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Extreme Weather Events and Malaria Outbreaks: Impacts of Floods, Droughts, and Cyclones on Vector Distribution and Transmission Dynamics

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ABSTRACT

Extreme weather events (EWEs), floods, droughts, and cyclones are increasing in frequency and intensity due to climate change. These events alter malaria epidemiology by reshaping Anopheles vector ecology, breeding site availability, vector survival, and human exposure patterns. Floods can both suppress and amplify vector populations depending on hydrological dynamics; droughts concentrate human–vector contact around residual water sources; cyclones restructure landscapes and disrupt health systems, facilitating outbreaks. This review synthesizes current evidence on how EWEs influence malaria vector distribution, species composition, vectorial capacity (VC), and outbreak risk, with emphasis on Sub-Saharan Africa (SSA) and other endemic regions. Mechanistic pathways, ecological thresholds, and implications for surveillance and control are discussed.

Keywords: extreme weather, floods, drought, cyclones, Anopheles, vector ecology, climate change, malaria outbreaks, vectorial capacity.

INTRODUCTION

Malaria remains one of the most climate-sensitive infectious diseases globally, with transmission dynamics intricately linked to environmental conditions [1]. Despite substantial progress in control and elimination efforts over the past two decades, malaria continues to impose a heavy burden, particularly in Sub-Saharan Africa, where ecological suitability for Anopheles mosquitoes persists. Climatic variables—including temperature (T), rainfall (R), and relative humidity (H)—regulate critical components of vector biology and parasite development, thereby shaping malaria transmission intensity. Temperature influences mosquito survival, feeding frequency, and parasite development rates within the vector [2]. Rainfall determines the availability and persistence of larval habitats, while humidity affects adult mosquito longevity [3]. These factors collectively determine vectorial capacity (VC), a key epidemiological metric that quantifies the transmission potential of mosquito populations. VC is commonly approximated as:

$$VC = \frac{ma^2p^n}{-\ln\, p}$$

where m represents vector density relative to humans, a denotes biting frequency, p is daily survival probability, and n is the duration of the extrinsic incubation period (EIP), the time required for Plasmodium parasites to develop within the mosquito to infectious stages. Each of these parameters is highly climate-dependent. Under stable seasonal conditions, malaria transmission exhibits predictable patterns. However, the accelerating pace of climate change has increased the frequency and intensity of extreme weather events (EWEs), including floods, droughts, heatwaves, cyclones, and anomalous rainfall episodes [4]. Unlike gradual seasonal variation, EWEs represent abrupt ecological shocks that can rapidly perturb vectorial capacity through nonlinear and often unpredictable pathways. Extreme rainfall events can generate transient breeding sites, increasing larval habitat availability and potentially boosting vector density (m). Conversely, flooding may flush out breeding sites, temporarily suppressing populations before ecological recovery [5]. Heatwaves can shorten the EIP (n), accelerating parasite development and enhancing transmission efficiency—provided temperatures remain within biologically tolerable thresholds.

Drought conditions may concentrate human populations near limited water sources, intensifying human-vector contact and increasing biting rates (*a*). Meanwhile, altered humidity patterns affect mosquito survival probability (*p*), further modulating transmission potential. Importantly, EWEs do not merely amplify existing seasonal transmission; they can redistribute vector populations geographically, shift species dominance among Anopheles complexes, and facilitate the invasion of new ecological niches [6]. These disruptions may compromise vector control interventions such as indoor residual spraying (IRS) and insecticide-treated nets (ITNs) by altering mosquito behavior, resting patterns, or breeding ecology. As climate variability intensifies globally, understanding how EWEs reshape malaria transmission dynamics is increasingly central to climate-resilient malaria elimination strategies. Traditional epidemiological models based on seasonal averages may be insufficient to capture the nonlinear transmission responses induced by ecological shocks [7].

Although the climate sensitivity of malaria transmission is well established, most research has focused on gradual seasonal or long-term climatic trends. There remains a critical knowledge gap regarding how extreme weather events—characterized by sudden onset and high magnitude—perturb malaria transmission dynamics [8]. Current malaria surveillance systems and predictive models often rely on mean temperature and rainfall data, assuming relatively stable ecological responses. However, EWEs can abruptly modify vectorial capacity parameters, leading to unexpected outbreaks, resurgence in low-transmission areas, or transient transmission suppression followed by rebound effects. These nonlinear responses challenge conventional forecasting models and may undermine progress toward elimination. Furthermore, empirical evidence linking specific types of EWEs (e.g., flooding vs drought vs heatwaves) to changes in vector survival (*p*), biting rates (*a*), EIP (*n*), and vector density (*m*) remains fragmented [9]. Few studies integrate entomological, climatological, and epidemiological data to quantify how extreme climate anomalies propagate through the transmission system. Geographic redistribution of vectors due to climate shocks also poses emerging risks. Highland regions, historically protected by cooler temperatures limiting parasite development, may become suitable following anomalous heat events. Similarly, extreme rainfall may expand breeding habitats into previously unsuitable urban or peri-urban environments [10].

Another concern is the disruption of malaria control programs during extreme events. Floods and storms can damage healthcare infrastructure, interrupt supply chains for antimalarials and insecticides, and displace populations into temporary shelters with increased exposure to vectors. These compounded vulnerabilities may produce outbreak conditions not captured in standard transmission models. Without a comprehensive understanding of EWE-driven malaria dynamics, elimination strategies risk being reactive rather than anticipatory [11]. Climate change projections indicate that extreme events will increase in both frequency and intensity in many malaria-endemic regions. Yet, predictive frameworks capable of integrating ecological shock responses into vectorial capacity models remain underdeveloped. Thus, there is an urgent need to systematically examine how extreme weather events modulate the parameters governing vectorial capacity and to evaluate their implications for malaria transmission stability, outbreak risk, and long-term elimination feasibility [12].

This study investigates how extreme weather events (EWEs) reshape malaria transmission dynamics by applying a vectorial capacity (VC) framework. Specifically, it examines how EWEs alter the key VC parameters—vector density (m), biting rate (a), daily survival probability (p), and the extrinsic incubation period (n)—and how these rapid ecological shocks generate nonlinear transmission responses that differ from gradual seasonal variation. It also evaluates whether EWEs shift vector distribution and species composition, including potential expansion into new ecological zones, and assesses how such disruptions affect malaria control interventions (e.g., insecticide-based strategies) and health system performance. Finally, the study identifies gaps in current predictive modeling and proposes conceptual pathways for integrating extreme climate variability into malaria forecasting and elimination planning. Its significance lies in advancing malaria theory under climatic instability, refining VC models that often assume stable parameter behavior, and strengthening climate-resilient elimination strategies by improving outbreak preparedness and early warning systems. By highlighting how floods, droughts, and heatwaves can undermine intervention continuity and healthcare delivery, the work informs policy and infrastructure resilience. More broadly, malaria functions as a sentinel climate-sensitive disease, so insights may translate to other vector-borne infections such as dengue, chikungunya, and Zika.

2. Floods and Malaria Vector Dynamics

Floods shape malaria vector ecology through three main phases. First, an immediate flushing phase can wash away or destroy larval habitats, causing a short-term drop in mosquito density. Next, a stagnation phase often follows as floodwaters recede and leave behind pools, puddles, and borrow pits that become highly productive breeding sites [13]. Finally, during the post-flood recovery phase, vegetation regrowth and settling sediments can stabilize these habitats, supporting renewed larval development. The overall effect of flooding on vector abundance depends on flood intensity, how long standing water persists, soil permeability (which affects water retention), and the quality of drainage infrastructure. Breeding-site characteristics also determine which vectors dominate: shallow, sunlit, temporary pools commonly favor *Anopheles gambiae* s.s., whereas larger or semi-permanent water bodies tend to favor *Anopheles funestus*. In many settings, this means floods may briefly suppress transmission potential, but later create conditions that amplify vector populations and increase malaria risk if stagnant water remains unmanaged or drainage is inadequate, especially in low-lying communities [14].

Table 1: Species-Specific Responses

Species	Flood Response	Habitat Preference
An. gambiae s.s.	Rapid colonizer post-flood	Temporary sunlit pools
An. arabiensis	Adaptable; thrives in peri-urban flood zones	Temporary habitats
An. funestus	Proliferates in stable post-flood water	Permanent vegetated water

Flood-driven habitat expansion can increase m (vector density), elevating VC.

Urban flooding promotes malaria transmission by creating stagnant-water habitats through blocked drainage systems, pooled water at construction sites, and water storage practices in informal settlements. These environments can shift malaria risk into urban zones that were previously low-risk by increasing mosquito breeding opportunities and human–vector contact. Epidemiological evidence shows post-flood malaria surges across East Africa during riverine flooding [15], South Asia during monsoon seasons, and Southern Africa in El Niño years. In most settings, transmission increases about 3–8 weeks after flooding, aligning with mosquito population build-up, vector maturation, and completion of the parasite's extrinsic incubation period (EIP) [16].

Drought and Malaria Transmission

Drought can paradoxically increase malaria transmission in some settings through several linked mechanisms. Ecologically, shrinking lakes and rivers leave behind shallow, sunlit pools, while predator populations (e.g., fish) decline and households expand water-storage practices (containers), collectively favoring drought-tolerant vectors—especially *Anopheles arabiensis*. A key "concentration effect" occurs when water scarcity clusters humans, livestock, and vectors around the few remaining water sources, raising the human biting rate (a); because vectorial capacity scales with a^2, even modest increases in biting can produce disproportionate rises in transmission potential [17]. Drought is also often accompanied by higher temperatures, which can shorten the extrinsic incubation period (EIP), accelerate parasite development, and increase biting frequency, further amplifying risk, although extreme heat (>34–36°C) may reduce vector survival (lowering p) and dampen transmission in the hottest conditions. In highland and semi-arid zones, drought-associated warming may allow malaria to expand into areas such as the East African highlands and Sahelian belts, where low population immunity can intensify morbidity during epidemics [18]. Cyclones, by contrast, drive outbreaks via heavy rainfall, habitat destruction, displacement, and health-system disruption. They can restructure environments by creating coastal brackish habitats, expanding mangrove-associated niches, and selecting for vectors with ecological plasticity. Displacement into overcrowded shelters and damaged housing increases human–vector contact, often before vector densities peak, while disrupted ITN delivery, IRS operations, RDT supply chains, and antimalarial availability delay treatment and prolong gametocyte carriage [18]. In cyclone-prone regions (e.g., Mozambique, Madagascar, South Asia), malaria commonly spikes 1–2 months post-event, fueled by stagnant debris-filled water and, in vegetated floodplains, increases in *An. funestus.*

Ecological Thresholds and Nonlinear Dynamics

Extreme weather events (EWEs) can trigger ecological thresholds that make malaria transmission highly nonlinear. Flooding illustrates this: excessive floods can wash out larvae and reduce vector survival, while moderate floods may create optimal breeding conditions; conversely, mild drought can stabilize habitats and sustain breeding, but severe drought may cause vector population collapse [19]. Because these responses are threshold-driven rather than gradual, climate–malaria models should incorporate key modifiers, including lag effects (≈2–8 weeks between climate shock and transmission), species-specific thermal limits, land-use interactions, and human adaptive behaviors that change exposure risk. EWEs also reshape vector distribution by enabling range expansion into new zones, such as higher altitudes (warming highlands), new latitudes, and urban settings, where climate anomalies may allow temporary establishment at ecological fringes. In parallel, extreme events can drive species replacement by suppressing dominant vectors and creating opportunities for secondary vectors, for example, post-flood shifts from *Anopheles gambiae* to *An. funestus*, or drought-associated increases in *An. Arabiensis* [20]. Such transitions can alter feeding and resting preferences (zoophilic vs anthropophilic; endophilic vs exophilic) and insecticide susceptibility, risking misalignment between current vector-control strategies and the emerging vector ecology.

Interaction with Socio-Environmental Factors

Extreme weather events (EWEs) interact with key socio-environmental drivers deforestation, agricultural irrigation, dam construction, and urbanization to reshape malaria transmission risk. Flooded agricultural landscapes, especially irrigated rice paddies, create persistent breeding habitats that sustain mosquito vectors and prolong transmission seasons. The public health impact of EWEs is often worst in vulnerable settings such as displacement camps, where limited access to insecticide-treated nets (ITNs), poor drainage, and constrained healthcare services magnify exposure and delay treatment, thereby increasing morbidity [21]. To reduce these climate-sensitive surges, climate-based malaria early warning systems (EWS) increasingly integrate rainfall anomalies, soil moisture indices, temperature forecasts, and vegetation indicators such as the Normalized Difference Vegetation Index (NDVI) to anticipate shifts in vector suitability and parasite development. When flood and drought risks are forecast in advance, programs can improve preparedness by pre-positioning antimalarial supplies, optimizing the timing of indoor residual spraying (IRS), and intensifying larval source management (LSM) in high-risk zones. Satellite remote sensing further strengthens EWS by enabling near–real-time risk mapping and targeted response, supporting faster, more efficient allocation of limited resources [22].

Implications for Vector Control

Extreme weather events (EWEs) require tailored, phase-specific malaria vector control. After floods, programs should rapidly map larval habitats to identify newly formed breeding sites, implement targeted larval source management (LSM) where feasible, and deploy emergency insecticide-treated nets (ITNs) to protect displaced and exposed populations, complemented by indoor residual spraying (IRS) focused on high-risk clusters [23]. During droughts, control should pivot to intensified monitoring of household and community water storage containers that become persistent breeding foci, alongside locally appropriate zooprophylaxis strategies and community-led larval control to suppress vectors around scarce water points. For cyclone preparedness, readiness hinges on stockpiling rapid diagnostic tests (RDTs) and artemisinin-based combination therapies (ACTs) to prevent case surges, deploying mobile vector surveillance units to track shifting hotspots, strengthening resilient supply chains for insecticides, diagnostics, and nets, and ensuring shelter-based ITN coverage for evacuees. Major research gaps remain, including defining species-specific resilience thresholds under extreme hydrological stress, generating longitudinal post-cyclone vector ecology datasets, integrating entomological indicators into disaster risk models, characterizing genomic adaptations to salinity and temperature extremes, and quantifying the contribution of EWEs to malaria resurgence in settings approaching elimination [24].

CONCLUSION

In conclusion, EWEs are no longer episodic shocks but recurring stressors that reshape mosquito ecology, human exposure, and malaria transmission dynamics. Effective control therefore demands climate-responsive, phase-specific packages that can be activated before, during, and after floods, droughts, and cyclones, rather than relying on routine interventions alone. Rapid habitat mapping, targeted LSM, surge ITN distribution, and focused IRS can blunt post-flood amplification, while drought periods require sustained attention to water storage–driven breeding and community-based suppression around scarce water points. Cyclone readiness must integrate mobile surveillance, shelter-centered protection, and resilient logistics to maintain continuous access to nets, insecticides, diagnostics, and ACTs. However, optimizing these strategies depends on closing key evidence gaps on vector resilience, post-cyclone ecology, genomic adaptation to environmental extremes, and the measurable contribution of EWEs to resurgence risk, especially in elimination settings. Embedding entomological intelligence within disaster risk frameworks is essential for timely, cost-effective, and equitable malaria prevention.

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