where colonial-era brick masonry drains are extensively cracked and infiltrated by tree roots and waste. In contrast, the Nimule Road corridor — where HDPE drainage was installed under recent donor-funded road rehabilitation — achieves a mean score of 7.8 with only 0.9 blockage events per km annually.

Blockage frequency exhibits a strong inverse correlation with condition score (Pearson $r = -0.88$, $p < 0.001$), confirming that structural deterioration and blockage risk are co-determined by material quality and age rather than by operational differences between districts. This finding supports a rehabilitation approach that addresses structural condition first, rather than investing in operational cleaning of structurally deteriorated infrastructure that will rapidly re-block.

4.2 IDF Curves and Design Rainfall

Table 2 presents the fitted Sherman IDF parameters for Juba. Goodness-of-fit R^2 values range from 0.968 to 0.982, confirming excellent representation of the observed intensity-duration relationship across all return periods. The 10-year, 60-minute design intensity of 56.9 mm/hr is the most widely used design value for primary urban drainage sizing in Juba, representing the standard adopted in the MoRB drainage design guidelines. Figure 1b illustrates the IDF family on log-log axes, revealing the characteristic power-law behaviour of tropical rainfall intensity with duration and the widening confidence interval at longer return periods reflecting greater extrapolation uncertainty.

Comparison of Juba IDF values with the nearest long-record regional stations — Kampala (Uganda) and Addis Ababa (Ethiopia) — confirms that Juba rainfall intensities are broadly consistent with the equatorial East African high-intensity regime, though the Juba 100-year, 30-minute intensity (134.9 mm/hr) is 12–18% higher than Kampala equivalents, likely reflecting Juba's proximity to the Imatong Mountain orographic enhancement zone and the Congo Air Boundary convergence dynamics that intensify short-duration convective events.

4.3 Sub-Catchment Runoff Analysis

Table 3 and Figure 3a reveal that 15 of 28 sub-catchments (54%) have drainage capacity ratios exceeding 1.5 for the 10-year design storm, with 8 sub-catchments exhibiting critical ratios above 2.5. The Munuki North sub-catchment records the highest capacity ratio of 5.04 — meaning the peak design runoff is more than five times the installed drainage capacity —

producing near-certain surface flooding during any storm approaching the 10-year return period. Nimule Road, Airport Road, and Customs Area sub-catchments demonstrate adequate drainage capacity, reflecting recent infrastructure upgrades.

The OLS regression analysis (Figure 3b) establishes a highly significant linear relationship between impervious cover and runoff coefficient across the 28 sub-catchments ($r = 0.94$, $R^2 = 0.88$, $p < 0.001$), with the fitted equation $C = 0.00918 * I_pct + 0.112$, where I_pct is percentage impervious cover. This relationship, calibrated to Juba conditions, provides a practical planning tool for estimating the drainage capacity implications of future densification or land use change in any Juba sub-catchment without requiring full hydrological survey, supporting integration into the urban master planning process.

Figure 3c reveals the troubling temporal dynamic underlying the drainage crisis: recorded flood-road closure events have increased monotonically from 18 events per year in 2012 to 54 events per year in 2024 — a tripling over twelve years — while drainage maintenance budget fluctuated without trend between USD 0.9 million and USD 3.2 million annually, averaging only USD 1.8 million per year. The inverse correlation between maintenance budget levels and event counts in individual years (Pearson $r = -0.62$, $p = 0.014$) confirms that maintenance investment, though insufficient at any observed level, does provide marginal protection — with the 2015 and 2021 budget peaks each associated with the only years in the record that broke the upward trend.

Figure 3: (a) Scatter plot of Rational Method peak runoff Q_peak vs existing drainage capacity Q_cap for 28 Juba sub-catchments — points coloured by capacity ratio; bubble size proportional to catchment area; dashed diagonal represents the threshold Q_peak = Q_cap; shaded region indicates the capacity deficit zone; (b) OLS Regression of impervious cover percentage (%) against Rational Method runoff coefficient C across 28 Juba sub-catchments — shaded band is the 95% prediction interval; (c) Temporal trend in annual flood-road closure events (bars) and drainage maintenance budget (line with squares) for Juba City (2012–2024) — dual-axis plot; note inverse relationship between budget peaks and event rates.

4.4 Failure Mode Analysis

Figure 2a presents the Pareto chart of the 1,166 recorded failure events. Inadequate capacity accounts for 312 events (26.8%), confirming hydraulic undersizing as the fundamental systemic deficiency of the network. Sediment and debris blockage is the second-ranked mode at 248 events (21.3%), closely linked to the absence of regular de-silting maintenance. Structural collapse and pipe deterioration account for 187 events (16.0%), concentrated in the CSP and brick drain materials. Together, these three modes account for 747 events (64.1%), and their cumulative percentage curve crosses the 80% threshold at four modes — confirming the Pareto principle and focusing rehabilitation attention on capacity augmentation, maintenance, and structural replacement.

Illegal solid waste dumping into drainage channels ranks fourth at 164 events (14.1%), reflecting the absence of solid waste collection infrastructure in large parts of Juba where residents have no alternative disposal route. This failure mode is unique in requiring a non-engineering intervention — community behaviour change and waste collection service provision — rather than structural rehabilitation, and represents an important interface between drainage engineering and public health programming.

4.5 Pipe Condition by Material Type

Figure 2b presents the violin distribution of structural condition scores by drainage material type across the 647 inspected drain sections. HDPE pipes achieve the highest median condition score (7.2) and lowest variance, consistent with their recent installation and chemical resistance. Corrugated steel pipes (CSP) and open earth channels exhibit the lowest median scores (3.2 and 2.9 respectively), with long lower tails extending to near-zero scores representing sections in advanced collapse. Concrete pipes cluster around a median of 4.8, representing borderline acceptable condition.

The bimodal distribution observed in the brick/masonry violin — with peaks at scores 2.5 and 6.5 — reflects the heterogeneous age distribution of the brick drain stock: pre-1980 colonial-era sections in very poor condition coexist with post-2010 rehabilitated sections in fair condition. This bimodality has important rehabilitation planning implications: rather than a uniform intervention approach across all brick drains, targeted replacement of the pre-1980 stock while maintaining the post-2010 sections with routine maintenance would optimise capital allocation.

4.6 Rehabilitation Scenario Evaluation

Table 5 and Figure 4a present the cost-benefit analysis results for