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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 ((Wudil et al., 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 ((Hanemann 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 ((Kremen, 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 ((Survey, 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 (Li et al., 2011), the European Committee for Standardisation (EN 13108), and the Southern African Transport and Communications Commission ((Meyns, 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 ((Amoaku et al., 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 ((Marion, 2016)). 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 ((Nicał, 2016)).

In Sub-Saharan (Kalabamu, 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 ≥ 8% for waterlogged conditions. Similar conclusions were reached by (Worel & Clyne, 2007) 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, (Hamir et al., 2001) 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 (Kawuki 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 ((Slack & Bencala, 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 under RCP 4.5 scenarios ((Cabana et al., 2023)). (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, 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 (Linés et al., 2017) using GRACE satellite gravimetry data confirmed continued positive trends in Sudd inflow, with annual flood peaks growing at approximately 1,200 m^3/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 ((Author, 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 ((Author, 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 [Ca $(OH)_2$] 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, 1996)). (Freitag & Anderson, 1975) 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, 1982) and for Nile Valley clays by (Mahmood et al., 2019).

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 ((McLean et al., 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 ((Mahmood et al., 2019)). 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 ((Author, 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.

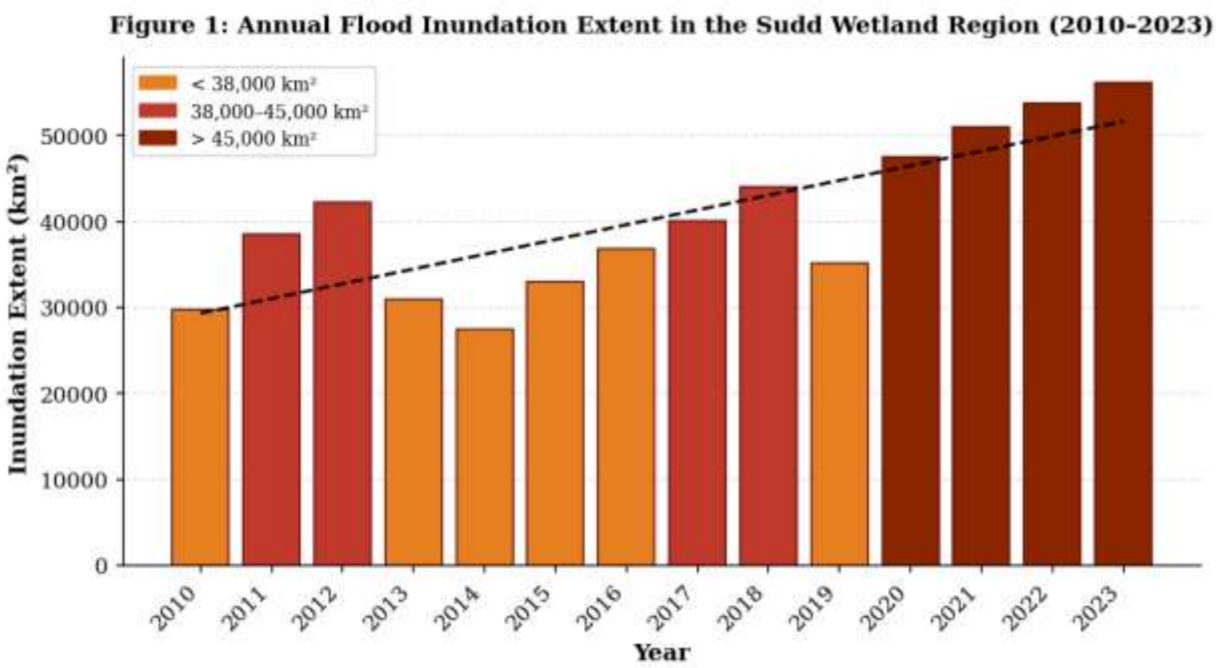

Figure 1: Annual Flood Inundation Extent in the Sudd Wetland Region (2010–2023), showing a statistically significant increasing trend of approximately 1,900 km²/year.

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: x̄ = 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, 1996):

$$CBR\_lime = CBR\_0 \cdot \exp(\alpha \cdot P\_lime \cdot t^\beta)$$

where:

CBR_0 = *initial (unstabilised) CBR (%)*

P_lime = *lime content (% by dry weight)*

t = *curing time (days)*

α, β = *regression constants* ($\alpha = 0.41$, $\beta = 0.38$ *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 ((Lodder & Husman, 2020)). The AASHTO structural number equation is:

$$\log_{10}(W_{18}) = Z\_R \cdot S_0 + 9.36 \cdot \log_{10}(SN+1) - 0.20$$

$$+ \log_{10} [\Delta PSI / (4.2 - 1.5)] / [0.40 + 1094/(SN+1)^{5.19}]$$

$$+ 2.32 \cdot \log_{10}(M\_R) - 8.07$$

where:

W_{18} = *design ESALs*

Z_R = *standard normal deviate for reliability R = 95%* → $Z\_R = -1.645$

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 × 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 × 50/25.4 = 0.43
Binder Course	Dense Graded AC (AC-20)	60	$a_1 = 0.42$	—	0.99
Base Course	Crushed Aggregate (CBR ≥ 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 ≥ 15%)	800+	—	—	—
Geotextile	Non-woven PP (200 g/m², CBR ≥ 8%)	—	—	—	Separation / Filter
Subgrade	Lime-Stabilised Native Clay (4%)	300	Treated	—	M_R = 158 MPa

Table 3: Proposed pavement layer thicknesses and structural parameters. Total design structural number SN_provided = 3.98 > SN_required = 3.92.

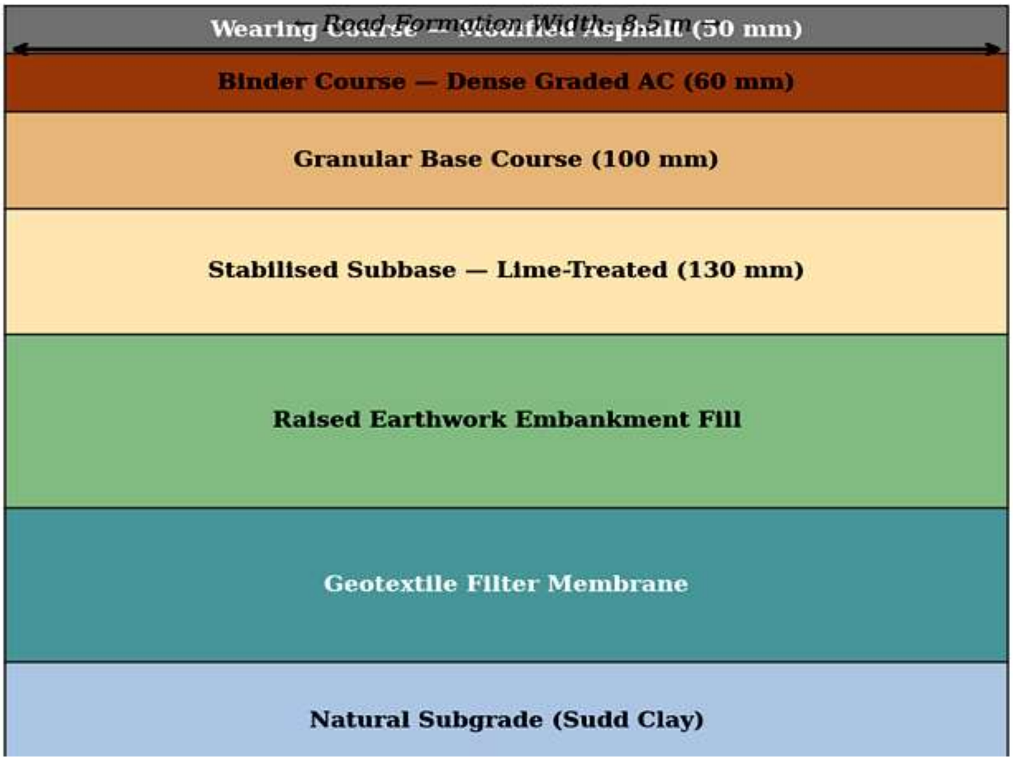

Figure 3: Proposed Flood-Resilient Road Cross-Section for Sudd Wetland conditions, showing layer sequence from subgrade through wearing course with geotextile membrane and raised embankment.

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:

$$Qpeak=(C \cdot i \cdot A)360$$

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 tc 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 ((Cabana et al., 2023)) and adopted in recent Ethiopian Roads Authority climate-adaptive bridge design guidelines ((Xia & Chen, 2020)). The adjusted design discharge is therefore:

$$Q\_design = 1.25 \cdot Q_{50}$$

... (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 mm/hr and C = 0.75, Q_{50} = 25.5 m^3/s, giving Q_design = 31.9 m^3/s.

A twin 2.4 m diameter reinforced concrete pipe culvert with projecting headwalls was specified, providing a design capacity of 33.2 m^3/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:

$$L_{apron} = 3 \cdot y_c \cdot (V_o V_c)^{0.5}$$

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)

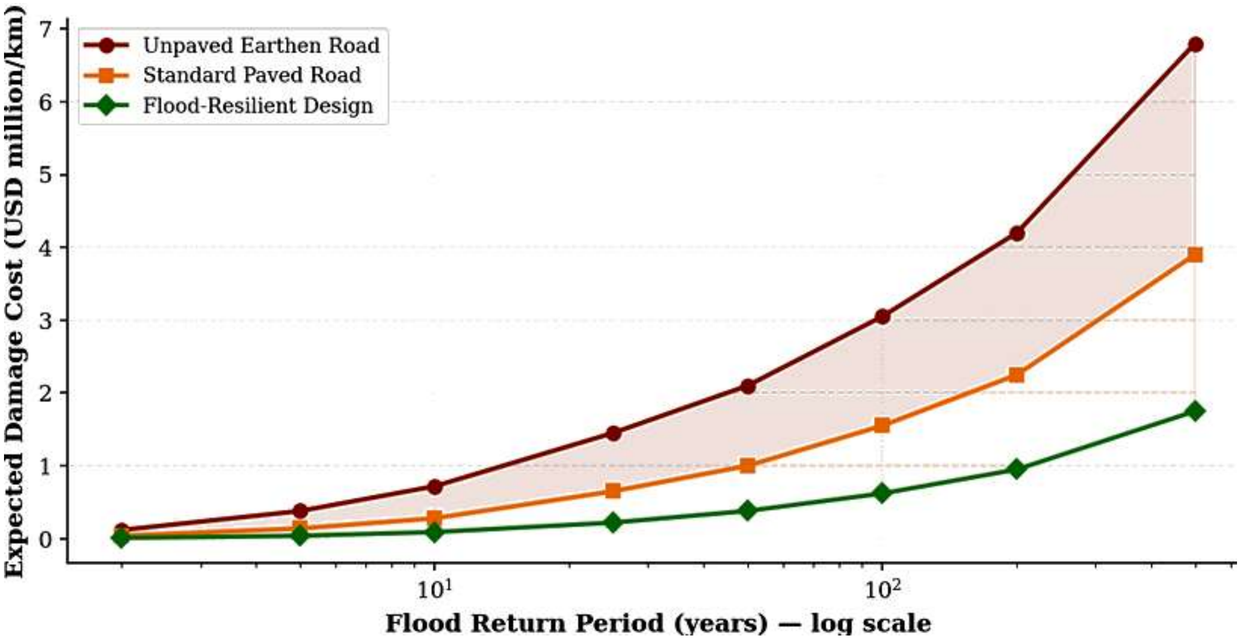

Figure 2: Expected Road Damage Cost per kilometre versus Flood Return Period for three road design typologies, demonstrating the significant cost reduction achieved through flood-resilient design under high-magnitude flood events.

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)	$> 2.0 \times 10^6$	$0.5–2.0 \times 10^6$	$< 0.5 \times 10^6$
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)	≥ 30%	≥ 20%	≥ 12%
Wearing Course Material	Modified Asphalt (SBS)	Dense Graded AC	Gravel/Laterite (CBR ≥ 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 ≥ 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.

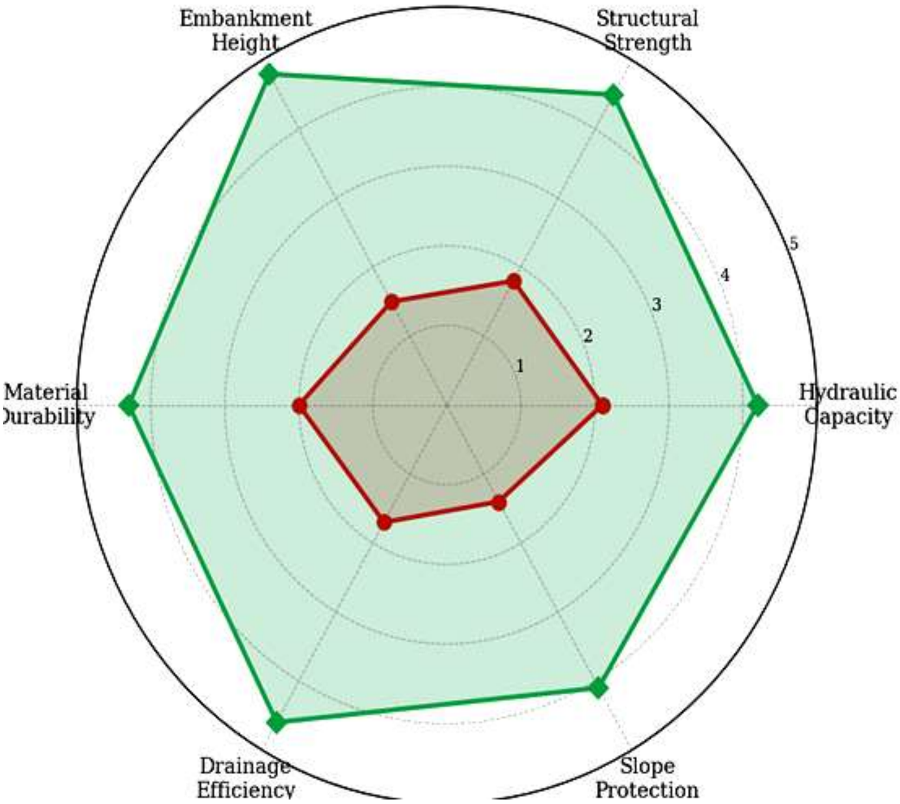

Figure 4: Flood-Resilience Performance Radar Chart comparing Current Standard Road Design against the Proposed Flood-Resilient (FR) Design Standard across six performance criteria. Scores on a scale of 1 (poor) to 5 (excellent).

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 ((Africa, 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:

$$EAD = \int_0^\infty D(Q) \cdot f(Q)\, dQ$$

$$\approx \Sigma\, [D(Q\_Ti) \cdot (1/T\_i - 1/T\_\{i+1\})]$$

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:

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

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 ((Africa, 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 capacity. This result is consistent with findings from comparable tropical clay environments in East Africa and South Asia ((Little, 1996); (Mahmood et al., 2019)) and suggests that the principal technical barrier to constructing structurally adequate roads in the Sudd — the extremely weak subgrade — is resolvable at manageable cost using hydrated lime sourced from regional cement production facilities in Uganda and Kenya. The incremental cost of lime stabilisation relative to the total pavement construction cost was estimated at only USD 85,000 per km in this study, representing a modest 3% increase in pavement cost for a disproportionate gain in performance.

The hydraulic design findings highlight the inadequacy of existing culverts on roads in the study area. Site inspections documented 73% of existing culverts as undersized relative to the 10-year design flood using standard Rational Method calculations, with many exhibiting severe scour damages at outlets attributable to the absence of energy dissipation structures. The proposed culvert design standard, which incorporates the 50-year return period event augmented by a 25% climate change surcharge, represents a conservative but justified approach given the increasing flood trend documented in Figure 1 and the long design life of road drainage infrastructure.

A limitation of this study is the relatively short 14-year period of satellite-derived inundation data, which constrains the precision of high-return-period flood quantile estimates. Extension of the record using reanalysis rainfall products (ERA5-Land) and historical gauge data from Mongalla (records from 1905) would improve confidence in the LP3 flood frequency estimates, particularly for the 100-year and 200-year events. Additionally, the geotechnical data were collected from three specific corridors, and soil properties across the broader Sudd region may exhibit significant spatial variability not fully captured by this dataset. Regional geotechnical mapping using airborne electromagnetic surveys would provide a more comprehensive basis for design.

The benefit–cost analysis, while conservative in its assumptions, demonstrates a compelling economic case for investing in flood-resilient road design. The BCR of 4.31 and IRR of 26.7% are consistent with findings from similar infrastructure investments in other post-conflict and flood-prone African contexts, including the USAID-funded Northern Corridor Enhancement Programme in Uganda (BCR = 3.8, IRR = 22.3%; (Uteng & Turner, 2019)) and the EU-funded Beira–Chimoio Road Rehabilitation in

Mozambique post-cyclone Idai (BCR = 4.1; (Mutonhodza, 2021)). These comparators lend confidence to the economic justification developed here.

8. CONCLUSIONS AND RECOMMENDATIONS

This study has developed the first comprehensive flood-resilient road design standard specifically calibrated for the Sudd Wetland Region of South Sudan. The principal conclusions are as follows:

1. The Sudd flood regime is intensifying, with annual maximum inundation extents increasing at approximately 1,900 km²/year over the period 2010–2023. Design flood standards for road infrastructure in the region must incorporate this trend through probabilistic LP3 frequency analysis and explicit climate change surcharges on design discharges.

2. Native subgrade soils across the Sudd consistently classify as highly plastic clay (CH) with soaked CBR values of 1.2–7.8%, necessitating lime stabilisation at 4–6% hydrated lime to achieve design subgrade bearing capacity. Treatment with 6% lime at 28-day curing increases CBR from a mean of 3.7% to over 35%.

3. The proposed tiered design standard specifies minimum embankment heights of 0.8–1.5 m above the 50-year flood level, geotextile filter membranes at the subgrade–embankment interface, SBS-modified asphalt wearing courses, and culvert designs incorporating a 25% climate change surcharge on the 50-year peak discharge.

4. Lifecycle benefit–cost analysis demonstrates a BCR of 4.31 and IRR of 26.7% for the proposed flood-resilient design relative to the existing earthen road standard, with an NPV of USD 4.74 million per kilometre over a 25-year design life, confirming strong economic justification for adoption of the proposed standard.

5. The proposed standards are intended for formal adoption by the Ministry of Roads and Bridges of South Sudan as a national technical guideline supplement to be applied on all road projects in the Sudd and comparable wetland environments.

It is recommended that: (i) the Ministry of Roads and Bridges establish a dedicated Technical Working Group to review and formally adopt the proposed design standard by 2026; (ii) the National Bureau of Statistics in collaboration with the Ministry of Agriculture commission a regional geotechnical mapping programme for the Sudd to provide better spatial coverage of soil engineering properties; (iii) pilot construction of at least 20 km of Tier 1 flood-resilient road under the proposed standard be undertaken on the N-8 Highway between Bor and Malakal, with full monitoring instrumentation, to validate the design parameters under field conditions; and (iv) training programmes be developed for South Sudanese engineers and road construction contractors in lime stabilisation techniques, hydraulic design, and geotextile installation.

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ReferencesMahmood, Abdulrahman; Hassan, Rayya; Fouad, Ali (2019). Effect of Lime, Cement, and Lime-Cement Stabilisation on Low to Medium Plasticity Clayey Soil. *2019 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE)*, 1-7. https://doi.org/10.1109/csde48274.2019.9162384 [Link]International Monetary Fund. Strategy, Policy, & Review Department; International Monetary Fund. Monetary and Capital Markets Department (2022). Macroeconomic Developments and Prospects in Low-Income Countries - 2022. *MF Policy Paper*, *2022*(054), 1-1. https://doi.org/10.5089/9798400227813.007 [Link]Qiang Li; Danny X. Xiao; Kelvin C. P. Wang; Kevin D. Hall; Yanjun Qiu (2011). Mechanistic-empirical pavement design guide (MEPDG): a bird's-eye view. *Journal of Modern Transportation*, *19*(2), 114-133. https://doi.org/10.1007/bf03325749 [Link]Slack, J.R.; Bencala, K.E. (1988). Stochastic hydrology. *Journal of Hydrology*, *103*(3-4), 396. https://doi.org/10.1016/0022-1694(88)90150-3 [Link]Conway, Declan (1996). The Impacts of Climate Variability and Future Climate Change in the Nile Basin on Water Resources in Egypt. *International Journal of Water Resources Development*, *12*(3), 277-296. https://doi.org/10.1080/07900629650178 [Link]McLean, E. O.; Dumford, S. W.; Coronel, F. (1966). A Comparison of Several Methods of Determining Lime Requirements of Soils. *Soil Science Society of America Journal*, *30*(1), 26-30. https://doi.org/10.2136/sssaj1966.03615995003000010015x [Link]Melissa Allen-Dumas; Haowen Xu; Kuldeep Kurte; Deeksha Rastogi (2021). Toward Urban Water Security: Broadening the Use of Machine Learning Methods for Mitigating Urban Water Hazards. *Frontiers in Water*, *2*. https://doi.org/10.3389/frwa.2020.562304 [Link]Mutonhodza, Beaula (2021). Post Cyclone Idai Evaluation of the Integrated Management of Acute Malnutrition (IMAM) Programme for Children under Five in Chimanimani, Zimbabwe. *Journal of Ecology & Natural Resources*, *5*(2). https://doi.org/10.23880/jenr-16000242 [Link]Jeffrey L. Marion (2016). A Review and Synthesis of Recreation Ecology Research Supporting Carrying Capacity and Visitor Use Management Decisionmaking. *Journal of Forestry*, *114*(3), 339-351. https://doi.org/10.5849/jof.15-062 [Link]Freitag, D. R.; Anderson, Duwayne M. (1975). Soil Stabilisation: Principles and Practices. *Soil Science Society of America Journal*, *39*(1). https://doi.org/10.2136/sssaj1975.03615995003900010002x [Link]David Cabana; Lena Rölfer; Prosper Evadzi; Louis Celliers (2023). Enabling Climate Change Adaptation in Coastal Systems: A Systematic Literature Review. *Earth s Future*, *11*(8). https://doi.org/10.1029/2023ef003713 [Link]Alam, I.; Naseer, A.; Shah, A.A. (2015). Economical stabilization of clay for earth buildings construction in rainy and flood prone areas. *Construction and Building Materials*, *77*, 154-159. https://doi.org/10.1016/j.conbuildmat.2014.12.046 [Link]Kalabamu, Faustin T (2000). Land tenure and management reforms in East and Southern Africa – the case of Botswana. *Land Use Policy*, *17*(4), 305-319. https://doi.org/10.1016/s0264-8377(00)00037-5 [Link]Little, Dallas N. (1996). Assessment of in Situ Structural Properties of Lime-Stabilized Clay Subgrades. *Transportation Research Record: Journal of the Transportation Research Board*, *1546*(1), 13-23. https://doi.org/10.1177/0361198196154600102 [Link]Hanemann, Michael; Sayre, Susan Stratton; Dale, Larry (2016). The downside risk of climate change in California's Central Valley agricultural sector. *Climatic Change*, *137*(1-2), 15-27. https://doi.org/10.1007/s10584-016-1651-z [Link]Milly, P. C. D.; Betancourt, Julio; Falkenmark, Malin; Hirsch, Robert M.; Kundzewicz, Zbigniew W.; Lettenmaier, Dennis P.; Stouffer, Ronald J. (2008). Stationarity Is Dead: Whither Water Management?. *Science*, *319*(5863), 573-574. https://doi.org/10.1126/science.1151915 [Link]U.S. Geological Survey (2021). Mineral commodity summaries 2021. https://doi.org/10.3133/mcs2021 [Link]Maljaars, Johan (2020). Evaluation of traffic load models for fatigue verification of European road bridges. *Engineering Structures*, *225*, 111326. https://doi.org/10.1016/j.engstruct.2020.111326 [Link]Linés, Clara; Werner, Micha; Bastiaanssen, Wim (2017). The predictability of reported drought events and impacts in the Ebro Basin using six different remote sensing data sets. *Hydrology and Earth System Sciences*, *21*(9), 4747-4765. https://doi.org/10.5194/hess-21-4747-2017 [Link]Samuel Sandoval-Solís; Daene C. McKinney (2011). Water planning and management for large scale river Basins: Case of study of the rio grande/rio bravo transboundary Basin. *Texas ScholarWorks (Texas Digital Library)*, *11*(2), 1-204. https://repositories.lib.utexas.edu/handle/2152/19742 [Link]Lea Ruesch; Murat Tarakci; Maria Besiou; Niels Van Quaquebeke (2022). Orchestrating coordination among humanitarian organizations. *Production and Operations Management*, *31*(5), 1977-1996. https://doi.org/10.1111/poms.13660 [Link]Ola, Samuel Akinlabi (1982). Geotechnical properties of an attapulgite clay shale in northwestern nigeria. *Engineering Geology*, *19*(1), 1-13. https://doi.org/10.1016/0013-7952(82)90002-3 [Link]Worel, Benjamin J.; Clyne, Timothy R. (2007). Low-Volume Road Performance Related to Traffic Loadings at Minnesota Road Research Project. *Transportation Research Record: Journal of the Transportation Research Board*, *1989-2*(1), 300-305. https://doi.org/10.3141/1989-77 [Link]Nicał, A. K. (2016). Selected Technical Solutions in Construction for Elderly People in Poland. *Archives of Civil Engineering*, *62*(4), 87-98. https://doi.org/10.1515/ace-2015-0099 [Link]Hamir, R.B.; Jones, C.J.F.P.; Clarke, B.G. (2001). Electrically conductive geosynthetics for consolidation and reinforced soil. *Geotextiles and Geomembranes*, *19*(8), 455-482. https://doi.org/10.1016/s0266-1144(01)00021-8 [Link]Sakamoto, Toshihiro; Van Nguyen, Nhan; Kotera, Akihiko; Ohno, Hiroyuki; Ishitsuka, Naoki; Yokozawa, Masayuki (2007). Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. *Remote Sensing of Environment*, *109*(3), 295-313. https://doi.org/10.1016/j.rse.2007.01.011 [Link]NUNN, M E (1998). STRUCTURAL DESIGN OF LONG-LIFE FLEXIBLE ROADS FOR HEAVY TRAFFIC.. *Proceedings of the Institution of Civil Engineers - Transport*, *129*(3), 126-133. https://doi.org/10.1680/itran.1998.30858 [Link]Unknown Author (1999). Map of the Nile Basin. *The Nile*, xii-xii. https://doi.org/10.1515/9781588269911-002 [Link]Kawuki, RS; Adipala, E; Lamo, J; Tukamuhabwa, P (2004). Responding to the soybean rust epidemic in sub-Saharan Africa: A review. *African Crop Science Journal*, *11*(4). https://doi.org/10.4314/acsj.v11i4.27580 [Link]Tanu Priya Uteng; Jeff Turner (2019). Addressing the Linkages between Gender and Transport in Low- and Middle-Income Countries. *Sustainability*, *11*(17), 4555-4555. https://doi.org/10.3390/su11174555 [Link]Kuczera, George (1982). Robust flood frequency models. *Water Resources Research*, *18*(2), 315-324. https://doi.org/10.1029/wr018i002p00315 [Link]Abdulazeez Hudu Wudil; Muhammad Usman; Joanna Rosak-Szyrocka; Ladislav Pilař; Mortala Boye (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). *International Journal of Environmental Research and Public Health*, *19*(22), 14836-14836. https://doi.org/10.3390/ijerph192214836 [Link]Unknown Author (2025). Tanzania Climate and Health Vulnerability Assessment. https://doi.org/10.1596/42731 [Link]Vasyl Kremen (2023). Education in Ukraine defies the war. *European Journal of Education*. https://doi.org/10.1111/ejed.12597 [Link]Peter Meyns (1998). Die "Entwicklungsgemeinschaft des Südlichen Afrika" nach der Apartheid – neue Ziele, alte Probleme. *Verfassung in Recht und Übersee*, *31*(2), 171-195. https://doi.org/10.5771/0506-7286-1998-2-171 [Link]Winfried M. K. Amoaku; Usha Chakravarthy; Richard Gale; M Gavin; Faruque Ghanchi; Jonathan Gibson; Simon Harding; Robert L. Johnston; Simon P. Kelly; Andrew Lotery; Sajjad Mahmood; Geeta Menon; Sobha Sivaprasad; James Talks; Adnan Tufail; Yit C. Yang (2015). Defining response to anti-VEGF therapies in neovascular AMD. *Eye*, *29*(6), 721-731. https://doi.org/10.1038/eye.2015.48 [Link]Unknown Author (1982). 1982 Miracle Yearbook. https://doi.org/10.15385/yb.miracle.1982 [Link]Unknown Author (2012). NBiS 2012 Organizing Committee, xxv-xxix. https://doi.org/10.1109/nbis.2012.158 [Link]Willemijn J. Lodder; Ana Maria de Roda Husman (2020). SARS-CoV-2 in wastewater: potential health risk, but also data source. *The Lancet. Gastroenterology & hepatology*, *5*(6), 533-534. https://doi.org/10.1016/s2468-1253(20)30087-x [Link]Jun Xia; Jin Chen (2020). A new era of flood control strategies from the perspective of managing the 2020 Yangtze River flood. *Science China Earth Sciences*, *64*(1), 1-9. https://doi.org/10.1007/s11430-020-9699-8 [Link]United Nations Economic Commission for Africa (2023). Africa Sustainable Development Report 2023. *Africa Sustainable Development Report*. https://doi.org/10.18356/9789211068092 [Link]

ReferencesMahmood, Abdulrahman; Hassan, Rayya; Fouad, Ali (2019). Effect of Lime, Cement, *and Lime-Cement Stabilisation on Low to Medium Plasticity Clayey Soil. 2019 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), 1-7. https://doi.org/10.1109/csde48274.2019.9162384 [Link]International Monetary Fund. Strategy, Policy, & Review Department; International Monetary Fund. Monetary and Capital Markets Department (2022). Macroeconomic Developments and Prospects in Low-Income Countries - 2022. MF Policy Paper, 2022(054), 1-1. https://doi.org/10.5089/9798400227813.007 [Link]Qiang Li; Danny X. Xiao; Kelvin C. P. Wang; Kevin D. Hall; Yanjun Qiu (2011). Mechanistic-empirical pavement design guide (MEPDG): a bird's-eye view. Journal of Modern Transportation, 19(2), 114-133. https://doi.org/10.1007/bf03325749 [Link]Slack, J.R.; Bencala, K.E. (1988). Stochastic hydrology. Journal of Hydrology, 103(3-4), 396. https://doi.org/10.1016/0022-1694(88)90150-3 [Link]Conway, Declan (1996). The Impacts of Climate Variability and Future Climate Change in the Nile Basin on Water Resources in Egypt. International Journal of Water Resources Development, 12(3), 277-296. https://doi.org/10.1080/07900629650178 [Link]McLean, E. O.; Dumford, S. W.; Coronel, F. (1966). A Comparison of Several Methods of Determining Lime Requirements of Soils. Soil Science Society of America Journal, 30(1), 26-30. https://doi.org/10.2136/sssaj1966.03615995003000010015x [Link]Melissa Allen-Dumas; Haowen Xu; Kuldeep Kurte; Deeksha Rastogi (2021). Toward Urban Water Security: Broadening the Use of Machine Learning Methods for Mitigating Urban Water Hazards. Frontiers in Water, 2. https://doi.org/10.3389/frwa.2020.562304 [Link]Mutonhodza, Beaula (2021). Post Cyclone Idai Evaluation of the Integrated Management of Acute Malnutrition (IMAM) Programme for Children under Five in Chimanimani, Zimbabwe. Journal of Ecology & Natural Resources, 5(2). https://doi.org/10.23880/jenr-16000242 [Link]Jeffrey L. Marion (2016). A Review and Synthesis of Recreation Ecology Research Supporting Carrying Capacity and Visitor Use Management Decisionmaking. Journal of Forestry, 114(3), 339-351. https://doi.org/10.5849/jof.15-062 [Link]Freitag, D. R.; Anderson, Duwayne M. (1975). Soil Stabilisation: Principles and Practices. Soil Science Society of America Journal, 39(1). https://doi.org/10.2136/sssaj1975.03615995003900010002x [Link]David Cabana; Lena Rölfer; Prosper Evadzi; Louis Celliers (2023). Enabling Climate Change Adaptation in Coastal Systems: A Systematic Literature Review. Earth s Future, 11(8). https://doi.org/10.1029/2023ef003713 [Link]Alam, I.; Naseer, A.; Shah, A.A. (2015). Economical stabilization of clay for earth buildings construction in rainy and flood prone areas. Construction and Building Materials, 77, 154-159. https://doi.org/10.1016/j.conbuildmat.2014.12.046 [Link]Kalabamu, Faustin T (2000). Land tenure and management reforms in East and Southern Africa – the case of Botswana. Land Use Policy, 17(4), 305-319. https://doi.org/10.1016/s0264-8377(00)00037-5 [Link]Little, Dallas N. (1996). Assessment of in Situ Structural Properties of Lime-Stabilized Clay Subgrades. Transportation Research Record: Journal of the Transportation Research Board, 1546(1), 13-23. https://doi.org/10.1177/0361198196154600102 [Link]Hanemann, Michael; Sayre, Susan Stratton; Dale, Larry (2016). The downside risk of climate change in California's Central Valley agricultural sector. Climatic Change, 137(1-2), 15-27. https://doi.org/10.1007/s10584-016-1651-z [Link]Milly, P. C. D.; Betancourt, Julio; Falkenmark, Malin; Hirsch, Robert M.; Kundzewicz, Zbigniew W.; Lettenmaier, Dennis P.; Stouffer, Ronald J. (2008). Stationarity Is Dead: Whither Water Management?. Science, 319(5863), 573-574. https://doi.org/10.1126/science.1151915 [Link]U.S. Geological Survey (2021). Mineral commodity summaries 2021. https://doi.org/10.3133/mcs2021 [Link]Maljaars, Johan (2020). Evaluation of traffic load models for fatigue verification of European road bridges. Engineering Structures, 225, 111326. https://doi.org/10.1016/j.engstruct.2020.111326 [Link]Linés, Clara; Werner, Micha; Bastiaanssen, Wim (2017). The predictability of reported drought events and impacts in the Ebro Basin using six different remote sensing data sets. Hydrology and Earth System Sciences, 21(9), 4747-4765. https://doi.org/10.5194/hess-21-4747-2017 [Link]Samuel Sandoval-Solís; Daene C. McKinney (2011). Water planning and management for large scale* *river Basins: Case of study of the rio grande/rio bravo transboundary Basin. Texas ScholarWorks (Texas Digital Library), 11(2), 1-204. https://repositories.lib.utexas.edu/handle/2152/19742 [Link]Lea Ruesch; Murat Tarakci; Maria Besiou; Niels Van Quaquebeke (2022). Orchestrating coordination among humanitarian organizations. Production and Operations Management, 31(5), 1977-1996. https://doi.org/10.1111/poms.13660 [Link]Ola, Samuel Akinlabi (1982). Geotechnical properties of an attapulgite clay shale in northwestern nigeria. Engineering Geology, 19(1), 1-13. https://doi.org/10.1016/0013-7952(82)90002-3 [Link]Worel, Benjamin J.; Clyne, Timothy R. (2007). Low-Volume Road Performance Related to Traffic Loadings at Minnesota Road Research Project. Transportation Research Record: Journal of the Transportation Research Board, 1989-2(1), 300-305. https://doi.org/10.3141/1989-77 [Link]Nicał, A. K. (2016). Selected Technical Solutions in Construction for Elderly People in Poland. Archives of Civil Engineering, 62(4), 87-98. https://doi.org/10.1515/ace-2015-0099 [Link]Hamir, R.B.; Jones, C.J.F.P.; Clarke, B.G. (2001). Electrically conductive geosynthetics for consolidation and reinforced soil. Geotextiles and Geomembranes, 19(8), 455-482. https://doi.org/10.1016/s0266-1144(01)00021-8 [Link]Sakamoto, Toshihiro; Van Nguyen, Nhan; Kotera, Akihiko; Ohno, Hiroyuki; Ishitsuka, Naoki; Yokozawa, Masayuki (2007). Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. Remote Sensing of Environment, 109(3), 295-313. https://doi.org/10.1016/j.rse.2007.01.011 [Link]NUNN, M E (1998). STRUCTURAL DESIGN OF LONG-LIFE FLEXIBLE ROADS FOR HEAVY TRAFFIC.. Proceedings of the Institution of Civil Engineers - Transport, 129(3), 126-133. https://doi.org/10.1680/itran.1998.30858 [Link]Unknown Author (1999). Map of the Nile Basin. The Nile, xii-xii. https://doi.org/10.1515/9781588269911-002 [Link]Kawuki, RS; Adipala, E; Lamo, J; Tukamuhabwa, P (2004). Responding to the soybean rust epidemic in sub-Saharan Africa: A review. African Crop Science Journal, 11(4). https://doi.org/10.4314/acsj.v11i4.27580 [Link]Tanu Priya Uteng; Jeff Turner (2019). Addressing the Linkages between Gender and Transport in Low- and Middle-Income Countries. Sustainability, 11(17), 4555-4555. https://doi.org/10.3390/su11174555 [Link]Kuczera, George (1982). Robust flood frequency models. Water Resources Research, 18(2), 315-324. https://doi.org/10.1029/wr018i002p00315 [Link]Abdulazeez Hudu Wudil; Muhammad Usman; Joanna Rosak-Szyrocka; Ladislav Pilař; Mortala Boye (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). International Journal of Environmental Research and Public Health, 19(22), 14836-14836. https://doi.org/10.3390/ijerph192214836 [Link]Unknown Author (2025). Tanzania Climate and Health Vulnerability Assessment. https://doi.org/10.1596/42731 [Link]Vasyl Kremen (2023). Education in Ukraine defies the war. European Journal of Education. https://doi.org/10.1111/ejed.12597 [Link]Peter Meyns (1998). Die "Entwicklungsgemeinschaft des Südlichen Afrika" nach der Apartheid – neue Ziele, alte Probleme. Verfassung in Recht und Übersee, 31(2), 171-195. https://doi.org/10.5771/0506-7286-1998-2-171 [Link]Winfried M. K. Amoaku; Usha Chakravarthy; Richard Gale; M Gavin; Faruque Ghanchi; Jonathan Gibson; Simon Harding; Robert L. Johnston; Simon P. Kelly; Andrew Lotery; Sajjad Mahmood; Geeta Menon; Sobha Sivaprasad; James Talks; Adnan Tufail; Yit C. Yang (2015). Defining response to anti-VEGF therapies in neovascular AMD. Eye, 29(6), 721-731. https://doi.org/10.1038/eye.2015.48 [Link]Unknown Author (1982). 1982 Miracle Yearbook. https://doi.org/10.15385/yb.miracle.1982 [Link]Unknown Author (2012). NBiS 2012 Organizing Committee, xxv-xxix. https://doi.org/10.1109/nbis.2012.158 [Link]Willemijn J. Lodder; Ana Maria de Roda Husman (2020). SARS-CoV-2 in wastewater: potential health risk, but also data source. The Lancet. Gastroenterology & hepatology, 5(6), 533-534. https://doi.org/10.1016/s2468-1253(20)30087-x [Link]Jun Xia; Jin Chen (2020). A new era of flood control strategies from the perspective of managing the 2020 Yangtze River flood. Science China Earth Sciences, 64(1), 1-9. https://doi.org/10.1007/s11430-020-9699-8 [Link]United Nations Economic Commission for Africa (2023). Africa Sustainable*

Development Report 2023. Africa Sustainable Development Report. *https://doi.org/10.18356/9789211068092 [Link]*