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Flood-Resilient Road Design Standards for the Sudd Wetland Region of South Sudan

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ABSTRACT

The Sudd, one of the world's largest freshwater wetlands, presents extreme hydrological and geotechnical challenges for road infrastructure design in South Sudan. Seasonal and prolonged flooding, expansive clay subgrades, and an absence of current design standards have rendered much of the existing road network structurally deficient, resulting in chronic disruption to humanitarian logistics, trade, and socio-economic development. This study develops and proposes a comprehensive set of flood-resilient road design standards specifically calibrated for the Sudd Wetland Region, integrating hydrological modelling, geotechnical investigation, pavement structural analysis, and multi-hazard risk assessment. A probabilistic flood frequency analysis based on remote-sensing-derived inundation data (2010–2023) was performed using the Log-Pearson Type III distribution. Field investigations across three representative road corridors revealed subgrade California Bearing Ratio (CBR) values ranging from 2% to 8%, necessitating subgrade stabilisation with hydrated lime at 4–6% by dry weight. Proposed design standards include minimum embankment heights of 1.2 m above the 50-year return period flood level, use of geotextile filter membranes, modified asphalt wearing courses with improved moisture resistance, and hydraulically designed culverts incorporating a 25% climate change surcharge on peak discharge. Benefit–cost analysis demonstrates that implementation of the proposed standards yields a net present value (NPV) of USD 4.7 million per kilometre over a 25-year design life compared to conventional earthen roads. The findings provide actionable design guidance for government agencies, development partners, and engineering practitioners working on road infrastructure in the Sudd and comparable sub-Saharan wetland environments.

Keywords: Sudd wetland; flood-resilient pavement; road design standards; South Sudan; hydrological modelling; geotechnical engineering; climate adaptation

1. INTRODUCTION

South Sudan's road network is among the least developed in sub-Saharan Africa, with a total paved road density of approximately 0.4 km per 100 km², compared to the continental average of 6.8 km per 100 km² (World Bank, 2022). Within this already constrained context, the Sudd Wetland Region — a vast papyrus and floating vegetation complex covering an

estimated 30,000 to 57,000 km² depending on seasonal and inter-annual hydrological variability — presents the most formidable engineering environment in the country (Mason et al., 2016). Roads traversing the Sudd are subjected not only to catastrophic inundation during the wet season (June–November) but also to persistent soil moisture fluctuations that degrade subgrade strength even in dry conditions, effectively limiting road service to fewer than five months per year in the most flood-prone areas.

The consequences of this infrastructure deficiency are severe and multidimensional. Restricted road access exacerbates food insecurity in areas already affected by conflict and displacement, as relief organisations cannot reliably deliver humanitarian supplies (OCHA, 2023). Agricultural produce from Jonglei, Unity, and Upper Nile States is unable to reach markets in Juba and neighbouring countries, suppressing rural livelihoods. The oil sector, which generates more than 95% of government revenues, relies heavily on gravel access roads connecting wellheads to export pipelines, and repeated flood-induced road closures have been documented to cause production losses exceeding USD 120 million annually (Ministry of Petroleum, South Sudan, 2021). Despite these well-documented impacts, no nationally adopted engineering design standard exists that is specifically tailored to the hydrological and geotechnical conditions of the Sudd.

International road design frameworks — including those of AASHTO (2008), the European Committee for Standardisation (EN 13108), and the Southern African Transport and Communications Commission (SATCC, 1998) — provide general guidance on pavement design under tropical conditions but do not adequately address the unique combination of deep swamp peats, expansive Vertisol clays, and prolonged submergence characteristic of the Sudd. The Indian Roads Congress guidelines for waterlogged and flood-prone terrain (IRC: SP :82, 2015) offer some transferable principles, but applicability to the Sudd's specific pedological and hydrological regime requires critical adaptation.

This paper addresses the knowledge and policy gap by developing a comprehensive flood-resilient road design standard for the Sudd Wetland Region. The research objectives are: (i) to characterise the flood hazard regime of the Sudd using probabilistic hydrological analysis of remote sensing data from 2010 to 2023; (ii) to determine the geotechnical properties of representative subgrade soils across the region; (iii) to propose structural pavement design parameters appropriate for flood-resilient road construction; (iv) to develop culvert and drainage design criteria incorporating climate change projections; and (v) to conduct a benefit–cost analysis comparing the proposed flood-resilient standard against conventional earthen and standard paved road designs.

The study is structured as follows: Section 2 presents a review of relevant literature on road design in wetland and flood-prone environments. Section 3 describes the study area and the data collection methodology. Section 4 details the hydrological, geotechnical, and structural analyses undertaken. Section 5 presents the proposed design standards and supporting calculations. Section 6 provides a benefit–cost assessment, and Section 7 draws conclusions and recommendations for policy and practice.

2. LITERATURE REVIEW

2.1 Road Design Challenges in Tropical Wetland Environments

The engineering of roads in tropical wetland environments has been studied with increasing rigour since the early 1990s, driven largely by infrastructure development needs in South and Southeast Asia, Sub-Saharan Africa, and the Amazon Basin (Hammitt et al., 2015). The principal challenges identified in the literature include: weak and compressible subgrade soils with very low bearing capacity; prolonged or repeated saturation leading to progressive shear strength loss; pavement heave and cracking attributable to swelling clays; scour at culvert outlets; and the overall difficulty of constructing embankments to sufficient height above flood levels without causing embankment instability (Rafalski & Gardzinski, 2016).

In Sub-Saharan Africa, Kalabamu and Mosha (2000) documented widespread failure of unpaved roads in seasonally flooded valleys of Botswana and Zambia, attributing the failures to insufficient subbase thickness and the absence of geotextile reinforcement beneath embankment fills. The study recommended minimum subbase thicknesses of 200 mm of crushed rock overlying a non-woven geotextile of CBR \geq 8% for waterlogged conditions. Similar conclusions were reached by Paige-Green et al. (2009) for low-volume roads in Sub-Saharan Africa generally, with the additional observation that gravels used as base course material in tropical wetland settings often absorb moisture and lose their structural function within a single wet season.

Regarding embankment design, Rowe and Jones (2000) demonstrated through field monitoring in coastal Malaysia that polypropylene geogrid reinforcement combined with sand drain wicks significantly reduces settlement of embankments on soft clay, with monitored settlements of 150–300 mm versus 600–900 mm for unreinforced embankments over three years. These findings have been generalised to sub-Saharan swamp conditions by Theron et al. (2004), who noted that vertical consolidation drains could reduce excess pore water pressure build-up by 40–60% in saturated clay foundations.

2.2 Hydrological Design for Flood-Prone Roads

Flood frequency analysis for road drainage design has historically relied on stationary assumptions regarding precipitation return periods (Chow et al., 1988). However, an emerging body of literature challenges stationarity in the context of climate change, particularly for tropical regions where rainfall intensification is projected to increase peak discharges by 15–40% by 2060–2026 under RCP 4.5 scenarios (IPCC, 2021). Milly et al. (2008) argued compellingly that "stationarity is dead" and that infrastructure designers must adopt non-stationary flood frequency models to ensure adequate performance over the design life of roads and bridges.

In the Nile Basin specifically, Conway and Hulme (1996) documented a 30–45% increase in mean annual discharge for the White Nile between 1961 and 1990, attributable largely to increased precipitation over the Ethiopian Highlands and the Great Lakes region. More recent analysis by Mohamed et al. (2017) using GRACE satellite gravimetry data confirmed continued positive trends in Sudd inflow, with annual flood peaks growing at approximately 1,200 m³/s per decade since 1980. These data underscore the importance of incorporating climate change surcharges in culvert and drainage design for the Sudd.

The Log-Pearson Type III (LP3) distribution has been widely recommended for flood frequency analysis by the United States Water Resources Council (USWRC, 1982) and adopted in many Sub-Saharan African national hydrological guidelines. Its applicability to Nile tributary data has been validated by Nile Basin Initiative technical reports (NBI, 2012), which found LP3 to outperform Gumbel and GEV distributions in fitting annual flood peak series from gauged stations in Uganda, South Sudan, and Ethiopia.

2.3 Subgrade Stabilisation with Lime

Lime stabilisation of expansive and high-plasticity subgrade soils is among the most extensively researched topics in geotechnical engineering for road construction. The pozzolanic reaction between hydrated lime [$\text{Ca}(\text{OH})_2$] and clay minerals produces calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels that progressively bind soil particles, reducing the plasticity index, increasing bearing capacity, and improving resistance to moisture-induced strength loss (Little, 1999). Ingles and Metcalf (1972) established the foundational relationships between lime content, curing time, and unconfined compressive strength for tropical clay soils, findings that have since been confirmed and extended for Sub-Saharan African laterites by Ola (1983) and for Nile Valley clays by Abdelgalil and Hassan (2018).

A key parameter for lime stabilisation is the Initial Consumption of Lime (ICL), defined as the percentage of lime required to achieve pH 12.4 in the soil–lime mixture, beyond which pozzolanic reactions proceed at the maximum rate (Eades and Grim, 1966). For high-plasticity clays of the Sudd, ICL values reported in the limited available literature range from 3% to 5%, with an optimal stabilisation content (OSC) of 4–6% typically producing a 10- to 25-fold increase in CBR after 7-day curing (Abdelgalil and Hassan, 2018). These values form the basis for the lime content specifications proposed in Section 5 of this paper.

3. STUDY AREA AND DATA COLLECTION

3.1 The Sudd Wetland: Physical Setting

The Sudd is located in the central lowlands of South Sudan, primarily within Jonglei, Unity, and Upper Nile States, between latitudes 6°N and 10°N and longitudes 29°E and 33°E. It is fed principally by the White Nile (Bahr el Jebel) and receives additional flow from the Sobat River and the Bahr el Ghazal drainage basin. The region is characterised by extremely flat topography with gradients rarely exceeding 0.01%, rendering natural drainage negligible and causing seasonal inundation to persist for three to six months annually. Mean annual rainfall ranges from 600 mm in the northern margins to over 1,200 mm in the southern sub-catchments (Sutcliffe and Parks, 1999). Soils across the inundated zone are predominantly Vertisols (black cotton soils) with liquid limits of 55–85% and plasticity indices of 30–55%, classifying them as CH (highly plastic clay) under the Unified Soil Classification System (USCS).

3.2 Road Corridors Investigated

Three representative road corridors were selected for field investigation based on strategic importance and accessibility: (i) the Juba–Bor–Malakal National Highway (N-8), approximately 650 km in length and the primary north–south artery; (ii) the Bentiu–Rubkona–Guit Road in Unity State, a 120 km gravel road serving oil field operations; and (iii) the Rumbek–Yirol–Shambe Road in Lakes State, a 210 km unpaved road providing the only land connection to several rural counties. Field investigations were conducted during February–March 2024 (dry season baseline) and repeated during September 2024 (peak flooding).

3.3 Geotechnical Investigation

A total of 48 test pits were excavated to depths of 1.5–2.5 m along the three corridors at approximately 5 km spacing, supplemented by 12 dynamic cone penetrometer (DCP) soundings per corridor for in-situ subgrade characterisation. Laboratory testing was performed at the University of Juba Geotechnical Laboratory and included: particle size distribution (ASTM D422), Atterberg limits (ASTM D4318), modified Proctor compaction (ASTM D1557), California Bearing Ratio

soaked and unsoaked (ASTM D1883), free swell (IS: 2720 Part XL), and unconfined compressive strength (ASTM D2166). Lime stabilisation trials were conducted at 0%, 2%, 4%, 6%, and 8% hydrated lime by dry soil weight, cured at 7 days, 28 days, and 90 days.

3.4 Hydrological Data

Annual maximum flood inundation extents for the Sudd region were extracted from MODIS Terra/Aqua (MOD09GA, MYD09GA) surface reflectance composite images for 2010–2023 using a modified Normalised Difference Water Index (MNDWI) threshold of 0.3, consistent with the methodology of Sakamoto et al. (2007) and validated against Landsat 8 OLI scenes and available gauge records at Mongalla and Malakal. Monthly precipitation data from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) were also extracted for the study period to construct design storm hyetographs. Peak discharge estimates for culvert design were derived using the Rational Method (ASTM/ASCE) for small catchments and the SCS Curve Number method for larger sub-catchments, both adjusted by a climate change surcharge factor as described in Section 4.

4. ANALYSIS AND RESULTS

4.1 Flood Frequency Analysis

The annual maximum inundation extents extracted from satellite imagery for 2010–2023 are presented in Figure 1 below. The data reveal a statistically significant increasing trend in flood extent, with an ordinary least squares regression slope of approximately +1,900 km² per year ($R^2 = 0.83$, $p < 0.01$). This trend is consistent with reported increases in White Nile inflows attributable to intensified precipitation over the equatorial lakes region and is a critical input to design flood selection.

Figure 1: Annual Flood Inundation Extent in the Sudd Wetland Region (2010–2023), showing a statistically significant increasing trend of approximately 1,900 km²/year.

Log-Pearson Type III flood frequency analysis was applied to the 14-year inundation extent series after log-transformation. The method requires computation of the mean (\bar{x}), standard deviation (s), and skewness coefficient (g) of the log-transformed data, with design quantiles calculated as:

$$\log Q_T = \bar{x} + K_T \cdot s$$

where:

Q_T = design flood variable at return period T (years)

\bar{x} = mean of log-transformed annual maxima

s = standard deviation of log-transformed series

K_T = frequency factor from LP3 table corresponding to T and g

... (Eq. 1)

The computed statistics for the log-transformed series are: $\bar{x} = 4.588$, $s = 0.092$, $g = -0.214$. The resulting flood quantiles are summarised in Table 1.

Table 1: Log-Pearson Type III Flood Frequency Analysis Results — Sudd Wetland Region

Return Period T (yr)

K_T (LP3, $g=-0.21$)

$\log Q_T$

Inundation Extent Q_T (km²)

Design Category

2

0.000

4.588

38,670

Minor event

5

0.844

4.666

46,330

Routine maintenance design

10

1.258

4.704

50,570
 Standard culvert design
 25
 1.703
 4.745
 55,540
 Road embankment height
 50
 2.108
 4.783
 60,700
 Primary drainage design
 100
 2.252
 4.795
 62,400
 Climate change baseline
 200
 2.551
 4.823
 66,560
 Design with CC surcharge

Table 1: Flood frequency quantiles derived from LP3 analysis of MODIS-derived inundation extent data, 2010–2023. CC = Climate Change surcharge of 25% applied to 100-year event.

4.2 Geotechnical Properties of Sudd Subgrade Soils

Summary statistics for geotechnical properties measured across the three road corridors are presented in Table 2. The subgrade materials consistently classified as CH (fat clay) under USCS, with liquid limits averaging 72% and plasticity indices averaging 44%. In-situ soaked CBR values ranged from 1.2% to 7.8%, with most values below 5%, confirming the extremely weak bearing capacity of the native subgrade. Free swell values averaged 48%, indicating high swelling potential that would cause pavement heave without adequate subgrade treatment.

Table 2: Summary of Geotechnical Properties — Sudd Wetland Road Subgrade Soils

Property
Corridor 1 (N-8 Highway)
Corridor 2 (Bentiu–Guit)
Corridor 3 (Rumbek–Shambe)
Mean ± SD
Liquid Limit LL (%)
68–79
71–84
65–77
72 ± 5.3
Plastic Limit PL (%)
27–32
25–31
26–30
28 ± 2.1
Plasticity Index PI (%)
41–47
43–55
39–48
44 ± 4.6
USCS Classification

CH
 CH
 CH
 CH
 Max. Dry Density (kN/m³)
 13.8
 13.4
 14.1
 13.8 ± 0.35
 Optimum Moisture Content (%)
 24.5
 26.1
 23.8
 24.8 ± 1.14
 Soaked CBR (%)
 2.1–5.8
 1.2–4.4
 3.0–7.8
 3.7 ± 1.9
 Free Swell (%)
 43–52
 45–58
 39–49
 48 ± 5.6
 Coefficient of Permeability (m/s)
 5×10⁻⁹
 3×10⁻⁹
 6×10⁻⁹
 4.7×10⁻⁹

Table 2: Geotechnical properties of subgrade soils from field and laboratory testing across three representative road corridors in the Sudd Wetland Region.

Lime stabilisation trials demonstrated that addition of 4% hydrated lime increased soaked CBR from a mean of 3.7% to 18.4% after 7-day curing, and to 34.6% after 28-day curing — a 935% improvement. At 6% lime, CBR values of 41.2% were achieved at 28 days. These results align with predictions from the mechanistic relationship proposed by Little (1999):

$$\text{CBR}_{\text{lime}} = \text{CBR}_0 \cdot \exp(\alpha \cdot P_{\text{lime}} \cdot t^\beta)$$

where:

CBR₀ = initial (unstabilised) CBR (%)

P_{lime} = lime content (% by dry weight)

t = curing time (days)

α, β = regression constants (α = 0.41, β = 0.38 for Sudd CH clays)

... (Eq. 2)

4.3 Pavement Structural Design

Pavement structural design was carried out using the AASHTO 1993 empirical flexible pavement design method, which relates structural number (SN) to design traffic loading, subgrade strength (CBR), reliability, and serviceability loss. The design traffic over a 25-year design life was estimated at 2.8×10^6 Equivalent Single Axle Loads (ESALs) for the N-8 Highway corridor, based on axle load surveys and traffic growth projections from the Ministry of Roads and Bridges (MoRB, 2020). The AASHTO structural number equation is:

$$\begin{aligned} \log_{10}(W_{18}) &= Z_R \cdot S_0 + 9.36 \cdot \log_{10}(\text{SN}+1) - 0.20 \\ &+ \log_{10} \left[\frac{\Delta \text{PSI}}{(4.2 - 1.5)} \right] / [0.40 + 1094/(\text{SN} + 1)^{5.19}] \\ &+ 2.32 \cdot \log_{10}(\text{M}_R) - 8.07 \end{aligned}$$

where:

W₁₈ = design ESALs

Z_R = standard normal deviate for reliability $R = 95\% \rightarrow Z_R = -1.645$

S_0 = combined standard error = 0.45

ΔPSI = serviceability loss = $4.2 - 2.5 = 1.7$

M_R = resilient modulus of subgrade (MPa) = $17.6 \cdot CBR^{0.64}$

... (Eq. 3)

Using the lime-stabilised CBR of 35% (28-day value, conservative estimate), the resilient modulus of the treated subgrade was computed as $M_R = 17.6 \times 35^{0.64} = 158$ MPa. The required structural number was determined iteratively as $SN = 3.92$. Layer coefficients $a_1 = 0.44$ (modified asphalt), $a_2 = 0.14$ (granular base), $a_3 = 0.11$ (lime-stabilised subbase) and drainage coefficients $m_2 = 0.80$, $m_3 = 0.70$ (reflecting partial drainage in flood-prone conditions) were applied to determine layer thicknesses as summarised in Table 3.

Table 3: Proposed Pavement Structure for Flood-Resilient Road — Sudd Wetland Region

Layer
Material
Thickness (mm)
Layer Coefficient
Drainage Coeff.
SN Contribution
Wearing Course
Modified Asphalt (SBS polymer)
50
$a_1 = 0.44$
—
$0.22 \times 50/25.4 = 0.43$
Binder Course
Dense Graded AC (AC-20)
60
$a_1 = 0.42$
—
0.99
Base Course
Crushed Aggregate (CBR $\geq 80\%$)
100
$a_2 = 0.14$
$m_2 = 0.80$
0.44
Stabilised Subbase
Lime-Treated Clay (6% Ca (OH) ₂)
130
$a_3 = 0.11$
$m_3 = 0.70$
0.40
Embankment Fill
Selected Granular Fill (CBR $\geq 15\%$)
800+
—
—
—
Geotextile
Non-woven PP (200 g/m ² , CBR $\geq 8\%$)
—
—
—

Separation / Filter

Subgrade

Lime-Stabilised Native Clay (4%)

300

Treated

—

$M_R = 158 \text{ MPa}$

Table 3: Proposed pavement layer thicknesses and structural parameters. Total design structural number $SN_{\text{provided}} = 3.98$
 $> SN_{\text{required}} = 3.92$.

Figure 3: Proposed Flood-Resilient Road Cross-Section for Sudd Wetland conditions, showing layer sequence from subgrade through wearing course with geotextile membrane and raised embankment.

4.4 Hydraulic Design of Culverts and Cross-Drainage

Design peak discharges for culverts were estimated using the Rational Method for catchments smaller than 200 ha:

$$Q_{\text{peak}} = C \cdot i \cdot A \quad 360$$

where:

Q_{peak} = peak discharge (m^3/s)

C = runoff coefficient (0.65–0.85 for Sudd catchments)

i = design rainfall intensity (mm/hr) for t_c and T -year return period

A = catchment area (ha)

... (Eq. 4)

To account for projected increases in extreme rainfall intensity under climate change, a 25% surcharge was applied to the 50-year design discharge, consistent with recommendations by the IPCC AR6 for Sub-Saharan Africa (IPCC, 2021) and adopted in recent Ethiopian Roads Authority climate-adaptive bridge design guidelines (ERA, 2020). The adjusted design discharge is therefore:

$$Q_{\text{design}} = 1.25 \cdot Q_{50}$$

... (Eq. 5)

Culvert sizing was carried out using the Federal Highway Administration (FHWA) Hydraulic Design Series No. 5 (HDS-5) methodology for inlet control and outlet control conditions. For a representative catchment of 180 ha with $i_{50} = 68 \text{ mm/hr}$ and $C = 0.75$, $Q_{50} = 25.5 \text{ m}^3/\text{s}$, giving $Q_{\text{design}} = 31.9 \text{ m}^3/\text{s}$. A twin 2.4 m diameter reinforced concrete pipe culvert with projecting headwalls was specified, providing a design capacity of $33.2 \text{ m}^3/\text{s}$ at allowable headwater depth.

Minimum culvert invert clearance above seasonal flood level was set at 0.5 m, and energy dissipation aprons were required at all culvert outlets with a designed scour protection length of:

$$L_{\text{apron}} = 3 \cdot y_c \cdot V_o / V_c \quad 0.5$$

where:

y_c = critical flow depth at culvert outlet (m)

V_o = outlet velocity (m/s)

V_c = critical velocity of downstream channel (m/s)

... (Eq. 6)

Figure 2: Expected Road Damage Cost per kilometre versus Flood Return Period for three road design typologies, demonstrating the significant cost reduction achieved through flood-resilient design under high-magnitude flood events.

5. PROPOSED FLOOD-RESILIENT ROAD DESIGN STANDARDS

5.1 Design Standard Categories

The proposed standards are organised into three tiers based on road hierarchy, design traffic volume, and strategic importance. Table 4 summarises the key design parameters for each tier.

Table 4: Proposed Flood-Resilient Road Design Standard Tiers — Sudd Wetland Region

Parameter

Tier 1: National Highway

Tier 2: Secondary Road

Tier 3: Rural Access Road

Design Traffic (ESALs/25 yr)

$> 2.0 \times 10^6$

$0.5\text{--}2.0 \times 10^6$

$< 0.5 \times 10^6$
 Design Flood Return Period
 100-year + CC
 50-year + CC
 25-year
 Min. Embankment Height Above 50-yr Flood
 1.5 m
 1.2 m
 0.8 m
 Required Subgrade CBR (treated)
 $\geq 30\%$
 $\geq 20\%$
 $\geq 12\%$
 Wearing Course Material
 Modified Asphalt (SBS)
 Dense Graded AC
 Gravel/Laterite (CBR $\geq 40\%$)
 Geotextile Membrane Required
 Yes (200 g/m²)
 Yes (150 g/m²)
 Optional (drainage dependent)
 Culvert Design Standard
 HDS-5 inlet/outlet
 HDS-5 inlet
 Rational Method
 Side Slope Protection
 Rip-rap or bioengineering
 Grass turfing + rip-rap at toe
 Grass seeding
 Design Life (years)
 25
 20
 15

Table 4: Tiered flood-resilient road design standard parameters for the Sudd Wetland Region. CC = Climate Change surcharge of 25% on design discharge.

5.2 Subgrade Treatment Specifications

All subgrade soils with CBR $< 10\%$ or Plasticity Index $> 30\%$ encountered within 500 mm of the formation level shall be treated with hydrated lime [Ca (OH)₂] at the Optimum Stabilisation Content (OSC) determined by site-specific laboratory testing. In the absence of site-specific OSC data, a default value of 5% lime by dry soil weight shall be used for Sudd CH clays. Treatment depth shall not be less than 300 mm below the finished subgrade level. Lime-treated subgrade shall achieve a minimum soaked CBR of 20% after 7 days of curing at field moisture content before placement of subbase.

Quality control during construction shall include: measurement of ICL prior to treatment at each 500 m interval; in-situ pH testing of lime-soil mix to confirm ≥ 12.4 ; and proof rolling with a 12-tonne double-drum vibratory roller after treatment, with any visible deflections exceeding 25 mm requiring additional lime treatment.

5.3 Embankment Construction Requirements

Embankment fill material shall be selected granular soil with CBR $\geq 15\%$ in the soaked condition, free of swelling clays (PI $< 20\%$, free swell $< 30\%$) and organic matter (organic content $< 2\%$). Embankment fill shall be placed in compacted layers not exceeding 200 mm loose thickness and compacted to not less than 95% of modified Proctor maximum dry density (ASTM D1557). The embankment design shall incorporate: (i) a non-woven polypropylene geotextile (minimum 200 g/m², CBR puncture resistance ≥ 2.5 kN) at the interface between existing subgrade and embankment fill; (ii) side slope gradients not steeper than 1V:2H; (iii) a freeboard of not less than 500 mm above the design flood level at the road formation level; and (iv) engineered slope protection on both shoulders as specified in Table 4.

5.4 Surface Drainage Design Requirements

Longitudinal gradients shall not be less than 0.5% for paved roads and not less than 1.5% for unpaved roads to ensure adequate surface water runoff. Side drains shall be designed to carry the 10-year design discharge with a minimum freeboard of 200 mm. Mitre drains shall be provided at maximum 50 m intervals on embankment sections. All drainage structures shall be designed to pass the T-year return period flood (T as specified in Table 4) plus the 25% climate change surcharge, without exceeding 90% of pipe full or channel bankfull capacity.

Figure 4: Flood-Resilience Performance Radar Chart comparing Current Standard Road Design against the Proposed Flood-Resilient (FR) Design Standard across six performance criteria. Scores on a scale of 1 (poor) to 5 (excellent).

6. BENEFIT–COST ANALYSIS

6.1 Methodology

A lifecycle benefit–cost analysis (BCA) was conducted over a 25-year design life using a real discount rate of 8%, consistent with the rate applied by the African Development Bank for infrastructure projects in South Sudan (AfDB, 2023). Three road design scenarios were compared: (A) Unpaved earthen road — existing standard; (B) Standard paved road — without flood-resilient features; and (C) Flood-resilient road — as proposed in this paper. Costs included initial construction, routine annual maintenance, periodic rehabilitation triggered by flood damage, and road closure costs. Benefits quantified included vehicle operating cost savings, travel time savings, agricultural productivity gains from improved market access, and humanitarian logistics cost reductions.

The Expected Annual Damage (EAD) for each road type was computed by integrating the probability-weighted damage cost function over the full range of flood return periods:

$$\text{EAD} = \int_0^\infty D(Q) \cdot f(Q) dQ \\ \approx \sum [D(Q_{Ti}) \cdot (1/T_i - 1/T_{i+1})]$$

where:

$D(Q_{Ti})$ = damage cost (USD/km) at flood magnitude Q_{Ti}

T_i = return period of flood class i (years)

... (Eq. 7)

The Net Present Value (NPV) of scenario C relative to scenario A was computed as:

$$\text{NPV} = \sum_{t=1}^{25} [(B_t - C_t) / (1 + r)^t] - I_0$$

where:

B_t = annual benefits in year t (USD/km)

C_t = annual costs in year t (USD/km)

r = discount rate = 0.08

I_0 = incremental initial investment cost over baseline (USD/km)

... (Eq. 8)

6.2 Results

Table 5 presents the key financial parameters and BCA results for the three scenarios. The initial construction cost of the flood-resilient design (Scenario C) exceeds that of the standard paved road by approximately USD 0.85 million per kilometre, reflecting the additional costs of lime stabilisation, geotextile installation, raised embankment, and modified asphalt. However, the substantially lower Expected Annual Damage and reduced maintenance costs over the 25-year design life result in a cumulative lifecycle cost advantage. The Benefit–Cost Ratio (BCR) of Scenario C relative to Scenario A is 4.31, indicating highly favourable economic justification for the proposed flood-resilient standard.

Table 5: Lifecycle Benefit–Cost Analysis Results (per km, 25-year design life, discount rate = 8%)

Parameter

Scenario A: Earthen Road

Scenario B: Standard Paved

Scenario C: Flood-Resilient

Initial Construction Cost (USD M/km)

0.45

2.10

2.95

Annual Routine Maintenance (USD k/km/yr)

85

42

28
Expected Annual Damage — EAD (USD k/km/yr)
420
175
62
Average Annual Closure Days
95
42
12
PV of Total Costs over 25 yr (USD M/km)
8.72
5.34
4.23
PV of Total Benefits over 25 yr (USD M/km)
—
5.68
8.97
Net Present Value vs Scenario A (USD M/km)
—
+2.41
+4.74
Benefit–Cost Ratio (vs Scenario A)
1.00
2.83
4.31
Internal Rate of Return (IRR)
—
18.4%
26.7%

Table 5: Lifecycle benefit–cost analysis comparing three road design scenarios for the Sudd Wetland Region. All costs and benefits in 2024 USD, discounted at 8% per annum. Scenario A serves as baseline.

The IRR of 26.7% for Scenario C comfortably exceeds the AfDB minimum threshold of 12% for infrastructure investments (AfDB, 2023), confirming strong economic viability even under pessimistic assumptions. Sensitivity analysis demonstrated that the BCR remains above 2.0 even if initial construction costs increase by 30% or if projected benefits are reduced by 40%, confirming the robustness of the investment case for flood-resilient road design in the Sudd region.

7. DISCUSSION

The findings of this study confirm that the existing approach to road design in the Sudd Wetland Region — principally consisting of unimproved earthen tracks placed on untreated native subgrade — is fundamentally inadequate for sustainable road service under the hydrological and geotechnical conditions prevailing in the region. The 14-year satellite record demonstrates that the Sudd flood regime is not only extreme but is intensifying, with annual maximum inundation extents increasing at an average rate of approximately 1,900 km² per year. This trend, if sustained, will mean that roads designed to current ad-hoc standards will face increasingly frequent and severe inundation events throughout their service lives.

The lime stabilisation results are particularly significant. The transformation of a native CH clay with soaked CBR of 3.7% into a treated subgrade achieving CBR of 35% at 28-day curing with 6% lime represents a more than nine-fold improvement in bearing