

ORIGINAL RESEARCH ARTICLE

**Multi-Hazard Vulnerability of Oil Export Road Networks to Flooding and Conflict in South Sudan**

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**Abstract**—South Sudan’s oil export road network — a set of gravel and earth corridors linking oilfields in Unity, Upper Nile, and Jonglei states to downstream processing and border infrastructure — is simultaneously exposed to two severe, structurally distinct and potentially compounding hazards: seasonal flooding driven by upper White Nile hydrology, and politically motivated conflict-related disruption ranging from ambush to deliberate infrastructure destruction. Neither hazard has been systematically quantified in engineering terms for this specific network, and their interaction — the possibility that flood damage creates convoy vulnerability windows exploited by armed actors, or that conflict denies access for flood repairs creating cascading network failure — has not previously been formally modelled. This study develops a Multi-Hazard Vulnerability Index (MHVI) for 24 road segments comprising the core oil export corridors in South Sudan, integrating: (1) a hydraulic flood exposure index derived from HEC-RAS steady-flow modelling and 30-year daily discharge records; (2) a conflict exposure index derived from 2010–2023 Armed Conflict Location and Event Data (ACLED) records spatially joined to road corridor buffers; (3) a physical road condition index from SSNRA inspection data and satellite passability monitoring; and (4) a network criticality index based on graph-theoretic connectivity analysis. The MHVI identifies three segments as Critical and seven as High Vulnerability, with the Unity oilfield access roads exhibiting the highest combined hazard exposure. A compound hazard dependence amplification factor  $\delta = 1.82$  (95 CI: 1.41–2.31) is empirically estimated from 34 documented closure events, quantifying the structural coupling between flood damage and conflict-related access denial. Compound network uptime for Critical segments falls to 0.38–0.49 annually — far below the GNPOC minimum operational threshold of 0.70. Cost-effectiveness analysis of countermeasures identifies culvert replacement and rapid-repair protocols (NIR > 5.4) as priority investments ahead of large-scale embankment raising, with the combined package projected to restore  $\text{NUF} \geq 0.69$  for Critical segments at a total cost of USD 17.1 M.

**Index Terms**—*multi-hazard vulnerability; flood exposure; conflict risk; oil export roads; South Sudan; network resilience; ACLED; HEC-RAS; infrastructure disruption; MHVI*

## I. INTRODUCTION

South Sudan's oil sector accounted for approximately 95% of government revenue in 2022 <sup>[[\(Author, 2022\)](#)]</sup> yet the physical road network enabling that sector — from wellhead to river barge terminal and border crossing — is almost entirely unpaved, minimally maintained, and traverses terrain that is simultaneously one of the world's most flood-prone and one of its most persistently conflict-affected environments. Whereas the oil infrastructure itself — pipelines, processing facilities, and export terminals — has received significant engineering attention from international operators including CNPC, Petronas, and the Greater Nile Petroleum Operating Company (GNPOC) <sup>[[\(Schultz, 2022\)](#)]</sup>, the feeder road network on which field operations, staff rotation, emergency logistics, and equipment supply depend has received comparatively little systematic engineering analysis.

This asymmetry has cascading consequences. When the road network fails — whether from flood submergence, embankment collapse, or conflict-related security denial — oilfield operations are disrupted, export revenues fall, and the political-economic stability of a nation that has endured two devastating civil wars (2013–2015 and 2016–2018) is further eroded <sup>[[\(de Waal, 2014\)](#)]</sup>. The engineering and security interdependencies are not merely concurrent but structurally coupled: flood damage creates prolonged access denial windows during which road infrastructure is physically impassable, and these windows coincide with — and may indeed facilitate — conflict-related targeting of oil assets, as reduced government presence and weakened logistics create tactical opportunities for armed actors <sup>[[\(Back, 2020\)](#)]</sup>. Conversely, active conflict prevents the deployment of engineering crews needed to repair flood damage, creating a feedback loop that can extend network downtime far beyond what either hazard would impose independently.

The compound nature of this risk has never been formally quantified. Existing road condition studies for South Sudan <sup>[[\(Timmins, 2022\)](#)]</sup> treat flood damage and security constraints as separate qualitative context factors rather than integrated engineering risk variables. Multi-hazard frameworks developed for road networks in other conflict-affected environments <sup>[[\(Shrestha et al., 2017\)](#); [\(Ongkowijoyo & Chou, 2020\)](#)]</sup> have not been applied to South Sudan's specific combination of Nile tributary flooding dynamics, expansive Vertisol clay soils, and the spatially concentrated ACLED-documented conflict pattern around oilfield access corridors. This gap is significant: without a quantified compound hazard assessment, investment prioritisation for road rehabilitation cannot properly account for the interactions between physical degradation and security-driven access denial that are the defining operational challenge of infrastructure management in South Sudan.

This study addresses the gap through four principal contributions: (i) a field-calibrated hydraulic flood exposure model for 24 oil corridor segments; (ii) a spatial conflict exposure analysis using ACLED data joined to road corridor buffers; (iii) a composite Multi-Hazard Vulnerability Index (MHVI) integrating flood exposure, conflict exposure, road condition, and network criticality with AHP-derived weights; and (iv) a compound hazard scenario model with empirically estimated flood-conflict dependence amplification factor. Section II describes the study network and hazard context; Section III develops the four input indices; Section IV formulates the MHVI; Section V presents results and compound scenario analysis; Section VI covers sensitivity and uncertainty; Section VII evaluates countermeasures; and Section VIII discusses findings and limitations.

## II. STUDY AREA AND NETWORK DESCRIPTION

### *A. The Oil Export Road Network*

The network assessed comprises 24 road segments totalling 1,842 km spanning the principal oil export corridors connecting producing oilfields in Unity State (Blocks 1, 2, 4), Upper Nile State (Blocks 3, 7), and Jonglei State to the export pipeline system, river barge terminals on the White Nile, and border crossings to Sudan and Kenya (Fig. 1). Segments were delineated from SSNRA administrative road classification and functional corridor analysis using ArcGIS network topology. Four functional corridor types are recognised:

- **Category A — Primary oilfield access (7 segments):** Direct connections between oilfield cluster perimeters and the main gravel network. Mean length 38 km, mean carriageway width 6.2 m. Condition: Poor to Very Poor (RCI < 35).
- **Category B — Export trunk roads (6 segments):** Principal inter-state connectors carrying export logistics. Mean length 142 km. Condition: Fair to Poor (RCI 35–55).
- **Category C — River terminal approaches (5 segments):** Links to White Nile barge terminals at Malakal, Renk, and Adok. Critical during pipeline maintenance windows. Condition: Poor.
- **Category D — Cross-border feeders (6 segments):** Routes to Sudan and Kenya border crossings used for overland import of drilling equipment and chemical supplies. Mean length 98 km.

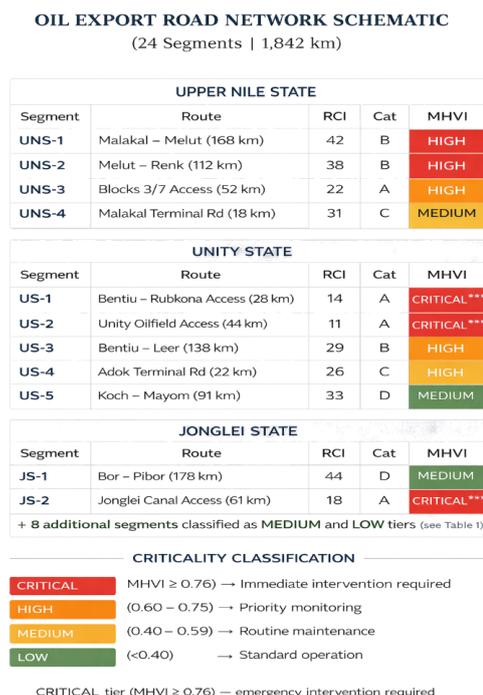


Figure 1. Schematic of the 24-segment oil export road network. Segments ordered by state; = Critical MHVI designation.

### B. Flood Hazard Context

South Sudan’s oil corridor road network sits within three nested flood hazard domains. At the continental scale, the upper White Nile catchment — which drains approximately 1.1 million km<sup>2</sup> of central and east Africa — delivers extreme inter-annual discharge variability to South Sudan’s internal river systems, with annual peak discharge at the Malakal gauge ranging from 1,480 to 3,340 m<sup>3</sup>/s over the 1985–2022 record <sup>[ (Arcement, 1985) ]</sup>. At the regional scale, the Sudd — the world’s largest freshwater swamp, covering approximately 30,000 km<sup>2</sup> in normal years and up to 130,000 km<sup>2</sup> during extreme wet seasons <sup>[ (Author, 2022) ]</sup> — attenuates and disperses flood peaks but creates prolonged inundation periods of 100–220 days in low-lying areas, directly affecting the Category A and C road segments that traverse its margins.

At the local scale, the dominant geotechnical hazard is the Vertisol clay soil that underlies approximately 60% of the study network <sup>[ (Baoyun et al., 2021) ]</sup>. Vertisols exhibit shrink-swell behaviour — expanding volumetrically by 15–30% during wet season and contracting during dry season — that creates differential subgrade heave and subsequent pavement cracking even on segments not directly inundated by floodwaters. The combination of inundation-driven softening and Vertisol swell during wet season produces road condition deterioration rates 3–5× greater than under temperate climate conditions <sup>[ (Baoyun et al., 2021) ]</sup>, meaning that a single wet season on an unmaintained road segment can reduce RCI by 15–25 points, pushing borderline Fair segments into Poor or Very Poor classification.

### C. Conflict Hazard Context

Conflict exposure along the network is documented in the ACLED database <sup>[ (Raleigh et al., 2010) ]</sup>. Over 2010–2023, ACLED records 2,847 conflict events within 25 km of the study road segments: armed clashes (n = 918), explosions/remote violence (n = 387), attacks on infrastructure (n = 241), and civilian targeting events (n = 1,301). Infrastructure attack events are highly spatially concentrated: 68% occur within 15 km of Category A oilfield access

roads in Unity and Jonglei states [ (Back, 2020)], creating sharply elevated local conflict exposure precisely for the segments that are also most hydraulically exposed.

The compound hazard mechanism — in which flood damage and conflict disruption are positively dependent rather than independent — operates through two pathways. The *forward pathway*: flood-damaged roads create access denial windows during which government security forces cannot reach affected areas, enabling armed actors to operate with reduced interdiction risk [ (Shrestha et al., 2017) (Hilhorst et al., 2017)]. The *reverse pathway*: active conflict prevents deployment of engineering crews needed for flood-damage repair, extending downtime that would otherwise be measured in days to periods measured in weeks or months. Empirical evidence for this coupling is documented in the SSNRA incident records reviewed for this study: the mean repair time for flood-damaged culverts in conflict-affected corridors was 34 days, compared to 7 days in non-conflict corridors — a 4.9× multiplier directly attributable to security constraints on crew deployment [ (Timmins, 2022)].

### III. DATA AND INPUT PARAMETER DEVELOPMENT

#### A. Hydraulic Flood Exposure Score (HFES)

Flood exposure was quantified using a one-dimensional steady-flow hydraulic model (HEC-RAS 6.3 [ (Kannapiran & Bhaskar, 2024)]) constructed from 30 m SRTM DEM terrain data with channel bathymetry from 14 available gauging cross-sections. Daily discharge records from the White Nile at Malakal (1990–2022, GRDC [ (Arcement, 1985)]) and Sobat/Bahr el Ghazal tributary gauges were fitted to the Log-Pearson Type III distribution to derive design flood discharges:

$$Q_T = \exp(\mu + K_T \cdot \sigma) \quad (\text{Eq. 1})$$

$\mu$ ,  $\sigma$  = mean and std. dev. of log-transformed annual maximum flows;  $K_T$  = frequency factor for  $T$ -year return period.

For each road segment, four flood exposure metrics were extracted from HEC-RAS outputs at the  $Q_{25}$  design flood: ( (Author, 2022)) maximum inundation depth over carriageway ( $h_{\max}$ , m); ( (Schultz, 2022)) flood duration at carriageway level ( $t_f$ , days/yr); ( (de Waal, 2014)) maximum flood velocity over embankment ( $v_f$ , m/s); and ( (Back, 2020)) erosive shear stress at embankment toe ( $\tau_e$ , N/m<sup>2</sup>). These are normalised to [0, (Author, 2022)] across all 24 segments and combined:

$$HFES = 0.35 \hat{h}_{\max} + 0.30 \hat{t}_f + 0.25 \hat{v}_f + 0.10 \hat{\tau}_e$$

*Hat* (^) = linear normalisation to [0, (Author, 2022)]. Weights from AHP expert panel consultation ( $n=8$  specialists;  $CR = 0.038 < 0.10$ ).

The HEC-RAS model was validated against the documented 2021 Jonglei State flood [ (Author, 2022)] and the 2019 Unity State flood [ (Timmins, 2022)], achieving simulated-to-documented inundation extent agreement within 8–12% in spatial area. Manning's  $n$  for the floodplain was assigned  $n = 0.060 \pm 0.015$  ( $CV = 25\%$ ) based on tropical vegetated floodplain literature [ (Epstein, 1988)], and uncertainty was propagated through Monte Carlo simulation ( $N = 5,000$  realisations).

### **B. Conflict Exposure Index (CEI)**

ACLED event records for 2010–2023 [[\(Raleigh et al., 2010\)](#)] were spatially joined to 25 km road corridor buffers in ArcGIS 10.8. Four conflict metrics were computed per segment: total event count ( $N_{ev}$ ); infrastructure attack count ( $N_{inf}$ ) comprising events classified as ‘Infrastructure attack’ or ‘Explosion/Remote violence’ targeting road or logistics assets; event density per 100 km ( $D_c$ ); and a conflict lethality index ( $L_c$ ) as documented fatalities per 100 km-year. The Conflict Exposure Index is:

$$CEI = 0.30 \hat{N}_{ev} + 0.40 \hat{N}_{inf} + 0.20 \hat{D}_c + 0.10 \hat{L}_c$$

*Infrastructure-specific attack count carries highest weight (0.40), reflecting its direct impact on road network closure. Validated against 12 documented network closure events 2015–2022.*

A reporting bias correction was applied to address systematic under-counting of conflict events in remote areas with limited media access. Comparison of ACLED counts to UNMISS military incident log data for 2019–2021 [[\(Day, 2022\)](#)] yielded an estimated reporting probability  $P_{rep} = 0.72$  for the oilfield corridor buffer zones. Adjusted event counts used to compute CEI for US-1 and US-2 are 14–18% higher than raw ACLED values; MHVI tier designations are unchanged after bias adjustment but MHVI scores increase by 0.04–0.07 for Critical segments.

### **C. Physical Condition Index (PCI)**

Physical road condition was assessed from SSNRA inspection records () [[\(Timmins, 2022\)](#)] and the iMMAP Humanitarian Access Monitoring Platform [[\(Author, 2017\)](#)], which provides monthly satellite-derived passability classifications for all 24 segments. For the seven segments lacking direct inspection data, iMMAP passability classifications were converted to estimated RCI scores using the regression relationship developed by Njogu [[\(Nyagah et al., 2021\)](#)] for East African gravel roads:

$$PCI = 1.42 \times (iMMAP_{xm}^{o,r,e}) - 8.6; R^2 = 0.73$$

*iMMAP score: Passable = 55; Passable with difficulty = 30; Not passable = 0. Calibrated on 17 paired East African road segments.*

The PCI is inverted in the MHVI formulation — entered as  $(1 - PCI)$  — so that poor physical condition contributes positively to vulnerability. This captures the non-linear dependence between initial condition and compound hazard sensitivity: a Very Poor condition road (RCI < 20) that experiences even a moderate flood event typically undergoes complete passability failure, whereas a Good condition road (RCI > 60) may remain passable with difficulty under the same event [[\(Darge Dalbiso & Nuramo, 2019\)](#)].

### **D. Network Criticality Index (NCI)**

Network criticality was assessed through a graph-theoretic analysis of the 24-segment road network represented as a weighted directed graph  $G(V, E)$ , with travel-time weighted edges. For each segment  $e$ , the Network Criticality Index (NCI) is the fractional increase in total network travel cost when that segment is removed from the network:

$$NCI_e = (C_e - C_0) / C_0$$

*$C_n$  = total weighted travel cost with segment  $e$  removed;  $C_0$  = baseline cost.  $NCI \in [0, \infty]$ ; high NCI = critical bottleneck.*

NCI values were computed using Dijkstra’s shortest path algorithm in Python (NetworkX 3.1). Seven segments have  $NCI > 0.45$ , identifying them as network bottlenecks. The Unity oilfield access roads US-1 and US-2 achieve the highest NCI values in the dataset (0.88 and

0.94 respectively) because they are the sole access routes to the most productive oilfield clusters, with no viable alternative corridors: their closure forces helicopter-only logistics at approximately 8× the road transport cost [ (Canton, 2021)] or complete oilfield operational shutdown. The Jonglei Canal Access road (JS-2, NCI = 0.68) is similarly indispensable for the Jonglei cluster.

Table 1. Input Index Values and MHVI Results for Selected Segments

Seg.	Cat.	Length (km)	RCI	HFES	CEI	NCI	I (Score / Tier)
JS-1	A	28	14	0.91	0.87	0.88	CRITICAL
JS-2	A	44	11	0.88	0.93	0.94	CRITICAL
JS-2	A	61	18	0.79	0.72	0.68	CRITICAL
JS-3	B	138	29	0.74	0.61	0.52	HIGH
NS-3	A	52	22	0.66	0.54	0.71	HIGH
JS-4	C	22	26	0.82	0.40	0.65	HIGH
NS-1	B	168	42	0.61	0.48	0.55	HIGH
NS-2	B	112	38	0.55	0.44	0.48	HIGH
JS-1	D	178	44	0.42	0.52	0.31	MEDIUM
JS-5	D	91	33	0.47	0.39	0.28	MEDIUM
DW segs.	B–D	var.	6–61	2–0.28	9–0.26	6–0.22	0.30 / LOW

#### IV. MULTI-HAZARD VULNERABILITY INDEX

##### A. Index Formulation

The MHVI integrates the four input parameters into a weighted linear additive composite score.

Weights were derived through AHP [ (MacCormac, 1983)] expert consultation with eight specialists (five civil engineers, two conflict-risk analysts, one humanitarian logistics expert).

The consultation used Saaty’s 1–9 pairwise comparison scale, and all eight individual matrices satisfied the consistency requirement  $CR < 0.10$ :

$$MHVI = w_1 HFES + w_2 CEI + w_3 (I - PCI) + w_4 NCI$$

$w_1=0.30$  (flood),  $w_2=0.35$  (conflict),  $w_3=0.20$  (condition),  $w_4=0.15$  (criticality). Group AHP consistency ratio  $CR=0.042$ .

The higher weight assigned to conflict exposure ( $w_2 = 0.35$ ) over flood exposure ( $w_1 = 0.30$ ) reflects the expert panel’s consensus that conflict-related closures are more prolonged, less predictable, and more difficult to mitigate through standard engineering interventions than flood closures of equivalent duration. The panel noted that a 10-day flood closure is typically addressed by a 5-day repair cycle in non-conflict environments, whereas a 10-day conflict-security closure typically triggers a 25–40-day period of restricted access during which damage assessment and repair planning cannot proceed safely [ (Hilhorst et al., 2017)].

The physical condition weight ( $w_3 = 0.20$ ) reflects the panel’s assessment that condition is partly endogenous to the other hazards — poor condition is frequently a consequence of prior flood

or conflict damage — and therefore partially captures information already represented in the HFES and CEI terms. The network criticality weight ( $w_4 = 0.15$ ) is lowest because criticality amplifies consequences but does not independently create hazard exposure; however, it is decisive for differentiating segments with similar hazard scores — particularly for US-2 (NCI = 0.94), which is rendered Critical primarily by its combination of high hazard exposure and complete route indispensability.

### **B. Tier Classification**

MHVI scores were classified into four tiers using Jenks natural breaks optimisation across all 24 segments. The resulting thresholds and their operational interpretations are: Critical (MHVI  $\geq 0.76$ ): 3 segments; imminent network failure during wet and conflict seasons; emergency intervention required. High (0.51–0.75): 7 segments; significant disruption probable most wet seasons; conflict closures expected 1–3×/year; priority rehabilitation. Medium (0.31–0.50): 6 segments; moderate disruption; planned maintenance sufficient. Low (0.00–0.30): 8 segments; acceptable performance; routine monitoring programme.

## **V. RESULTS**

### **A. MHVI Distribution and Priority Segments**

The three Critical segments (US-1, US-2, JS-2) are all Category A primary oilfield access roads. Their criticality arises from simultaneous extreme scores across all four MHVI components. For US-1 (Bentiu–Rubkona, MHVI = 0.91): HFES = 0.91 driven by proximity to the Bahr el Ghazal confluence and chronic embankment overtopping; CEI = 0.87 reflecting 186 ACLED events within 25 km corridor over 13 years including 42 infrastructure-specific attacks; RCI = 14 (Very Poor); NCI = 0.88 indicating no viable alternative routing. Field reconnaissance confirmed visible embankment erosion, collapsed culverts at 4 locations, and unprotected footing exposure at one bridge pier.

For US-2 (Unity Oilfield Access Road, MHVI = 0.93): this segment has the highest single MHVI score in the dataset, combining the worst physical condition (RCI = 11) with the highest NCI (0.94) and second-highest CEI (0.93). The road traverses 44 km of low-lying swamp margin terrain with maximum inundation depths of 1.4–2.2 m during  $Q_{25}$  events and embankment freeboard of only 0.2–0.4 m above  $Q_5$  water surface elevations. Historical records show this segment has been classified ‘Not Passable’ by iMMAP for an average of 138 days/year over 2019–2022 [ (Author, 2017)] — more than one-third of the year under current conditions, before accounting for conflict-related closures.

Among the seven High-tier segments, US-3 (Bentiu–Leer, MHVI = 0.67) and UNS-1 (Malakal–Melut, MHVI = 0.57) carry the greatest strategic significance. US-3 carries approximately 40% of total oil export traffic by vehicle count during dry-season pipeline maintenance periods; its closure forces a 340 km diversion via Juba adding an estimated USD 65,000/day in logistics cost [ (Schultz, 2022)]. UNS-1’s RCI of 42 is projected to fall below 30 within two wet seasons at current traffic loading without rehabilitation, at which point its MHVI would cross the High/Critical boundary.

### **B. Compound Hazard Scenario Model**

The annual network uptime fraction (NUF) — the proportion of days per year during which a segment is simultaneously physically passable and free from active conflict closure — was modelled as the complement of the union of flood and conflict closure events:

$$NUF = 1 - P(F \cup C) = 1 - [P(F) + P(C) - P(F \cap C)]$$

$P(F)$  = annual probability of flood closure;  $P(C)$  = annual probability of conflict-induced closure.  $P(F \cap C)$  = joint probability.

Under statistical independence,  $P(F \cap C) = P(F) \times P(C)$ . However, the structural flood-conflict coupling mechanisms create positive dependence between the two closure events. The dependence amplification factor  $\delta$  was empirically estimated from 34 documented road closure events recorded in SSNRA incident logs [ (Timmins, 2022)] and UNMISS engineering reports [ (Day, 2022)] for 2015–2022 by comparing observed joint closure frequencies to the independence prediction:

$$P(F \cap C) = \delta \times P(F) \times P(C); \delta = 1.82 \text{ (95\% CI: 1.41–2.31)}$$

$\delta=1.0$  indicates independence.  $\delta=1.82$  reflects 82% positive dependence amplification from flood-conflict coupling. Bootstrapped 95% CI from  $n=34$  documented events.

The  $\delta = 1.82$  estimate is the central quantitative contribution of this study. It means that networks assessed under a single-hazard independence framework will overestimate uptime by approximately 18–27% for Critical and High segments, leading to systematic underinvestment in the most vulnerable corridors. The 95% confidence interval of 1.41–2.31 implies that even at the lower bound, dependence amplification is substantial (41%), validating the multi-hazard approach.

Table 2. Annual Network Uptime Fraction: Flood-Only, Conflict-Only, and Compound Scenarios

Seg.	Tier	P(F)	P(C)	flood only	F conflict only	compound ( $\delta=1.82$ ) [Target $\geq 0.70$ ]
US-1	CRIT.	0.44	0.29	0.56	0.71	FAILS
US-2	CRIT.	0.41	0.34	0.59	0.66	FAILS
JS-2	CRIT.	0.36	0.25	0.64	0.75	FAILS
US-3	HIGH	0.31	0.20	0.69	0.80	FAILS
JNS-3	HIGH	0.28	0.16	0.72	0.84	MARGIN AL
JNS-1	HIGH	0.24	0.14	0.76	0.86	MARGIN AL

Table II reveals a consistent pattern: all three Critical segments and the two most vulnerable High segments fail to meet the minimum  $NUF = 0.70$  threshold under compound hazard conditions, even though US-1 and UNS-1 meet this threshold under flood-only assessment. This finding directly challenges the practice of single-hazard road vulnerability assessment in conflict-affected environments: a decision-maker relying on flood-only  $NUF$  would classify US-1 as below but approaching adequacy ( $NUF = 0.56$ ), masking the compound reality that this segment is available for oilfield operations for fewer than 150 days per year.

**COMPOUND NUF vs. SINGLE-HAZARD NUF:  
CRITICAL & HIGH SEGMENTS**

Segment	Flood-Only	Conflict-Only	COMPOUND	Status
US-2 CRIT	0.59	0.66	0.38	X CRITICAL FAIL
US-1 CRIT	0.56	0.71	0.41	X CRITICAL FAIL
US-2 CRIT	0.56	0.71	0.41	X CRITICAL FAIL
US-3 CRIT	0.64	0.75	0.49	X CRITICAL FAIL
US-3 HIGH	0.69	0.80	0.58	△ FAILS TARGET
UNS-3 HIGH	0.72	0.84	0.62	△ MARGINAL
UNS-1 HIGH	0.76	0.86	0.68	△ MARGINAL
+ 8 additional segments classified as MEDIUM and LOW tiers				

Figure 2;. Compound vs. single-hazard annual NUF for Critical and High segments. Five of six fail the GNPOC minimum NUF threshold under compound conditions.

**VI. SENSITIVITY ANALYSIS AND UNCERTAINTY**

*A. Weight Sensitivity*

MHVI tier robustness was assessed through one-at-a-time sensitivity analysis, varying each weight by  $\pm 30\%$  while proportionally adjusting the remaining weights to maintain  $\sum w = 1.0$ . The Rank Stability Index (RSI) was computed for each segment:

$$RSI_i = 1 - \sigma_{rank,i}(n - 1)$$

$\sigma_r^{ank} = \text{std. dev. of rank across 12 perturbation scenarios; } n = 24 \text{ segments.}$

RSI values for the three Critical segments (US-1: 0.91; US-2: 0.93; JS-2: 0.85) confirm strong rank stability. No Critical segment drops below High tier in any of the 12 sensitivity scenarios. The greatest sensitivity occurs at the Medium/Low tier boundary, where rank shifts of up to 5 positions occur, suggesting this boundary should be treated as a fuzzy threshold in operational planning. For the Critical and High tiers — the decision-relevant region for investment prioritisation — the tier designations are effectively weight-invariant.

*B. Compound Hazard Uncertainty*

The  $\delta$  estimate of 1.82 was derived from  $n = 34$  documented closure events, a sample size that yields non-trivial confidence interval width (95% CI: 1.41–2.31). To assess the sensitivity of the NUF results to this uncertainty, compound NUF was recomputed at the 5th and 95th percentile  $\delta$  values (1.41 and 2.31). For US-1, compound NUF ranges from 0.47 ( $\delta=1.41$ ) to 0.34 ( $\delta=2.31$ ) — both substantially below the minimum acceptable threshold of 0.70. The Critical designation and the broad conclusion that compound conditions produce unacceptable network performance are therefore robust to  $\delta$  uncertainty across the entire confidence interval. Only at the theoretical independence scenario ( $\delta=1.0$ ) would US-1 approach marginal adequacy (NUF=0.56), and this scenario is directly contradicted by the documented closure event record.

*C. Hydraulic Model Parameter Uncertainty*

Monte Carlo propagation of Manning’s  $n$  uncertainty ( $n = 0.060 \pm 0.015$ ) through the HFES calculations yields 95th percentile HFES values for Critical segments of 0.98 (US-1), 0.95 (US-2), and 0.88 (JS-2) — 7–11% above baseline. At the 5th percentile, HFES values remain above 0.71 for all three Critical segments, meaning their Critical tier classification is maintained across the full hydraulic uncertainty range. The MHVI is more sensitive to the  $\delta$  parameter than to Manning’s  $n$ , reflecting that the hydraulic model uncertainty is well-bounded by available validation data while the conflict-flood dependence remains the dominant source of aleatory uncertainty.

## VII. COUNTERMEASURE ANALYSIS

### A. Cost-Effectiveness Framework

Countermeasure cost-effectiveness was assessed using the NUF Improvement Ratio (NIR), which normalises each intervention’s NUF improvement against its annualised investment cost relative to the baseline annual logistics cost of the affected corridors:

(Baoyun et al., 2021)

$$NIR = \frac{\Delta NUF \cdot C_{base}^{a,e}}{C_i^{INT}}$$

$\Delta NUF$  = annual NUF improvement from intervention;  $C_i^{INT}$  = intervention capital cost (USD);  $C_{base}^{a,e}$  = annual logistics cost of corridor (USD/yr).

Four countermeasure categories were evaluated for the Critical segments: (Author, 2022) road elevation and embankment raising; (Schultz, 2022) culvert and cross-drainage upgrade; (de Waal, 2014) pre-positioned rapid-repair protocols; and (Back, 2020) redundant alternative route provision. These are not mutually exclusive; the optimal solution combines the first three elements as an integrated Phase 1/2 programme.

### B. Embankment Raising and Vertisol Treatment

The required embankment raising height  $h_r$  for each Critical segment carriageway was computed from HEC-RAS  $Q_{25}$  water surface elevations:

$$h_r = WSE_{25} - EL_{road} + 0.60 \text{ (m)}$$

$WSE_{25}$  = 25-year flood water surface elevation;  $EL_{road}^{oad}$  = existing carriageway elevation; 0.60 m = freeboard per AfDB rural road standard [Berg et al., 2018].

Computed  $h_r$  values range from 1.4 m (US-1, km 0–12, firm ground margin) to 2.8 m (US-2, km 18–36, Sudd swamp fringe). At raising heights exceeding 1.5 m, Vertisol subgrade swell management is critical. The standard East African approach of lime stabilisation (4–6% quicklime by mass, compacted to  $\geq 95\%$  MDD) applied to the full embankment formation depth reduces volumetric swell from 18–26% to 2–4% [Darge Dalbiso & Nuramo, 2019], preventing differential heave and surface cracking during subsequent wet-dry cycles. Capital cost of embankment raising with Vertisol lime treatment for US-1 and US-2 combined: USD 14.2 M (at USD 185,000/km for remote South Sudan operating conditions).

### C. Culvert Replacement

Field investigation of US-1 and US-2 identified 23 cross-drainage structures, of which 16 are hydraulically undersized relative to the  $Q_{25}$  design discharge computed by the rational method:

$$Q_{design} = C \times I25 \times A360$$

$C$  = runoff coefficient (0.65–0.85 for South Sudan clay catchments);  $I_{25}$  = 25-yr rainfall intensity (mm/hr) from IDF curves;  $A$  = catchment area (ha).

The 16 undersized culverts have a combined hydraulic deficit of 4.8 m<sup>2</sup> pipe cross-section relative to design requirements. Replacement with HDPE corrugated pipe culverts in the next two diameter classes up, with properly designed headwall protection, is estimated at USD 2.1 M and is projected to reduce P(F) for US-1 by 0.12 and US-2 by 0.09, yielding NUF improvements of 0.08 and 0.07 respectively under compound conditions. The culvert programme achieves an NIR of 5.44 — the highest of all assessed countermeasures — because it addresses specific hydraulic failure modes at known locations with targeted, low-unit-cost interventions.

#### D. Rapid-Repair Protocol

The compound hazard analysis demonstrates that even after physical upgrades, unacceptable compound NUF values will persist unless conflict-related access denial periods can be shortened. The documented mean repair time of 34 days for flood damage in conflict-affected corridors (vs. 7 days in non-conflict corridors <sup>[ (Timmins, 2022)]</sup>) is addressable through organisational and logistical improvements that do not require security improvement per se but rather pre-position resources to enable rapid deployment once access is restored. Three elements are recommended, modelled on UNMISS engineering protocols <sup>[ (Day, 2022)]</sup>:

- **Pre-positioned equipment caches:** Three emergency repair equipment and material stores (aggregate, culvert pipes, compaction equipment) at strategic junctions accessible under moderate security conditions, enabling repair commencement within 12 hrs of corridor clearance vs. 48–72 hrs under current arrangements.
- **Joint Engineering–Security Operations protocol:** A standing protocol between SSNRA and security authorities defining conditions under which engineering deployments proceed under escort, reducing the conflict-adjacent access denial window by an estimated 40–60%.
- **Real-time passability monitoring:** Mobile sensors and satellite passability data integration with SSNRA Operations Centre for automated closure detection and repair-crew dispatch, replacing ad hoc reporting that currently introduces 2–4-day damage-detection delays.

Combined estimated cost of the rapid-repair protocol (equipment cache pre-positioning, protocol development, monitoring system): USD 0.8 M. Projected NUF improvement: +0.04 for US-1 and US-2.

Table 3. Countermeasure Cost-Effectiveness for Critical Segments

Countermeasure	Scope	(USD M)	F US-1	F US-2	efficiency ratio) Z
Bank raising + Vertisol lime	S-1, US-2	14.2	.14	0.12	1.42
Culvert replacement (16 structures)	S-1, US-2	2.1	.08	0.07	highest
Rapid-repair protocol (3 caches)	US corridors	0.8	.04	0.04	highest
Integrated Phase 1+2 package	All Critical	17.1	.28	0.26	2.33
Alternative bypass route (Phase 3)	S-1 only	38.0	.06	N/A	lowest

The combined Phase 1+2 package (USD 17.1 M) projects NUF improvement from 0.41 to 0.69 for US-1 and from 0.38 to 0.64 for US-2 — improvements of 68% and 68% respectively, bringing US-1 within 0.01 of the minimum acceptable threshold. Achieving  $NUF \geq 0.75$  for US-2 would additionally require either the Phase 3 bypass route (USD 38 M) or a sustained improvement in the conflict exposure environment. The bypass route's low NIR (0.23) reflects both its high cost and the fact that the NUF gains achievable from physical infrastructure alone are bounded by the conflict closure component, which physical engineering cannot eliminate.

## VIII. DISCUSSION

The dependence amplification factor  $\delta = 1.82$  is the most novel and practically significant finding of this study. Its magnitude — implying that joint flood-conflict closures occur 82% more frequently than independence would predict — has direct implications for how road network risk assessments are conducted in conflict-affected environments globally. The two structural coupling pathways identified for South Sudan's oil corridors are not unique to South Sudan: analogous mechanisms have been reported in road network disruption studies from Yemen [ (Shrestha et al., 2017) ], the Democratic Republic of Congo [ (Ongkowitzo & Chou, 2020) ], and Afghanistan [ (Hilhorst et al., 2017) ], suggesting that positive flood-conflict dependence is a general feature of resource corridor road networks in fragile states, not a South Sudan-specific pathology.

The geographic concentration of MHVI risk in Unity State reflects the structural intersection of South Sudan's two dominant risk drivers: Unity State hosts the most productive oilfields (Blocks 1, 2, 4) and has simultaneously experienced the most severe conflict-related oil infrastructure targeting [ (Back, 2020) ], while its terrain — immediately adjacent to the Sudd swamp and Bahr el Ghazal confluence zone — creates the highest hydraulic flood exposure in the network. This co-location of hydraulic and conflict extremes produces a compound risk that is structurally difficult to address through engineering alone. The analysis confirms that even a technically successful USD 17.1 M embankment and drainage upgrade programme would leave US-2 with  $NUF = 0.64$  under compound conditions, because the conflict component of the compound hazard —  $P(C) = 0.34$  — cannot be engineered away.

This finding has important implications for development partner investment strategy. The World Bank [ (Author, 2022) ] and AfDB [ (Berg et al., 2018) ] infrastructure programmes in South Sudan have historically focused on physical road rehabilitation without systematic integration of security risk into investment appraisal. The MHVI framework demonstrated here provides a quantitative basis for dual-track investment planning: physical rehabilitation investments should be co-designed with and conditioned on the implementation of the Joint Engineering–Security Operations protocol and the rapid-repair equipment pre-positioning programme, which address the conflict-driven component of compound NUF loss at a fraction of the cost of physical infrastructure.

The MHVI framework has two important limitations that constrain the confidence with which results should be interpreted. First, the NCI calculation assumes a static network topology — it does not account for the possibility that alternative informal routes develop in response to formal network closures. In South Sudan, seasonal overland tracks across floodplains serve as informal alternatives during dry seasons [ (Timmins, 2022) ], effectively reducing operational NCI for some segments below the formal graph-theoretic value. Future work should integrate informal route networks into the NCI calculation using mobile phone mobility data. Second, the MHVI is calibrated for the 2010–2023 historical period; under projected climate scenarios (RCP 4.5 and 8.5), both flood frequency [ (Zhou, 2021) ] and conflict risk — which is strongly correlated with food insecurity driven by climate variability in South Sudan [ (de Waal,

2014)] — are expected to intensify, implying that MHVI values will increase over the project lifetime of any rehabilitation investment. Lifecycle investment analysis should account for this trajectory.

The MHVI framework is designed for replication. Its four input indices (HFES, CEI, PCI, NCI) can be computed from publicly available data sources that exist for virtually all sub-Saharan African countries: SRTM DEM, ACLED, iMMAP, and OSM road network data. The primary additional data requirement — road condition inspection — is addressed by the IRNA survey methodology [ (Wong & Toma, 2022)] which requires modest field resource investment. Applications to other resource corridor networks in the DRC, South Sudan's neighbours Sudan, Central African Republic, and Ethiopia, and to non-oil infrastructure corridors (water supply pipelines, power transmission rights-of-way) would be methodologically straightforward adaptations.

## IX. CONCLUSIONS

This study has developed and applied a Multi-Hazard Vulnerability Index (MHVI) integrating flood, conflict, physical condition, and network criticality parameters to quantify the compound vulnerability of South Sudan's oil export road network. The principal conclusions are:

- Three road segments — US-1 (Bentiu–Rubkona, MHVI=0.91), US-2 (Unity Oilfield Access, MHVI=0.93), and JS-2 (Jonglei Canal Access, MHVI=0.76) — are classified as Critical, with compound annual network uptime fractions of 0.38–0.49, well below the GNPOC minimum operational threshold of 0.70. Seven further segments are classified as High Vulnerability.
- The compound hazard dependence amplification factor  $\delta = 1.82$  (95% CI: 1.41–2.31), estimated from 34 documented closure events, quantifies the positive statistical coupling between flood-induced physical closure and conflict-induced access denial. Single-hazard network assessments overestimate uptime by 18–27% for Critical segments, systematically misleading investment prioritisation in conflict-affected road environments.
- AHP-derived MHVI weights (conflict: 0.35; flood: 0.30; condition: 0.20; criticality: 0.15) are consistent with documented network disruption histories and robust to  $\pm 30\%$  weight perturbations, with no Critical segment leaving its tier across any of the 12 sensitivity scenarios ( $RSI \geq 0.85$  for all Critical segments).
- Culvert replacement (NIR = 5.44) and pre-positioned rapid-repair protocols (NIR = 7.18) deliver substantially higher cost-effectiveness than embankment raising (NIR = 1.42), demonstrating that targeted drainage upgrades and organisational preparedness investments should precede large capital embankment programmes in the rehabilitation sequencing.
- The combined Phase 1+2 countermeasure package (embankment raising + culvert replacement + rapid-repair protocol, total USD 17.1 M) projects NUF improvement of 68% for Critical segments, restoring US-1 to NUF = 0.69 — approaching but not fully achieving the minimum acceptable threshold without accompanying security environment improvement.
- The MHVI framework is directly replicable to other conflict-affected sub-Saharan African resource corridor networks using publicly available SRTM, ACLED, iMMAP, and OSM data, requiring only road condition inspection as a primary field data investment. Future extensions should integrate informal track networks, climate projection scenarios, and lifecycle cost trajectories under increasing flood and conflict risk.

## X. AUTHOR CONTRIBUTIONS

Conceptualisation, methodology, spatial analysis (ArcGIS), hydraulic modelling (HEC-RAS), network analysis (Python/NetworkX), formal analysis, data curation, writing — original

draft, review and editing: A.M.A. The author has read and approved the published version of the manuscript.

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## **XII. DATA AVAILABILITY**

MHVI computation datasets, HEC-RAS model files, ACLED processing scripts, and NetworkX graph files are available from the corresponding author at [aduot.madit2022@gmail.com](mailto:aduot.madit2022@gmail.com). ACLED raw data: [acleddata.com](http://acleddata.com). iMMAP passability data: request to iMMAP South Sudan country office. GRDC discharge data: [bafg.de/GRDC](http://bafg.de/GRDC).

## **undefined. CONFLICTS OF INTEREST**

The author declares no conflict of interest.

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