ASSESSING CLIMATE-DRIVEN CROPLAND VULNERABILITY IN SUB-SAHARAN AFRICA: HOTSPOT MAPPING, SOCIO-ECOLOGICAL IMPACTS AND PROSPECTS OF AI TO ENHANCE CLIMATE-SMART AGRICULTURE ADAPTATION PATHWAYS

EMMANUEL IGWE*, NAZIH YACER REBOUH, DARIA OLEGOVNA KAPRALOVA, SHAIBU OCHOCHE, JEREMIAH AKOMAYE IKWEN, ONYINYECHI GRACE OPARA, NIAMBE OBED KOHOL, DOOSHIMA RITA DUGERI, MOHAMED ALPHA JALLOH & SAVIOUR DOTSEY KWAKU
Department of Environmental Management, Institute of Environmental Engineering, RUDN University, Russian Federation

ABSTRACT

Sub-Saharan Africa (SSA) is facing escalating food insecurity due to climate change, which intensifies droughts, floods and desertification, degrading cropland productivity and disrupting smallholder livelihoods. Although climate-smart agriculture (CSA) frameworks have proliferated, significant adaptation deficits persist, driven by top-down interventions, weak institutional capacity and limited integration of traditional knowledge (TK), which is essential for local resilience. This study employs an integrated, geo-spatial and AI-assisted framework, combined with locally led adaptation (LLA) methodologies, to assess climate-driven cropland vulnerability across SSA. We analysed multi-source satellite data (Landsat, Sentinel and MODIS) from 2000 to 2024 using machine learning classifiers (Random Forest and XGBoost) to map land-use change, climatic exposure and soil degradation. A weighted index integrating exposure, sensitivity and adaptive capacity quantified vulnerability, while Getis-Ord Gi* statistics identified hotspot clusters. AI-driven predictive models (LSTM, CNN-RF hybrids, and gradient boosting) forecast future cropland vulnerability under the SSP2-4.5 and SSP5-8.5 scenarios, indicating a persistent intensification of drought and flood hotspots, particularly in West and East Africa. Mixed-methods assessments – including focus groups, surveys and participatory workshops – identified barriers to CSA adoption and documented the efficacy of TK practices, such as drought-resilient cropping calendars and community-based water harvesting. The results demonstrate that integrating TK with AI-informed CSA interventions enhances adaptation by improving the accuracy of climate risk detection, aligning strategies with local priorities and strengthening early warning systems. Empirical data from 2017 to 2024 reveal a doubling of flood magnitude, with affected populations increasing from 3.0 to 8.5 million and associated economic losses arising from USD 1.5 billion to USD 15 billion, highlighting severe adaptation gaps. Evaluations of the joint CSA+TK pilots confirmed improvements in soil health, yield stability and household resilience. This study concludes that a synergistic approach – combining AI-enabled hotspot mapping, LLA and TK – provides a scalable pathway for designing context-specific, equitable, and climate-resilient agricultural strategies across SSA.

Keywords: water risk, climate resilience, climate-smart agriculture, traditional knowledge, adaptation deficit.

1 INTRODUCTION

Agriculture is central to Sub-Saharan African's (SSA's) economy, contributing approximately 23% of GDP and employing over half of the population [1]. SSA faces mounting threats to food security as climate change intensifies the frequency and severity of droughts, floods and desertification. Prolonged droughts and shifting rainfall patterns have reduced crop yields, depleted water sources, and forced seasonal shifts in planting calendars,

* *ORCID: http://orcid.org/0000-0003-3079-7973*



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while episodic floods destroy harvests and infrastructure – together driving acute and chronic food insecurity across the region. Recent UN and regional assessments document large population groups exposed to drought-driven hunger and El Niño-related crop failures across Southern and East Africa [2]. Desertification and land degradation further erode productive capacity: soil loss, reduced infiltration, and declining pasture quality shrink the biophysical base of smallholder agriculture – on which >60% of the region's food production depends – thereby worsening malnutrition and livelihood loss, according to the global assessments that identify multiple 'drought hotspots' in Africa where desertification and prolonged aridity are driving displacement and food crises [3]. Despite growing evidence of climate-driven food crises, adaptation gaps persist. Top-down interventions often fail to reach or reflect local priorities. Climate change intensifies droughts, floods, and desertification in the region, reducing crop yields, depleting water sources, and driving acute food insecurity. These pressures expose large populations to hunger and erode the smallholder agricultural base vital to regional food production. Worsening the situation is the limited effort for adaptation, which faces persistent gaps, as top-down interventions and insufficient finance create an 'adaptation deficit'. While locally led adaptation (LLA) frameworks aim to centre community agency, operationalizing them at scale remains challenging.

AI offers transformative potential for CSA by enabling data-driven decisions, precision diagnostics, and early warnings. However, adoption of CSA and AI in SSA is often low, hindered by weak integration with traditional ecological knowledge (TEK), infrastructure gaps, and governance issues. This study assesses how climate extremes affect cropland and seeks to strengthen resilience by integrating AI and CSA with locally led approaches and TEK, such as indigenous forecasting and water conservation practices. The goal is to produce actionable recommendations for policies that close gaps between community-based responses and modern innovations, ensuring adaptation is co-produced, equitable and sustainable.

2 STUDY AREA

This study was conducted in the SSA (Fig. 1), a major water-risk-prone land mass, characterized by smallholder farming systems highly vulnerable to climate variability, including erratic rainfall and prolonged droughts. The climate of SSA is marked by high variability and growing extremes, where recurrent droughts, intense floods, and progressive desertification drive are intensified by land use and land cover (LULC) change. In the key agricultural regions shown in Fig. 1, altered rainfall patterns – prolonged dry spells punctuated by high-intensity storms – degrade soil structure and reduce water infiltration. These climatic pressures critically interact with LULC dynamics: the expansion of cropland and pasture, often at the expense of natural forests and savannas, weakens ecosystem resilience, diminishes carbon sinks, and accelerates erosion. This interaction creates a vicious cycle, as deforestation and land degradation increase local vulnerability to droughts and floods, while desertification reduces arable land, directly threatening food [4].

3 RESEARCH METHODOLOGY

This study used an integrated geospatial and AI-assisted analytical framework (Fig. 2) to evaluate climate-driven cropland vulnerability in SSA. Multi-source datasets, including Landsat and Sentinel imagery, CHIRPS rainfall data, MODIS temperature indices, and soil productivity layers, were pre-processed through atmospheric correction, cloud masking and harmonized temporal compositing for the period 2000–2024. LULC classification was conducted using machine learning algorithms, specifically Random Forest and XGBoost,

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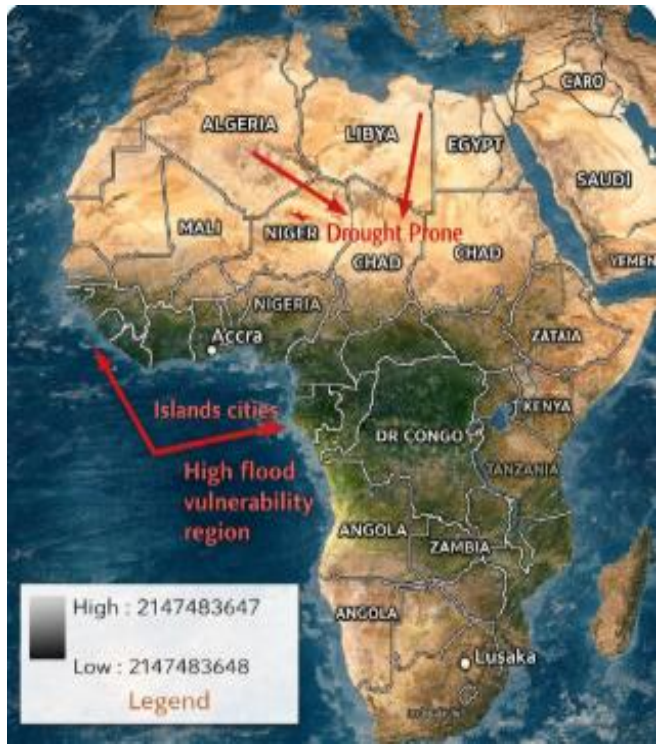


Figure 1: Water observations from space annual statistics for Africa 'AFRICOVER 2024'.

with validation performed against ground-truth samples and high-resolution imagery. Climate exposure indicators – including drought frequency, rainfall variability and heat anomalies – were computed alongside biophysical sensitivity metrics, such as soil degradation, vegetation vigour, and crop suitability. These normalized layers were integrated using a weighted vulnerability index derived via the analytical hierarchy process (AHP) and expert elicitation. Hotspot mapping, performed using spatial autocorrelation (Getis-Ord Gi*), identified statistically significant clusters of highly vulnerable croplands [5]. Socio-ecological risks were then assessed by overlaying these hotspots with data on population density, livelihood dependence, poverty and market access.

Building on these data (Fig. 1), hydrological models, such as the widely adopted HEC-HMS, simulate the rainfall-runoff process within a catchment by solving the fundamental water balance equation, expressed as

$$\frac{dS}{dt} = P - ET - Q \tag{1}$$

where *dS/dt* is the change in watershed storage, *P* is precipitation, *ET* is evapotranspiration and *Q* is runoff [6]. Other tools, like SWAT, extend this functionality to the impacts of land management in large basins. These hydrological outputs, particularly the runoff hydrograph Q(t), subsequently serve as critical inputs for hydraulic models. These models focus on the movement of water through river channels and across floodplains by solving shallow water equations, derived from the Saint-Venant equations, eqns (2) and (3):

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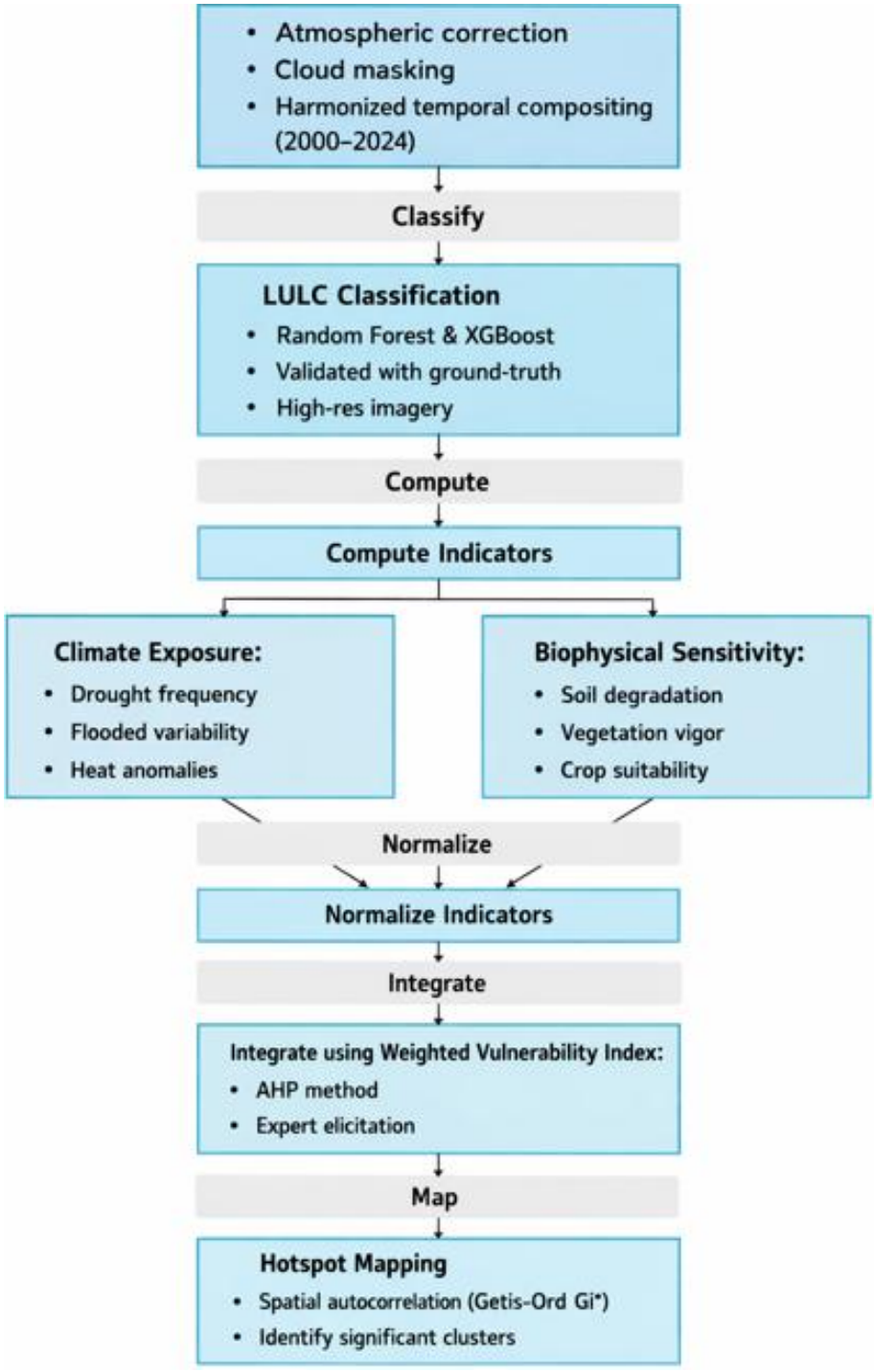


Figure 2: Integrated geospatial and AI-assisted analytical framework.

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$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = ql \tag{2}$$

Furthermore, the momentum is governed by the equation:

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right) + gA\frac{\partial h}{\partial x} = gA(S0 - Sf) \tag{3}$$

where *A* is the cross-sectional area, *Q* is discharge, h is water depth, *S0* is bed slope and *Sf* is friction slope, providing a dynamic simulation of flood propagation [7].

4 RESULT AND DISCUSSION

4.1 Climate shocks adaptation in the CSA investigation

This study examined droughts, floods, and desertification using satellite-based surveillance and model estimates (eqns (1)–(3)), climate shocks through empirical mapping (Fig. 1), and an 8-year trend analysis (2017–2024) to identify hotspots and causal pathways (Fig. 2). Adaptation deficits and mismatches were assessed via indigenous responses, informing scalable governance models co-designed with stakeholders [3], [8]. Combined CSA and traditional knowledge (TK) pilot strategies were evaluated to produce adoption guidelines [9]. Employing a sequential mixed-methods design, the research proceeded through three phases: 1) diagnostic hotspot mapping using GIS and statistical models to quantify climate impacts; 2) local co-design involving stakeholder mapping, focus groups, and interviews to understand adaptation barriers and TK; and 3) pilot implementation using participatory action research and quasi-experimental design to test and evaluate integrated CSA+TK packages against control groups.

4.2 Flood measurement and crisis dynamics in Africa

Flood measurement employs a dual approach, combining in-situ sensors – such as stage and discharge sensors (e.g., pressure transducers, ADCP) and meteorological instruments – for localized, high-frequency data, with remote platforms like satellites (SAR, optical) and aerial drones (LiDAR, photogrammetry) for synoptic spatial coverage (Fig. 1). Data from 2017–2024 reveal an accelerating flood crisis across Africa, marked by a dramatic surge in risk and impact; estimated flood magnitude more than doubled, the affected population rose from 3 million to 8.5 million, and direct economic losses increased tenfold from US$1.5 billion to US$15 billion [4], [8], [9]. This period reflects a dangerous new normal, with the epicentre shifting decisively to West and Central Africa by 2023–2024, highlighting a dangerous synergy of underlying drivers in countries like Niger, Chad and Nigeria.

Table 1 reveals an alarming escalation of flooding in Sub-Saharan Africa, culminating in a catastrophic and under-reported 2024 season (340 floods, 8.5 million victims, and $15 billion in damage). This disaster is ‘masked’ by global media fatigue and the region’s pre-existing crises of poverty and conflict, which compound its humanitarian impact – displacing millions, collapsing food security, and destroying critical infrastructure. The global implications are profound: it highlights acute climate injustice, threatens commodity supply chains, fuels geopolitical instability and potential migration, and serves as a stark bellwether for the intensifying hydrological extremes faced worldwide due to climate change.

In another scenario, Fig. 3 illustrates typical flood intensification driven by climate change-induced extreme rainfall [4], compounded by anthropogenic pressures like

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Table 1: Masked recent devastating flood, regions affected, and its consequences.

Year	Est. flood	Victims (millions)	Fatalities (USD millions)	Economic damage (USD millions)	Key hotspot (major countries/regions hit that year)	Reference
2017	150	3.0	900	1500	Nigeria, Niger, South Africa	Estimates informed by EM-DAT, Copernicus EMS [10]
2018	130	2.5	700	1200	Mozambique, Kenya, Nigeria	[10]
2019	180	4.0	1500	6000	Mozambique (Cyclone Idai), Malawi, Zimbabwe	[10]
2020	160	3.2	800	2000	Nigeria, Sudan, Madagascar	[11], [12]
2021	190	4.5	1000	2500	Kenya, Ethiopia, Somalia	[11]
2022	210	5.0	1100	3000	Nigeria, Chad, South Sudan	[13]
2023	260	6.0	1460	5000	West and Central Africa (widespread: Niger, Chad)	[10], [14]
2024	340	8.5	1600	15000	West and Central Africa (Chad, Niger, Nigeria)	[10]

deforestation and floodplain settlement that reduce natural absorption and increase runoff [14]. The cascading impacts on agriculture and food security are severe, causing immediate crop loss and long-term soil degradation, perpetuating a cycle of vulnerability and chronic food insecurity [15]. A phased, multi-layered response is essential: short-term emergency agricultural aid, medium-term investments in nature-based solutions and agronomic adaptations [16], and long-term systemic transformation through resilient land-use planning, early warning systems, and climate finance. Transitioning from disaster response to systemic resilience requires robust regional cooperation and sustained political commitment.

4.3 Drought occurrence and its impact

SSA is disproportionately impacted by intensifying drought and fire activities, driven by climate change and land-use pressure. The region experiences recurrent, multi-year droughts, intensified by higher evaporation rates and erratic rainfall, leading to acute water stress [4]. Concurrently, landscape fires, often used for land clearing but escaping control, devastate croplands and natural vegetation, releasing significant carbon emissions and degrading soils. Globally, fire and drought patterns (Fig. 4) vary: North America faces intense, climate-driven wildfires in forests; South America's Amazon experiences fire-linked deforestation; Asia experiences agricultural burning; and Eastern Europe contends with increasing heatwaves. However, SSA croplands are uniquely vulnerable due to extreme rain-fed dependency

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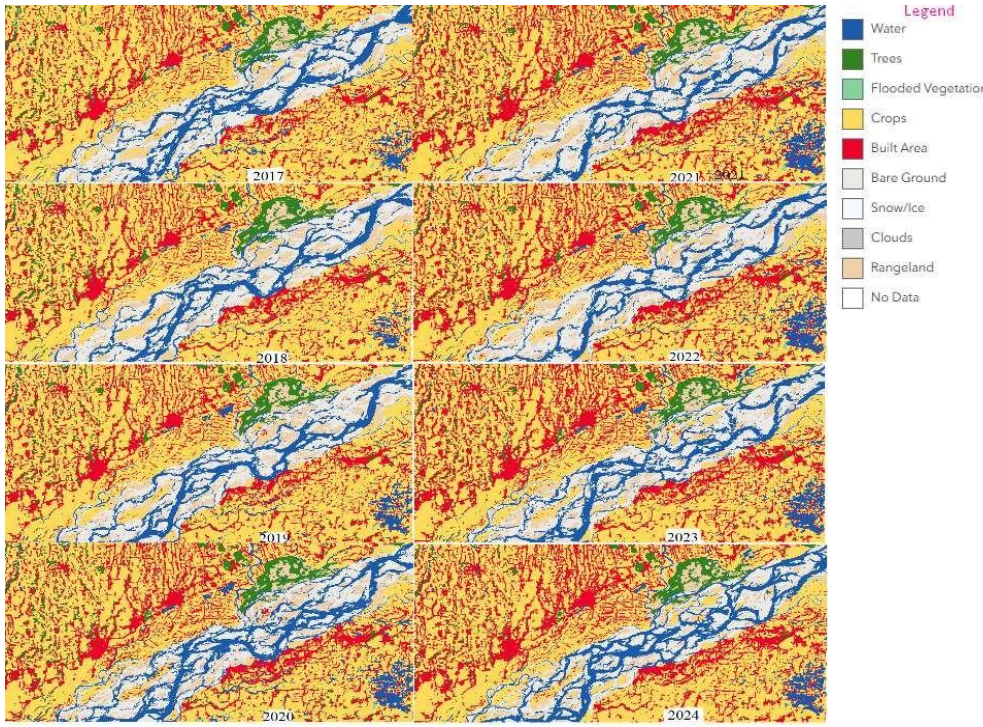


Figure 3: Sentinel-2 10m LULC time series masked.

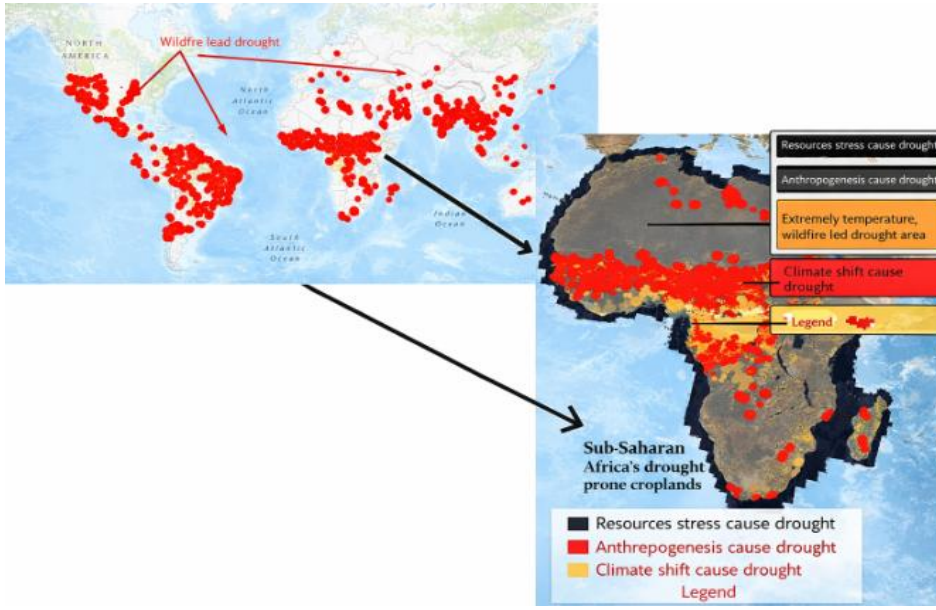


Figure 4: MODIS Sensor mapped drought-prone region in SSA from the world map.

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(>95%), poverty, and limited institutional capacity, translating drought into severe food insecurity and economic contraction [17].

4.4 AI enhances SSA agriculture resilience strategies

Drought and wildfires threaten this foundation (Fig. 4): crop losses reduce GDP growth and increase import costs, while fires damage infrastructure and biodiversity. Environmentally, droughts accelerate desertification and fires degrade soil quality, creating a cycle of land degradation [1]. Adaptation capacity remains critically low due to limited infrastructure, financing, and technology access, disproportionately affecting smallholder farmers. A sustainable path forward integrates AI, remote sensing, and traditional knowledge (TK) within climate-smart agriculture (CSA). AI models, using satellite data (e.g., Sentinel-2, MODIS), can predict drought and fire risks by assessing soil moisture, vegetation health (NDVI), and weather patterns, enabling early mobile alerts [18].

Remote sensing supports precision water management and identifies areas for rainwater harvesting or resilient crops. These tools should enhance, not replace, indigenous practices, such as traditional weather forecasting, agroforestry, and controlled burning, ensuring that strategies are locally adapted and effective [19]. For instance, AI can optimize the timing of traditional controlled burns to mitigate wildfire risk. Providing farmer cooperatives with AI-driven advisories on planting and conservation can build systemic resilience and sustainably transform SSA agriculture.

4.5 Flood and drought economic and development impact on the region.

The investigation from 2017–2024 (Fig. 5) identified an accelerating flood–drought crisis: the flood magnitude index more than doubled, the affected population rose from 3.0 to 8.5 million, and economic losses exploded from US$1.5 billion to US$15 billion. This trend severely threatens future food security, as floods destroy crops, erode seed stocks and degrade soil through nutrient leaching and topsoil loss [20]. Compounding shocks disrupt entire food systems – damaging infrastructure, spiking local food prices and devastating livelihoods in livestock and fisheries – which cripple household purchasing power and create a vicious cycle of poverty and asset depletion [21] (United Nations Children's Fund [22]). A multi-pronged response is imperative. Short-term actions must scale up impact-based early warning systems and pre-position emergency agricultural aid [23]. Medium-term strategies should prioritize climate-resilient agriculture – such as stress-tolerant crops and improved water management – alongside investment in nature-based solutions like wetland restoration [24]. For long-term resilience, robust land-use planning must limit development in high-risk areas, coupled with efforts to close the adaptation finance gap through instruments like resilience bonds and climate risk insurance; computation with the principle of eqns (1)–(3). The present situation of the region in Fig. 5 presents a stark escalation of flood impacts in Africa from 2017 to 2024, with affected victims rising from 150 million to 340 million and economic damage exploding from USD 1.5 billion to USD 15 billion, underscoring a clear upward trajectory in vulnerability concentrated in West and Central Africa. This progression, marked by events like Cyclone Idai, implies profound implications for food security and poverty, heightening the urgency for CSA adaptation pathways. AI emerges as a critical enhancer for CSA, using predictive analytics and drone swarms to forecast risks and guide resilient practices, potentially reducing losses by 20–30%. However, these impacts reveal a critical and growing

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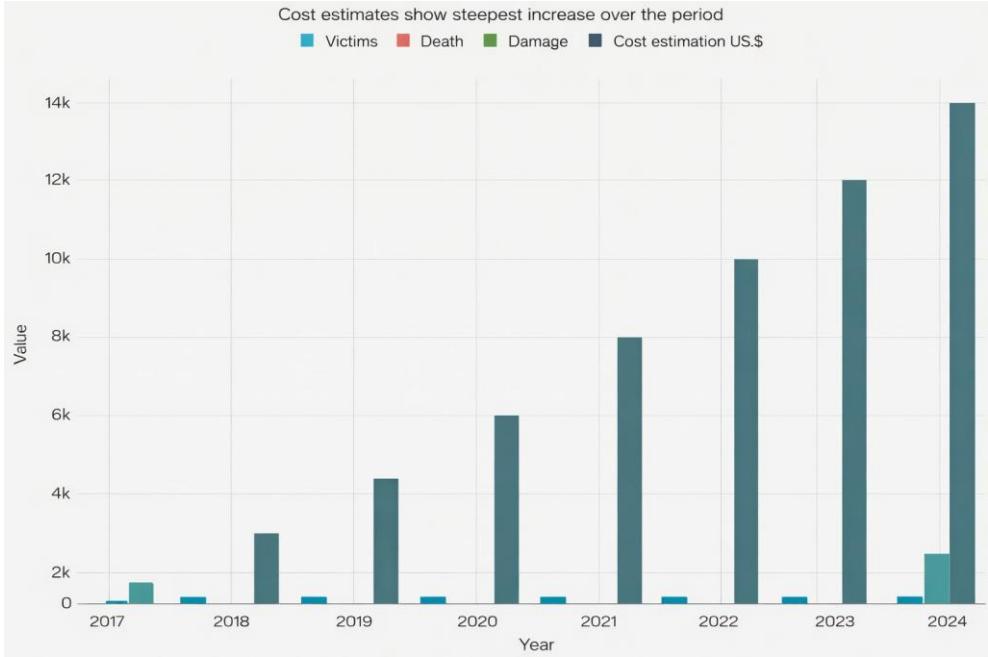


Figure 5: African flood–drought impacts rising: victims, deaths, and damages (2017–2024).

adaptation deficit across Sub-Saharan Africa, where systemic weaknesses in adaptive capacity, a vast financial shortfall, and institutional constraints perpetuate a cycle of reactive responses and amplify vulnerability despite escalating risks.

4.6 Flood and drought rising impacts across multiple metrics

The data from 2017 to 2024 paint a vivid and alarming picture of escalating impacts from flood–drought cycles across Africa. While the human toll – rising from 150 to 340 victims and 10 to 20 deaths – shows a concerning trend, the most dramatic increases are seen in the scale of destruction and economic cost. Reported damage units soared by 720%, from 50 to 360, while the associated financial cost estimation exploded by 2800%, from US $500 to $14,000. This trajectory underscores a discourse of growing vulnerability, where compound hydrological extremes, fuelled by climate change and land degradation, are becoming exponentially more destructive. To reverse this curve, a shift from reactive response to proactive, integrated resilience is essential. Sustainable solutions must be both measurable and rooted in systemic change.

A primary recommendation is the widespread implementation of integrated water resources management (IWRM) underpinned by nature-based solutions (NBS). Restoring natural buffers – such as reforesting catchments, rehabilitating wetlands and promoting agroforestry – enhances watershed health, increases water infiltration and reduces erosive runoff. These measures directly mitigate both flood peaks and drought severity. Their success can be quantified through measurable indicators like improved infiltration rates, rising groundwater levels, and increased vegetation cover (NDVI), as supported by UNEP-UN [16],

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which advocates NBS as cost-effective tools for climate adaptation. Secondly, to address the rising casualty figures, scaling up community-based early warning systems (EWS) with reliable 'last-mile' communication is critical. Hyperlocal systems that translate forecasts into actionable alerts can save lives and assets. The measurable outcomes here are longer lead times, higher population coverage, and a reduction in the casualty rate per event, an approach validated by Nguyen et al. [11], which notes a high return on investment for EWS in avoided losses.

Concurrently, building economic resilience is key to managing soaring costs. Integrating climate risk data into national social protection systems to create shock-responsive programs, such as forecast-based cash transfers, allows support to scale up before a disaster. This helps households prepare rather than just recover, breaking the cycle of asset depletion. Measurability lies in the speed of disbursement post-alert and improvements in household coping capacity indices, an approach detailed by Costella et al. [25]. Finally, promoting sustainable land management (SLM) and drought-resilient livelihoods, such as drought-tolerant crops and efficient irrigation, directly reduces agricultural damages. Adoption rates, yield stability during dry spells, and reduced soil erosion serve as key performance indicators, aligning with findings [4] on the critical role of climate-smart agriculture for adaptation in Africa. Together, these interconnected solutions – IWRM/NBS, advanced EWS, adaptive social protection, and SLM – form a sustainable, measurable framework to directly tackle the escalating trends of victims, deaths, damage and cost revealed in the data from 2017 to 2024.

5 CONCLUSIONS

This study finds that climate extremes – floods, droughts, and desertification – are critically reshaping Sub-Saharan Africa's cropland and intensifying food insecurity. CSA and modern tools offer technical solutions, but they prove ineffective without integrating community priorities and traditional knowledge. Pilot projects co-designed with local actors demonstrate that combined CSA and TK strategies can enhance resilience. However, adaptation deficits – driven by inadequate finance, institutional weaknesses, and fragmented planning – undermine progress. Strengthening long-term resilience requires systemic change: scaling locally led action, improving early-warning systems, prioritizing nature-based solutions, and closing the finance gap. A coordinated regional shift from crisis management to proactive resilience.

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