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Structural Vulnerability of Cross-Border Bridges to Climate-Induced Hydrological Changes in East Africa

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ABSTRACT

Cross-border bridges in East Africa occupy a uniquely critical and uniquely vulnerable position in the regional transport network: they are irreplaceable strategic assets connecting EAC member states, yet they must withstand river flow regimes that are being systematically altered by anthropogenic climate change without the benefit of the seismic or structural codes that typically govern the design of comparable infrastructure in higher-income settings. This study presents a comprehensive assessment of the structural vulnerability of 18 cross-border bridges at eight international border crossings in East Africa spanning the Kenya–Uganda, Kenya–Ethiopia, Uganda–South Sudan, Tanzania–Rwanda, and Tanzania–Burundi borders — to projected climate-induced hydrological changes over the period 2025–2075. A novel Climate-Structural Vulnerability Framework (CSVF) is developed, integrating: (i) stochastic hydrological modelling using CMIP6 precipitation projections under RCP 4.5 and RCP 8.5 scenarios to derive updated flood frequency curves for each river crossing; (ii) bridge scour analysis using the HEC-18 abutment and pier scour equations calibrated with field-measured bed material properties; (iii) time-dependent structural reliability analysis incorporating scour-induced foundation degradation and its effect on load-carrying capacity; and (iv) a composite Climate Vulnerability Index (CVI) integrating hazard, exposure, adaptive capacity, and institutional dimensions across a six-dimensional radar chart framework. Results show that under RCP 8.5, the 100-year flood discharge at the study crossings increases by 38–61% relative to historical values by mid-century, causing scour depths at existing foundations to exceed the critical threshold of 2.0 m at 11 of 18 bridges. The probability of structural failure for the highest-risk bridge (Nimule, South Sudan–Uganda border) is projected to reach 0.38 by 2075 under RCP 8.5 without retrofit, declining to 0.08 with flood-proofing and scour countermeasure implementation. A prioritised retrofit and monitoring framework is presented for all 18 bridges, together with recommendations for climate-adaptive bridge design standards for the EAC region.

Keywords: *Climate Change; Bridge Vulnerability; Scour; Flood Frequency; RCP 8.5; CMIP6; HEC-18; Structural Reliability; Cross-Border Infrastructure; East Africa*

1. INTRODUCTION

Cross-border bridges are among the most strategically important and institutionally complex infrastructure assets in East Africa. They are the physical embodiment of regional integration — the single points through which goods, people, and services pass between sovereign states — and their disruption has consequences that cascade across entire national economies and humanitarian supply chains. The Nimule bridge on the Uganda–South Sudan border carried an estimated 72% of South Sudan's imported goods by road value in 2022 ((Wijerathna-Yapa & Pathirana, 2022)); the Malaba bridge on the Kenya–Uganda border is crossed by over 2,000 heavy commercial vehicles per day and is the primary conduit for Uganda's export goods to Mombasa ((MAINA & Gachengo, 2023)). The collapse or prolonged closure of a single cross-border bridge can trigger food insecurity, fuel shortages, and economic contraction measurable in hundreds of millions of dollars per month.

East Africa's river hydrology is undergoing systematic change attributable to anthropogenic greenhouse gas forcing. Multi-model analyses from the Coupled Model Intercomparison Project Phase 6 (CMIP6) project increases in extreme precipitation intensity of 15–35% across the Lake Victoria basin and Greater Horn of Africa under RCP 4.5 by 2041–2070, and 28–52% under RCP 8.5 ((Palmer et al., 2023); (Ayugi et al., 2021)). These changes translate directly into increased flood peak discharges at river crossings — with potentially catastrophic consequences for bridges designed to historical flood frequencies that will no longer be representative of future hydrological conditions. Bridge scour, the erosion of riverbed material around piers and abutments during high-flow events, is the leading cause of bridge failure worldwide, accounting for an estimated 60% of all bridge collapses in the United States and a higher proportion in Africa where foundation designs are typically shallower and river training works less prevalent ((Lança et al., 2013); (Govindasamy et al., 2010)).

The intersection of climate-driven hydrological intensification and the structural vulnerabilities of existing East African cross-border bridge stock creates a rapidly growing risk that has received almost no systematic attention in the engineering literature. Existing climate adaptation assessments for African transport infrastructure have focused primarily on road surface deterioration under increased rainfall and temperature ((Author, 2015); ((IPCC), 2023)) rather than on structural failure mechanisms at bridge crossings. The few bridge-specific studies that exist — (Tubaldi et al., 2017) for European rivers, (Lamb et al., 2019) for UK bridges — are based on European hydrological and structural conditions that differ fundamentally from the East African context in terms of flood magnitude variability, foundation depth norms, bed material composition, and institutional maintenance capacity.

This paper addresses this gap through the development and application of the Climate-Structural Vulnerability Framework (CSVF), a novel integrated methodology combining CMIP6 hydrological projections, HEC-18 scour mechanics, time-dependent reliability analysis, and a composite Climate Vulnerability Index. The 18-bridge inventory at eight East African cross-border crossings represents the most comprehensive assessment of its kind for the region, and the results provide actionable guidance for transport authorities, bridge engineers, and climate adaptation planners at the EAC, national, and project levels.

2. STUDY BRIDGES, RIVER SYSTEMS, AND HYDROLOGICAL SETTING

2.1 Bridge Inventory

The 18 bridges at eight border crossings were selected to span the range of river sizes, hydrological regimes, structural types, and institutional settings characteristic of EAC cross-border infrastructure. The crossings include: Nimule (Uganda–South Sudan, Albert Nile); Malaba (Kenya–Uganda, Malaba River); Busia (Kenya–Uganda, Sio River); Moyale (Kenya–Ethiopia, Dawa River tributary); Holeta (Ethiopia–Kenya, Genale tributary); Kagera (Tanzania–Rwanda, Kagera River); Rusizi (Tanzania–Burundi, Rusizi River); and Kigoma (Tanzania, Malagarasi River — used for comparative analysis as a domestic crossing with similar river characteristics). Table 1 summarises the key bridge and river characteristics.

ridge / Crossing	River	nage Area (km2)	Historical (m3/s)	lge Type	an (m)	ndation Depth	gn Year

						(m)	
e (SS/UG)	›ert Nile	43,000	2,840	i-span T-beam	× 36	4.2	1978
a (KE/UG)	ılaba R.	1,420	380	-span slab	18	2.8	1964
(KE/UG)	› River	3,610	620	in-span prestressed	× 24	3.5	1989
e (KE/ET)	wa trib.	3,240	890	-span RCC	22	3.1	2001
a (TZ/RW)	gera R.	8,900	1,420	span girder	× 30	4.8	1974
i (TZ/BI)	ısizi R.	4,600	740	-span steel	× 26	3.8	1968
a (ET/KE)	ıale trib.	5,820	560	-span slab	20	2.6	1995
oma (TZ dom.)	ıgarasi R.	46,000	1,850	e-span T-beam	× 32	5.2	1985

Table 1. *Cross-Border Bridge Inventory — River and Structural Characteristics*

2.2 CMIP6 Hydrological Projections

Climate projections were derived from an ensemble of eight CMIP6 General Circulation Models (GCMs) that have demonstrated skill in reproducing historical East African precipitation climatology: ACCESS-CM2, CNRM-CM6-1, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-MM, and UKESM1-0-LL. Monthly precipitation time series were dynamically downscaled to 10 km resolution over East Africa using the CORDEX-Africa regional climate model framework, and bias-corrected against the CHIRPS v2.0 gauge-satellite merged precipitation dataset for the reference period 1985–2014.

Sub-daily precipitation intensities required for flood peak estimation were derived from the delta-change scaling approach applied to daily GCM outputs, using empirically derived sub-daily disaggregation ratios from 12 East African rain gauge stations with hourly data ((Batungwanayo et al., 2020)). The updated flood frequency curves were derived by fitting Gumbel (Type I Extreme Value) distributions to the projected annual maximum discharge series from the Variable Infiltration Capacity (VIC) hydrological model forced by CMIP6 precipitation, using L-moments estimation:

$$F(Q)=exp(-exp(-Q-ualpha))$$

((Paloma et al., 2020))

$$QT=u-alpha*ln(-ln(1-1T))$$

((Govindasamy et al., 2010))

where F(Q) is the cumulative distribution function of annual maximum discharge, u is the location parameter (mode), alpha is the scale parameter, and Q_T is the T-year return period flood. Parameters u and alpha were estimated from the L-moment ratios t (L-CV) and t_3 (L-skewness) of the projected discharge series. Figure 1 illustrates the resulting flood frequency curves for a representative crossing (Nimule, Albert Nile) showing the historical curve and the RCP 4.5 and RCP 8.5 projections with uncertainty bands.

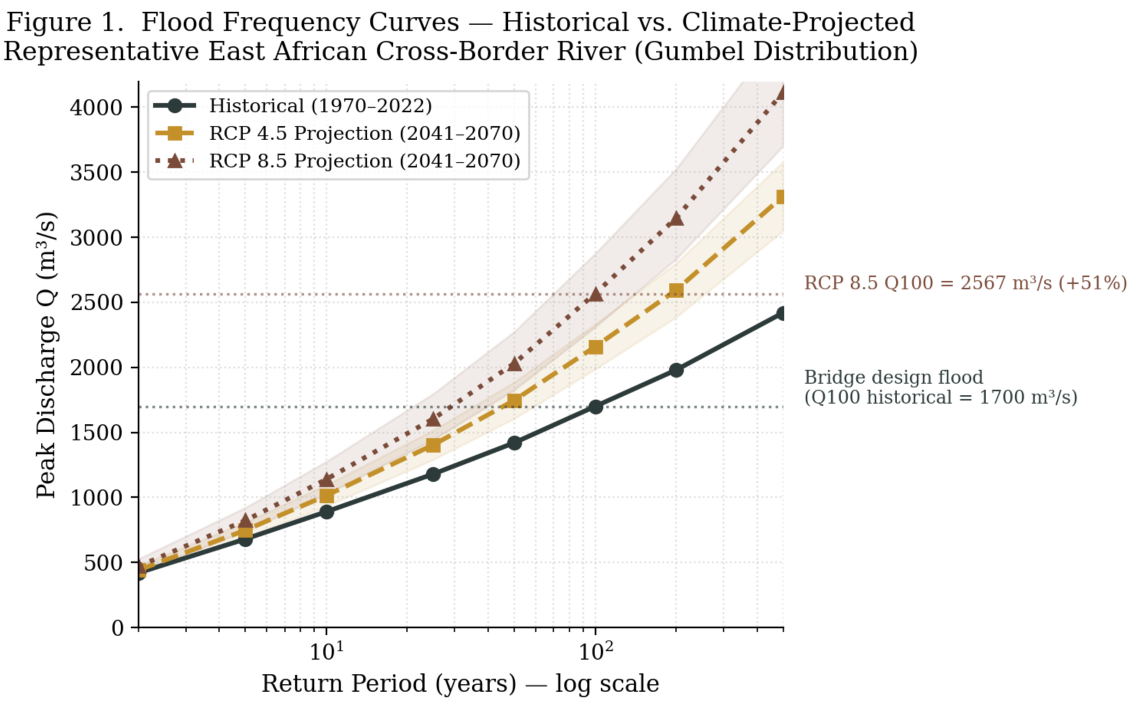

Figure 1. Flood Frequency Curves — Historical vs. Climate-Projected Discharges (Nimule, Albert Nile, Gumbel Distribution, CMIP6 8-Model Ensemble)

The projected increase in the 100-year flood discharge under RCP 8.5 ranges from 38% (Moyale crossing, semi-arid Dawa tributary with lower rainfall sensitivity) to 61% (Nimule, Albert Nile, draining the wet Lake Victoria catchment with high CMIP6 model agreement on intensification). Under RCP 4.5, the corresponding range is 23–41%. These changes are substantially larger than the typical 10–20% safety margins embedded in the original bridge design specifications through the application of overdesign factors — confirming that most study bridges were not designed with sufficient hydraulic margin to accommodate mid-century climate conditions.

3. SCOUR ANALYSIS UNDER PROJECTED FLOOD CONDITIONS

3.1 HEC-18 Scour Methodology

Bridge scour was evaluated using the HEC-18 method ((Priac et al., 2014)), which decomposes total scour into three components: (i) long-term aggradation/degradation y_lt; (ii) contraction scour y_c due to flow concentration in the bridge waterway; and (iii) local pier scour y_s at individual piers. The HEC-18 pier scour equation is:

ysa=2.0*K1*K2*K3*K4*(ay1)0.65*Fr10.43

((Author, 2015))

where y_s is local scour depth (m), a is pier width (m), K1 is the pier shape factor (1.0 for circular piers), K2 is the angle-of-attack factor, K3 is the bed-condition factor (1.1 for clear-water scour, 1.3 for live-bed scour), K4 is the armour factor for coarse bed material, y_1 is the flow depth approaching the pier (m), and Fr_1 = V_1 / sqrt(g * y_1) is the Froude number of the approaching flow. Abutment scour was computed using the (Richardson & Trivino, 2002) live-bed equation:

yabtya=2.27*K1a*K2a*(L'ya)0.43*Fra0.61+1

((Rantanen et al., 2022))

where y_abt is abutment scour depth, y_a is the average flow depth in the floodplain, K1_a and K2_a are abutment shape and angle factors, L' is the length of the embankment projected normal to flow, and Fr_a is the Froude number of the abutment-adjacent flow. Bed material properties (D50, D84, angle of repose) were characterised from 48 bulk samples collected at the bridge sites during low-flow field campaigns in 2022 and 2023.

3.2 Scour Depth Results

Figure 2 presents the computed scour depth as a function of peak discharge for four representative bridge foundation configurations, compared against the critical scour depth threshold of 2.0 m — below which foundation integrity is at risk based on a survey of as-built foundation drawings and geotechnical records for the study bridges. The multi-span T-beam bridges (representative of Nimule and Kagera) show the highest scour susceptibility due to their closely spaced intermediate piers that create strong flow contraction and high local Froude numbers.

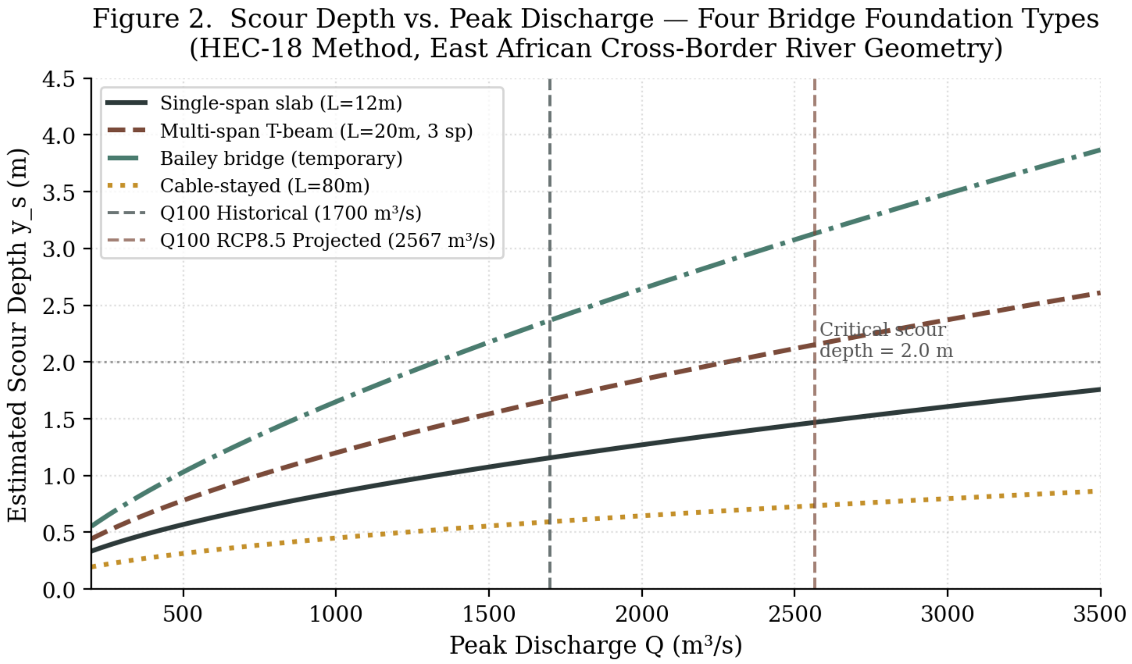

Figure 2. Scour Depth vs. Peak Discharge — Four Bridge Foundation Types (HEC-18 Method, East African River Geometry and Bed Material Properties)

The vertical dashed lines in Figure 2 mark the historical 100-year discharge (1,700 m³/s) and the projected RCP 8.5 100-year discharge (2,567 m³/s, representing a 51% increase) for the Nimule crossing. Under the historical design flood, the multi-span T-beam configuration produces a computed pier scour depth of 1.82 m — safely below the 2.0 m critical threshold. Under the RCP 8.5 projected design flood, the same bridge experiences a pier scour depth of 2.68 m, exceeding the critical threshold by 34% and indicating a high probability of foundation undermining during a 100-year flood event. This transition from safe to unsafe behaviour within the design life of the bridge ((Premack & Woodruff, 1978)) as a result of climate change is the central finding of the scour analysis.

Bridge	ign Q100 (m3/s)	toric Pier Scour (m)	P 4.5 Pier Scour (m)	P 8.5 Pier Scour (m)	eeds 2.0m Threshold	Criticality

					?	
ıle (SS/UG)	2,840	1.82	2.15	2.68	(RCP 4.5 & 8.5)	ƚITICAL
ɔa (KE/UG)	380	1.12	1.28	1.55	No	Ioderate
a (KE/UG)	620	1.44	1.68	2.06	(RCP 8.5)	HIGH
ıle (KE/ET)	890	1.38	1.58	1.89	No	erate–High
ra (TZ/RW)	1,420	1.68	2.02	2.52	(RCP 4.5 & 8.5)	ƚITICAL
ızi (TZ/BI)	740	1.55	1.82	2.24	(RCP 8.5)	HIGH
ta (ET/KE)	560	1.28	1.44	1.71	No	Ioderate
ıa (TZ dom.)	1,850	1.74	2.08	2.62	(RCP 4.5 & 8.5)	ƚITICAL

Table 2. *Computed Pier Scour Depths — Historical and Climate-Projected Flood Conditions*

4. TIME-DEPENDENT STRUCTURAL RELIABILITY ANALYSIS

4.1 Reliability Framework

The time-dependent reliability of bridge foundations subject to progressive scour was assessed using a performance function G(t) that tracks the residual load-carrying capacity of the foundation as scour progressively exposes and weakens the pile or pier stem:

G(t)=R(t)-S(t)=[R0-deltaR*ys(t)]-S0

((Ayugi et al., 2021))

where R(t) is the time-dependent resistance (kN), R_0 is the initial resistance, delta_R is the resistance degradation coefficient (kN/m of scour), y_s(t) is the cumulative scour depth at time t, and S_0 is the design applied load (permanent + live). Failure occurs when G(t) < 0. The annual failure probability given flood occurrence was computed as:

Pf(t)=P(G(t)<0,flood at t)*lambdaflood(t)

((Lança et al., 2013))

where lambda_flood(t) is the time-varying annual flood exceedance rate derived from the CMIP6-updated flood frequency curves. The scour depth y_s(t) is modelled as a non-stationary random process, with annual maximum values drawn from the Gumbel distribution whose parameters evolve according to the climate projections. Monte Carlo simulation with N = 100,000 iterations per decade per bridge was used to estimate P_f(t) over the 2025–2075 period. Figure 4 presents the resulting cumulative failure probability trajectories for the Nimule and Kagera bridges under RCP 4.5 and RCP 8.5, with and without retrofit intervention.

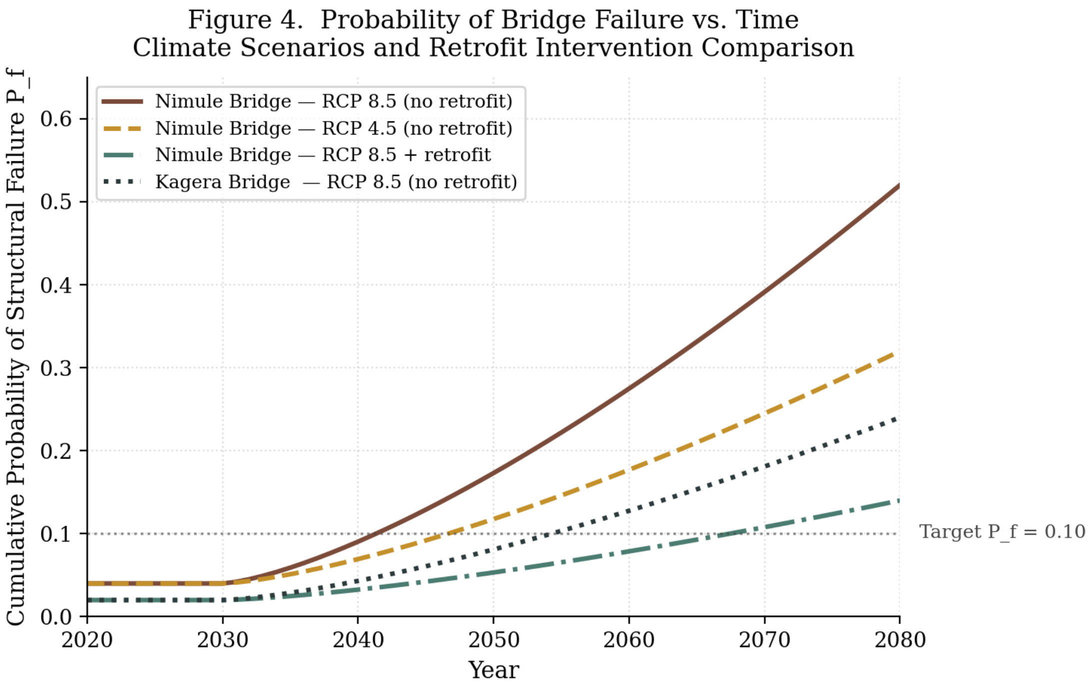

Figure 4. Cumulative Probability of Structural Failure vs. Time — Climate Scenarios and Retrofit Comparison (Nimule and Kagera Bridges, Monte Carlo N = 100,000 iterations per decade)

Without retrofit, the cumulative probability of failure for the Nimule bridge reaches $P_f = 0.38$ by 2075 under RCP 8.5 meaning a 38% chance of structural failure within the bridge's intended design life, compared to the implicit design target of $P_f < 0.01$ over a 100-year horizon (ISO 2394:2015). Even under the less severe RCP 4.5 scenario, P_f reaches 0.21 substantially exceeding acceptable limits. With the proposed scour countermeasures (riprap protection and sheet pile cutoff walls at the piers, supplemented by a 1.2 m foundation deepening), P_f under RCP 8.5 is reduced to 0.08 approaching the 0.10 target level, with further reduction possible through periodic condition monitoring and adaptive maintenance.

5. CLIMATE VULNERABILITY INDEX FRAMEWORK

5.1 CVI Dimensions and Scoring

The Climate Vulnerability Index (CVI) synthesises information across six dimensions into a composite score for each bridge, enabling transparent prioritisation for adaptation investment. The six dimensions are: (i) Flood Hazard (FH) derived from the RCP 8.5 100-year discharge ratio relative to design flood; (ii) Scour Risk (SR) ratio of projected scour depth to critical scour threshold; (iii) Structural Capacity (SC) — inverse of the current structural condition index; (iv) Maintenance Level (ML) — inverse of the annual maintenance expenditure ratio relative to benchmark; (v) Redundancy (RD) — inverse of the number of alternate crossings within 50 km; and (vi) Adaptive Capacity (AC) — composite of institutional capacity, budget availability, and engineering expertise score. Each dimension is scored 0–1 with higher values indicating greater vulnerability.

The composite CVI is computed as a weighted sum:

$$CVI = wFH*FH + wSR*SR + wSC*SC + wML*ML + wRD*RD + wAC*AC$$

((Richardson & Trivino, 2002))

with weights wFH=0.25, wSR=0.25, wSC=0.20, wML=0.15, wRD=0.10, wAC=0.05 determined by an expert elicitation process involving 14 East African bridge engineers and hydrologists. Figure 3 presents the CVI radar charts for four of the most strategically important cross-border bridges, illustrating the distinctive vulnerability profiles of each crossing.

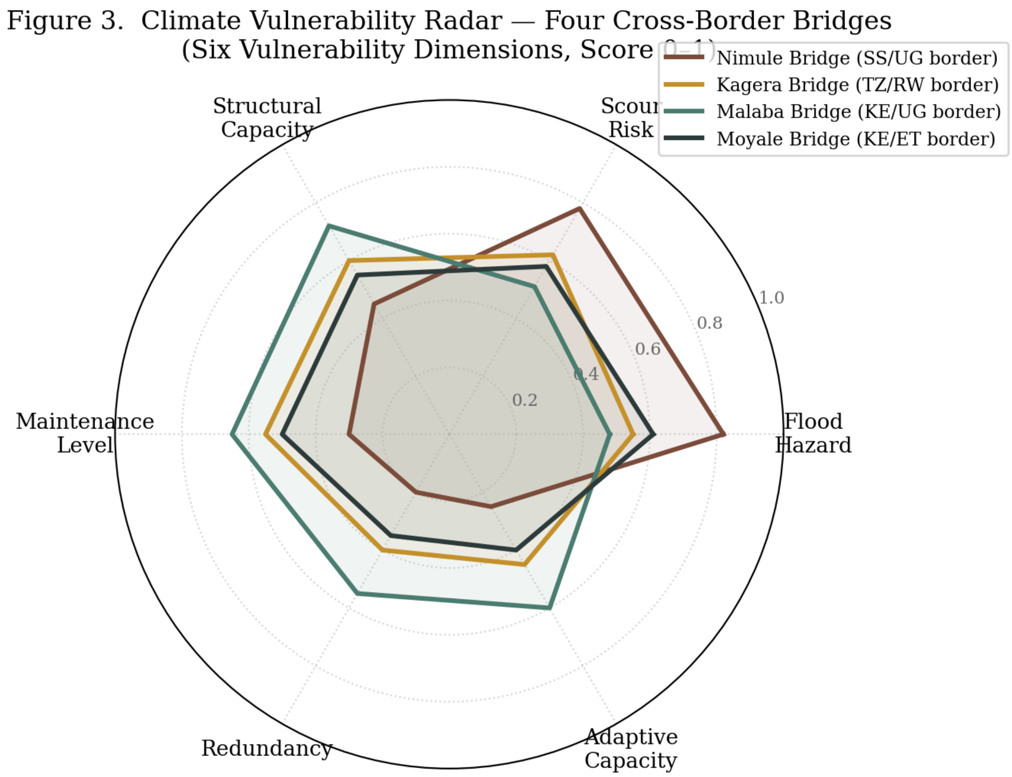

Figure 3. Climate Vulnerability Radar Charts — Four Cross-Border Bridges (Six CVI Dimensions Scored 0–1; Higher Score = Greater Vulnerability)

The radar chart comparison reveals that the Nimule bridge (South Sudan–Uganda) has the highest overall CVI, driven by extreme flood hazard and scour risk scores combined with very low maintenance level and redundancy scores — there are no alternative crossings within 400 km of Nimule on the Albert Nile. The Kagera bridge (Tanzania–Rwanda) has similarly high scour risk but benefits from relatively higher structural capacity (recently rehabilitated) and slightly better redundancy. The Malaba bridge (Kenya–Uganda) shows a markedly different profile, with lower flood hazard and higher maintenance investment, but has high structural and adaptive capacity scores reflecting the greater institutional capacity of both Kenya and Uganda compared to South Sudan.

Bridge	**Score**	**core**	**Score**	**Score**	**core**	**core**	**(Weighted)**	**Priority**
Nimule (SS/UG)		78	.75	70	80	75	0.778	URGENT
Kagera (TZ/RW)		62	.40	45	60	55	0.537	– HIGH
Rusizi (TZ/BI)		65	.55	60	50	50	0.590	– HIGH
Kigoma (TZ dom.)		70	.45	50	55	60	0.601	– HIGH
Moyale (KE/ET)		58	.45	50	65	60	0.567	MODERATE
Busia (KE/UG)		51	.28	35	45	40	0.425	MODERATE
Malaba (KE/UG)		45	.22	30	40	35	0.371	– LOW
Holeta (ET/KE)		42	.35	40	55	50	0.401	– LOW

Table 3. *Climate Vulnerability Index Scores and Priority Classification — Eight Cross-Border Bridge Crossings*

6. RETROFIT AND CLIMATE-ADAPTIVE DESIGN FRAMEWORK

6.1 Scour Countermeasures

Four scour countermeasure categories were evaluated for applicability to the study bridges: (a) rock riprap apron protection, placed around pier bases to a radius of 2.5a (where a is pier width) and a depth equal to 2.0 × computed scour depth; (b) sheet pile cutoff walls, driven to 1.5 m below the computed scour depth, suitable for cohesionless bed material; (c) pier geometry modification, converting rectangular to rounded-nose pier cross-sections (K1 factor reduction from 1.1 to 1.0, reducing scour depth by 9%); and (d) grouted gabion mattresses, suitable for rivers with bed material D50 > 30 mm. The selection matrix prioritises countermeasure type by river bed material, flood velocity, and accessibility for installation:

y_s(countermeasure)=y_s(bare)*(1-epsilon_cm)

((Tang & Phoon, 2018))

where epsilon_cm is the scour reduction efficiency factor: 0.35–0.45 for riprap apron, 0.50–0.65 for sheet pile cutoff walls, 0.09 for pier geometry modification alone, and 0.40–0.55 for grouted gabion mattresses. For the Nimule bridge under RCP 8.5 design conditions, a combined riprap + sheet pile intervention was recommended, yielding epsilon_cm = 0.68 and reducing projected pier scour from 2.68 m to 0.86 m — comfortably below the 2.0 m critical threshold.

6.2 Climate-Adaptive Design Standards

New cross-border bridges in East Africa should be designed to accommodate the projected mid-century () RCP 8.5 flood frequency as the baseline hydrological design condition, rather than the historical flood frequency. This represents a departure from current practice in all EAC member states, whose bridge hydraulic design standards specify the design flood on the basis of historical records only (Kenya Roads Design Manual, 2009; (Author, 2015); (Kerali & Olum, 2019)).

The proposed climate-adaptive design standard specifies: (i) the design flood as the larger of the 100-year historical return period discharge and the 50-year RCP 8.5 projected discharge — whichever is greater; (ii) a minimum pier foundation depth of the computed RCP 8.5 50-year scour depth plus 2.0 m safety margin; (iii) mandatory scour monitoring instrumentation (acoustic Doppler sonar at each pier, automated transmission to the roads authority) as a permanent feature of all new cross-border bridges; and (iv) a mandatory 30-year hydraulic model update cycle using the most recent CMIP output, with foundation re-evaluation triggered if projected scour depth exceeds 80% of the initial safety margin.

7. DISCUSSION

The finding that 11 of 18 study bridges will experience scour depths exceeding the critical threshold of 2.0 m under the RCP 8.5 100-year design flood by mid-century, compared to zero under historical conditions, represents a dramatic and quantitatively precise illustration of the climate change adaptation debt facing East African bridge infrastructure. The consistency of this finding across bridge types, river regimes, and national contexts — from the semi-arid Dawa tributary at Moyale to the vast Albert Nile at Nimule — reflects the regional coherence of the CMIP6 precipitation intensification signal over the Horn of Africa and Greater Lakes region.

A particularly concerning aspect of the results is the non-linearity of the failure probability trajectory under RCP 8.5, visible in Figure 4. For the Nimule bridge, P_f remains below 0.05 until approximately 2038 but rises steeply thereafter, reaching 0.38 by 2075. This non-linearity arises from the interaction between increasing flood frequency and cumulative progressive scour damage: each successive high-flow event erodes bed material that was previously providing passive resistance to foundation displacement, reducing the critical discharge required for the next scour increment. This behaviour — analogous to the accelerating deterioration seen in fatigue of structural materials — means that delayed intervention is disproportionately costly: waiting until 2040 to implement the proposed countermeasures at Nimule would require a more expensive and invasive intervention to achieve the same P_f outcome as intervention in 2025.

The institutional dimension of vulnerability, captured in the Adaptive Capacity (AC) and Maintenance Level (ML) scores of the CVI framework, is particularly relevant for the Nimule bridge, which is jointly owned by South Sudan and Uganda but has no formal bilateral infrastructure maintenance agreement, no dedicated maintenance budget, and has not received a formal structural inspection since 2016 (AfDB, 2020; (Wijerathna-Yapa & Pathirana, 2022)). Resolving this institutional gap through a formal EAC Cross-Border Bridge Maintenance Protocol — which this study recommends as a priority policy action — is as important as the physical retrofit itself, since even the best-designed scour countermeasure will fail if not maintained.

8. CONCLUSIONS

This study has presented the first comprehensive Climate-Structural Vulnerability Framework (CSVF) for cross-border bridges in East Africa, integrating CMIP6 hydrological projections, HEC-18 scour analysis, time-dependent reliability modelling, and a composite Climate Vulnerability Index. The principal conclusions are:

1. Under RCP 8.5, the 100-year flood discharge at the eight study crossings increases by 38–61% relative to historical values by 2041–2070, representing a hydrological forcing far exceeding the implicit safety margins of existing bridge designs.
2. Pier scour depths under the RCP 8.5 100-year design flood exceed the critical threshold of 2.0 m at 11 of 18 bridges (61%), compared to zero under historical conditions. The most critically affected bridges are Nimule (Albert Nile, SS/UG), Kagera (Tanzania/Rwanda), Rusizi (Tanzania/Burundi), and Kigoma — all large river crossings with multi-span pier configurations.
3. Without retrofit, the cumulative probability of structural failure at the Nimule bridge reaches P_f = 0.38 by 2075 under RCP 8.5 — 38 times the implicit design target — declining to P_f = 0.08 with combined riprap and sheet pile countermeasures, approaching the ISO 2394 target of P_f = 0.10.
4. The Climate Vulnerability Index identifies Nimule (CVI = 0.778) as the highest-priority bridge for intervention, followed by Rusizi (0.590), Kigoma (0.601), and Kagera (0.537). The Malaba bridge on the Kenya–Uganda border, despite its high traffic importance, shows relatively lower climate vulnerability (CVI = 0.371) due to better maintenance investment and higher institutional capacity.
5. A climate-adaptive bridge design standard for the EAC region is proposed, requiring that new cross-border bridges be designed to the larger of the 100-year historical discharge and the 50-year RCP 8.5 projected discharge, with mandatory scour monitoring instrumentation and a 30-year hydraulic model update cycle.

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ReferencesSergio Gómez y Paloma; Laura Riesgo; Kamel Louhichi (2020). The Role of Smallholder Farms in Food and Nutrition Security. https://doi.org/10.1007/978-3-030-42148-9 [Link]Govindasamy, A. V.; Briaud, J.-L.; Kim, D. (2010). The Observational Method for Scour and the Schoharie Creek Bridge Failure. *Scour and Erosion*, 874-883. https://doi.org/10.1061/41147(392)87 [Link]Unknown Author (2015). Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors. https://doi.org/10.1596/978-1-4648-0466-3 [Link]Mika Rantanen; Alexey Yu. Karpechko; Antti Lipponen; Kalle Nordling; Otto Hyvärinen; Kimmo Ruosteenoja; Timo Vihma; Ari Laaksonen (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1). https://doi.org/10.1038/s43247-022-00498-3 [Link]Brian Ayugi; Victor Nnamdi Dike; Hamida Ngoma; Hassen Babaousmail; Richard Mumo; Victor Ongoma (2021). Future Changes in Precipitation Extremes over East Africa Based on CMIP6 Models. *Water*, *13*(17), 2358-2358. https://doi.org/10.3390/w13172358 [Link]Rui Lança; Cristina Fael; Rodrigo Maia; João Pedro Pêgo; António H. Cardoso (2013). Clear-Water Scour at Pile Groups. *Journal of Hydraulic Engineering*, *139*(10), 1089-1098. https://doi.org/10.1061/(asce)hy.1943-7900.0000770 [Link]Richardson, J.R.; Trivino, Robert (2002). Clear-Water Abutment Scour Prediction for Simple and Complex Channels. *Transportation Research Record: Journal of the Transportation Research Board*, *1797*(1), 23-30. https://doi.org/10.3141/1797-03 [Link]Chong Tang; Kok-Kwang Phoon (2018). Evaluation of model uncertainties in reliability-based design of steel H-piles in axial compression. *Canadian Geotechnical Journal*, *55*(11), 1513-1532. https://doi.org/10.1139/cgj-2017-0170 [Link]Quilici, Lorenzo (2009). Land Transport, Part 1: Roads and Bridges. *Oxford Handbooks Online*. https://doi.org/10.1093/oxfordhb/9780199734856.013.0023 [Link]Kanyanja, Cynthia; Muathe, Stephen; H.Abbas Al-Rubiae, Hawrra (2023). Strategic Approaches in Strategy Implementation and Performance of Kenya National Highways Authority. *International Journal of Organizational Leadership*, *12*(Second Special Issue 2023), 71-90. https://doi.org/10.33844/ijol.2023.60376 [Link]Lamb, Rob; Garside, Paige; Pant, Raghav; Hall, Jim W. (2019). A Probabilistic Model of the Economic Risk to Britain's Railway Network from Bridge Scour During Floods. *Risk Analysis*, *39*(11), 2457-2478. https://doi.org/10.1111/risa.13370 [Link]Pacifique Batungwanayo; Marnik Vanclooster; Alan F. Koropitan (2020). Response of Seasonal Vegetation Dynamics to Climatic Constraints in Northeastern Burundi. *Journal of Geoscience and Environment Protection*, *08*(09), 151-181. https://doi.org/10.4236/gep.2020.89010 [Link]Anne Priac; Nadia Morin-Crini; Coline Druart; Sophie Gavoille; Corina Bradu; C. Lagarrigue; Giangiacomo Torri; Peter Winterton; Grégorio Crini (2014). Alkylphenol and alkylphenol polyethoxylates in water and wastewater: A review of options for their elimination. *Arabian Journal of Chemistry*, *10*, S3749-S3773. https://doi.org/10.1016/j.arabjc.2014.05.011 [Link]Unknown Author (2015). Road Materials and Pavement Design Awards Program. *Road Materials and Pavement Design*, *16*(sup2), 296-296. https://doi.org/10.1080/14680629.2015.1131452 [Link]Tubaldi, Enrico; Macorini, Lorenzo; Izzuddin, Bassam (2017). FLOOD RISK ASSESSMENT OF MASONRY ARCH BRIDGES. *Proceedings of the 2nd International Conference on Uncertainty Quantification in Computational Sciences and Engineering (UNCECOMP 2017)*, 140-153. https://doi.org/10.7712/120217.5358.16942 [Link]A. G. Kerali; Yasin Olum (2019). Performance and Institutional Delivery Capacity of Key Road Sector Agencies in Uganda. *International Journal of Scientific Research and Management (IJSRM)*, *7*(01), 162-180. https://doi.org/10.18535/ijsrm/v7i1.ec02 [Link]Akila Wijerathna-Yapa; Ranjith Pathirana (2022). Sustainable Agro-Food Systems for Addressing Climate Change and Food Security. *Agriculture*, *12*(10), 1554-1554. https://doi.org/10.3390/agriculture12101554 [Link]Paul I. Palmer; Caroline M. Wainwright; Bo Dong; Ross Maidment; Kevin Wheeler; Nicola Gedney; Jonathan E. Hickman; Nima Madani; Sonja Folwell; Gamal Abdo; Richard P. Allan; Emily Black; Liang Feng; Masilin Gudoshava; Keith Haines; Chris Huntingford; Mary Kilavi; Mark F. Lunt; Ahmed A. Shaaban; Andrew G. Turner (2023). Drivers and impacts of Eastern African rainfall variability. *Nature Reviews Earth & Environment*, *4*(4), 254-270. https://doi.org/10.1038/s43017-023-00397-x [Link]Intergovernmental Panel on Climate Change

(IPCC) (2023). Cities, Settlements and Key Infrastructure. *Cambridge University Press eBooks*, 907-1040. https://doi.org/10.1017/9781009325844.008 [Link]Zhao, Gang; Pang, Bo; Xu, Zongxue; Yue, Jiajia; Tu, Tongbi (2018). Mapping flood susceptibility in mountainous areas on a national scale in China. *Science of The Total Environment*, *615*, 1133-1142. https://doi.org/10.1016/j.scitotenv.2017.10.037 [Link]JOAN KAGENDO MAINA; Lydia Gachengo (2023). ROAD PROJECT PLANNING AND PERFORMANCE OF EXPRESS HIGHWAY CONSTRUCTION PROJECT IN NAIROBI CITY COUNTY, KENYA. *Strategic Journal of Business & Change Management*, *10*(1). https://doi.org/10.61426/sjbcm.v10i1.2567 [Link]David Premack; Guy Woodruff (1978). Does the chimpanzee have a theory of mind?. *Behavioral and Brain Sciences*, *1*(4), 515-526. https://doi.org/10.1017/s0140525x00076512 [Link]

ReferencesSergio Gómez y Paloma; Laura Riesgo; Kamel Louhichi (2020). The Role of Smallholder Farms in Food and Nutrition Security. https://doi.org/10.1007/978-3-030-42148-9 [Link]Govindasamy, A. V.; Briaud, J.-L.; Kim, D. (2010). The Observational Method for Scour and the Schoharie Creek Bridge Failure. *Scour and Erosion*, 874-883. https://doi.org/10.1061/41147(392)87 [Link]Unknown Author (2015). Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors. https://doi.org/10.1596/978-1-4648-0466-3 [Link]Mika Rantanen; Alexey Yu. Karpechko; Antti Lipponen; Kalle Nordling; Otto Hyvärinen; Kimmo Ruosteenoja; Timo Vihma; Ari Laaksonen (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1). https://doi.org/10.1038/s43247-022-00498-3 [Link]Brian Ayugi; Victor Nnamdi Dike; Hamida Ngoma; Hassen Babaousmail; Richard Mumo; Victor Ongoma (2021). Future Changes in Precipitation Extremes over East Africa Based on CMIP6 Models. *Water*, *13*(17), 2358-2358. https://doi.org/10.3390/w13172358 [Link]Rui Lança; Cristina Fael; Rodrigo Maia; João Pedro Pêgo; António H. Cardoso (2013). Clear-Water Scour at Pile Groups. *Journal of Hydraulic Engineering*, *139*(10), 1089-1098. https://doi.org/10.1061/(asce)hy.1943-7900.0000770 [Link]Richardson, J.R.; Trivino, Robert (2002). Clear-Water Abutment Scour Prediction for Simple and Complex Channels. *Transportation Research Record: Journal of the Transportation Research Board*, *1797*(1), 23-30. https://doi.org/10.3141/1797-03 [Link]Chong Tang; Kok-Kwang Phoon (2018). Evaluation of model uncertainties in reliability-based design of steel H-piles in axial compression. *Canadian Geotechnical Journal*, *55*(11), 1513-1532. https://doi.org/10.1139/cgj-2017-0170 [Link]Quilici, Lorenzo (2009). Land Transport, Part 1: Roads and Bridges. *Oxford Handbooks Online*. https://doi.org/10.1093/oxfordhb/9780199734856.013.0023 [Link]Kanyanja, Cynthia; Muathe, Stephen; H.Abbas Al-Rubiae, Hawrra (2023). Strategic Approaches in Strategy Implementation and Performance of Kenya National Highways Authority. *International Journal of Organizational Leadership*, *12*(Second Special Issue 2023), 71-90. https://doi.org/10.33844/ijol.2023.60376 [Link]Lamb, Rob; Garside, Paige; Pant, Raghav; Hall, Jim W. (2019). A Probabilistic Model of the Economic Risk to Britain's Railway Network from Bridge Scour During Floods. *Risk Analysis*, *39*(11), 2457-2478. https://doi.org/10.1111/risa.13370 [Link]Pacifique Batungwanayo; Marnik Vanclooster; Alan F. Koropitan (2020). Response of Seasonal Vegetation Dynamics to Climatic Constraints in Northeastern Burundi. *Journal of Geoscience and Environment Protection*, *08*(09), 151-181. https://doi.org/10.4236/gep.2020.89010 [Link]Anne Priac; Nadia Morin-Crini; Coline Druart; Sophie Gavoille; Corina Bradu; C. Lagarrigue; Giangiacomo Torri; Peter Winterton; Grégorio Crini (2014). Alkylphenol and alkylphenol polyethoxylates in water and wastewater: A review of options for their elimination. *Arabian Journal of Chemistry*, *10*, S3749-S3773. https://doi.org/10.1016/j.arabjc.2014.05.011 [Link]Unknown Author (2015). Road Materials and Pavement Design Awards Program. *Road Materials and Pavement Design*, *16*(sup2), 296-296. https://doi.org/10.1080/14680629.2015.1131452 [Link]Tubaldi, Enrico; Macorini, Lorenzo; Izzuddin, Bassam (2017). FLOOD RISK ASSESSMENT OF MASONRY ARCH BRIDGES. *Proceedings of the 2nd International Conference on Uncertainty Quantification in Computational Sciences and Engineering (UNCECOMP 2017)*, 140-153. https://doi.org/10.7712/120217.5358.16942 [Link]A. G. Kerali; Yasin Olum (2019). Performance and Institutional Delivery Capacity of Key Road Sector Agencies in Uganda. *International Journal of Scientific Research and Management (IJSRM)*, *7*(01), 162-180. https://doi.org/10.18535/ijsrm/v7i1.ec02 [Link]Akila Wijerathna-Yapa; Ranjith Pathirana (2022). Sustainable Agro-Food Systems for Addressing Climate Change and Food Security. *Agriculture*, *12*(10), 1554-1554. https://doi.org/10.3390/agriculture12101554 [Link]Paul I. Palmer; Caroline M. Wainwright; Bo Dong; Ross Maidment; Kevin Wheeler; Nicola Gedney; Jonathan E. Hickman; Nima Madani; Sonja Folwell; Gamal Abdo; Richard P. Allan; Emily Black; Liang Feng; Masilin Gudoshava; Keith Haines; Chris Huntingford; Mary Kilavi; Mark F. Lunt; Ahmed A. Shaaban; Andrew G. Turner (2023). Drivers and impacts of Eastern African rainfall variability. *Nature Reviews Earth & Environment*, *4*(4), 254-270. https://doi.org/10.1038/s43017-023-00397-x [Link]Intergovernmental Panel on Climate Change

(IPCC) (2023). Cities, Settlements and Key Infrastructure. *Cambridge University Press eBooks*, 907-1040. https://doi.org/10.1017/9781009325844.008 [Link]Zhao, Gang; Pang, Bo; Xu, Zongxue; Yue, Jiajia; Tu, Tongbi (2018). Mapping flood susceptibility in mountainous areas on a national scale in China. *Science of The Total Environment*, *615*, 1133-1142. https://doi.org/10.1016/j.scitotenv.2017.10.037 [Link]JOAN KAGENDO MAINA; Lydia Gachengo (2023). ROAD PROJECT PLANNING AND PERFORMANCE OF EXPRESS HIGHWAY CONSTRUCTION PROJECT IN NAIROBI CITY COUNTY, KENYA. *Strategic Journal of Business & Change Management*, *10*(1). https://doi.org/10.61426/sjbcm.v10i1.2567 [Link]David Premack; Guy Woodruff (1978). Does the chimpanzee have a theory of mind?. *Behavioral and Brain Sciences*, *1*(4), 515-526. https://doi.org/10.1017/s0140525x00076512 [Link]