

POLICYBRIEF

July 2026

More Than Climate: Understanding Malaria Occurrence in Sudan

Focus Area: Public Health, Vector Ecology, Humanitarian Crises

Malaria remains one of the primary public health challenges in Sudan, where outbreaks are increasingly shaped by the combined impacts of climate change, flooding, conflict, population displacement, and disruptions to health services. While temperature, rainfall, and humidity influence the environmental suitability for malaria transmission, climate alone cannot explain why outbreaks occur in some places and years but not others. Conflict driven displacement, damaged health infrastructure, and reduced access to diagnosis and treatment can substantially alter transmission patterns and hinder effective malaria control. Understanding how these environmental and humanitarian factors interact is essential for strengthening malaria preparedness. This policy brief summarizes the findings from a comprehensive analysis covering 2000-2024. By utilizing a simplified Climate Suitability Index (CSI) alongside flooding, displacement, and health infrastructure capacity metrics, this study aims to understand malaria occurrence in highly unstable humanitarian settings.

1. The Challenge: Complex Multi-Layered Drivers

Sudan represents a highly complex epidemiological landscape where geographic transition zones, ranging from hyper-arid northern deserts to wet southern savannahs, coexist with severe civil conflict.

- **Civil Conflict:** Escalating armed conflict, particularly since April 2023, has severely disrupted basic public services, caused widespread physical damage to health facilities, and restricted physical access to care.
- **Displacement & Demographics:** Massive forced displacement, reaching nearly 12,500 IDPs per 100,000 population during peak conflict periods, concentrates vulnerable populations in temporary settlements with poor shelter, heightened vector exposure, and inadequate sanitation.
- **Health System & WASH Fragility:** Insecurity has directly damaged healthcare facilities and created severe operational barriers. Low water and sanitation (WASH) coverage alongside non-functional primary care centers heavily restrict community access to basic diagnostic tools and antimalarial treatments.

2. Conceptual Framework & Data Inventory

Rather than treating climate suitability, flooding emergencies, and conflict-driven displacement as independent variables, this analysis demonstrates that malaria transmission in Sudan operates as a complex system. The true disease burden emerges from the interaction of these environmental and anthropogenic pressures. Therefore, this research is anchored in a conceptual framework that views malaria occurrence in Sudan as an interactive product of four pillars: Climate (suitability and flooding), Conflict (displacement and health system disruption), Governance (surveillance and healthcare access), and WASH (water infrastructure). Temperature, humidity, precipitation, and flooding dictate biological vector suitability, while drinking water infrastructure influences localized breeding risks. Simultaneously, conflict drives population displacement and health system disruptions. Governance factors, including surveillance and reporting capacity, dictate how effectively occurrence is detected.

A multiplicative CSI was formulated to represent the principal climate sensitive components of the Ross-Macdonald malaria transmission framework, mapping daily environmental variables across Sudan's 18 states (Smith et al., 2012):

$$CSI(T, RH, P, species) = S_{bite}(T) \times S_{PDR}(T) \times S_{survival}(T, RH) \times S_{habitat}(P)$$

While climate and surface water data drive the quantitative models, governance and health infrastructure metrics (HeRAMS) are used qualitatively to contextualize reporting gaps, such as when active conflict masks true disease occurrence. To ensure strict consistency across all layers, the analysis is geographically bound to Sudan's 18 states (excluding Abyei PCA) and temporally aligned to a 2000-2024 window. The datasets included in the study are given in Table 1.

Table 1. Datasets included in the study

Data theme	Data source	Data resolution
Malaria occurrence	World Health Organization (WHO) Global Health Observatory (GHO) - laboratory confirmed case counts from the National Malaria Control Program	National, Annual (2015-2024)
Climate	ERA5 / ERA5-Land reanalysis	Gridded, Daily (2000-2024)
Population	WorldPop gridded population rasters	Gridded, Annual (2000-2024)
Flooding	European Commission Joint Research Centre Global Surface Water monthly history	Gridded, Monthly (2000-2021)
Health system capacity	WHO HeRAMS Sudan Baseline Report 2025 series	State&national, Annual (September 2023-June 2025)
WASH	WHO/UNICEF Joint Monitoring Programme (JMP)	National, Annual (2003-2024)
Displacement	Internal Displacement Monitoring Center (IDMC) Global Internal Displacement Database (GIDD)	National, Annual (2009-2024)

Establishment of the Humanitarian Malaria Reporting Database

A humanitarian malaria reporting database for 2000-2024 was established using ReliefWeb as the primary retrieval platform and AI based text search. This database was developed to identify reported malaria drivers and operational interventions, ultimately to assist interpreting the quantitative datasets. The resulting database contained 273 malaria related reports consisting of 136 OCHA reports, 123 WHO reports, and 14 MSF reports.

3. Key Findings

Spatiotemporal Gradients and Climate Suitability

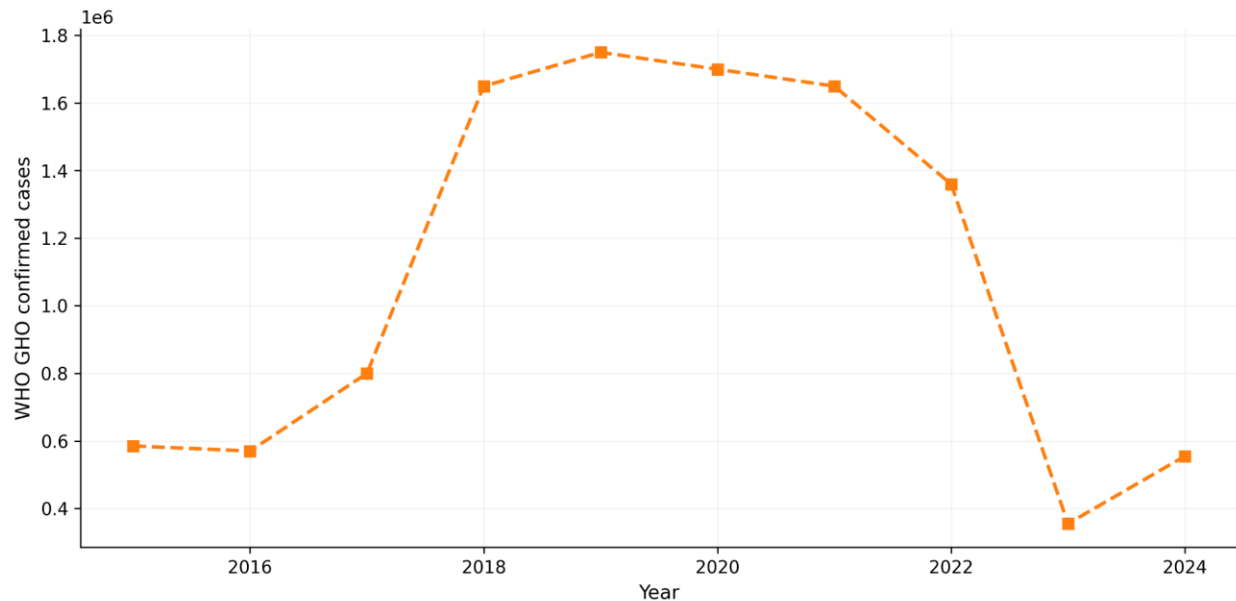


Figure 1. Laboratory confirmed malaria case numbers

Trends in WHO GHO confirmed cases show a sharp decline following the outbreak of civil conflict in April 2023.

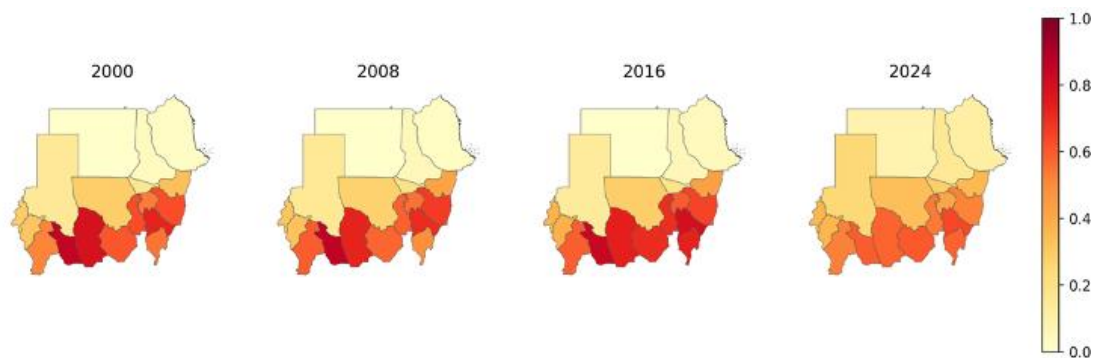


Figure 2. Climate suitability across Sudanese states

Figure 2 shows the state level normalized CSI values. The hyper-arid northern states (Northern, River Nile, Red Sea) consistently display minimal suitability due to extreme desiccation stress on vectors. Conversely, southern and southeastern states (South Darfur, South Kordofan, Blue Nile, Sennar, White Nile) demonstrate persistently elevated multi-year suitability due to intensive seasonal rainfall.

When comparing the high climate suitability across these southern and southeastern regions with the sudden post-2023 drop in confirmed cases, it becomes clear that this decline does not reflect an actual reduction in transmission, but rather severe health system disruption and underreporting caused by active conflict.

Distinct Temporal Differences: Flooding vs Climate Effects

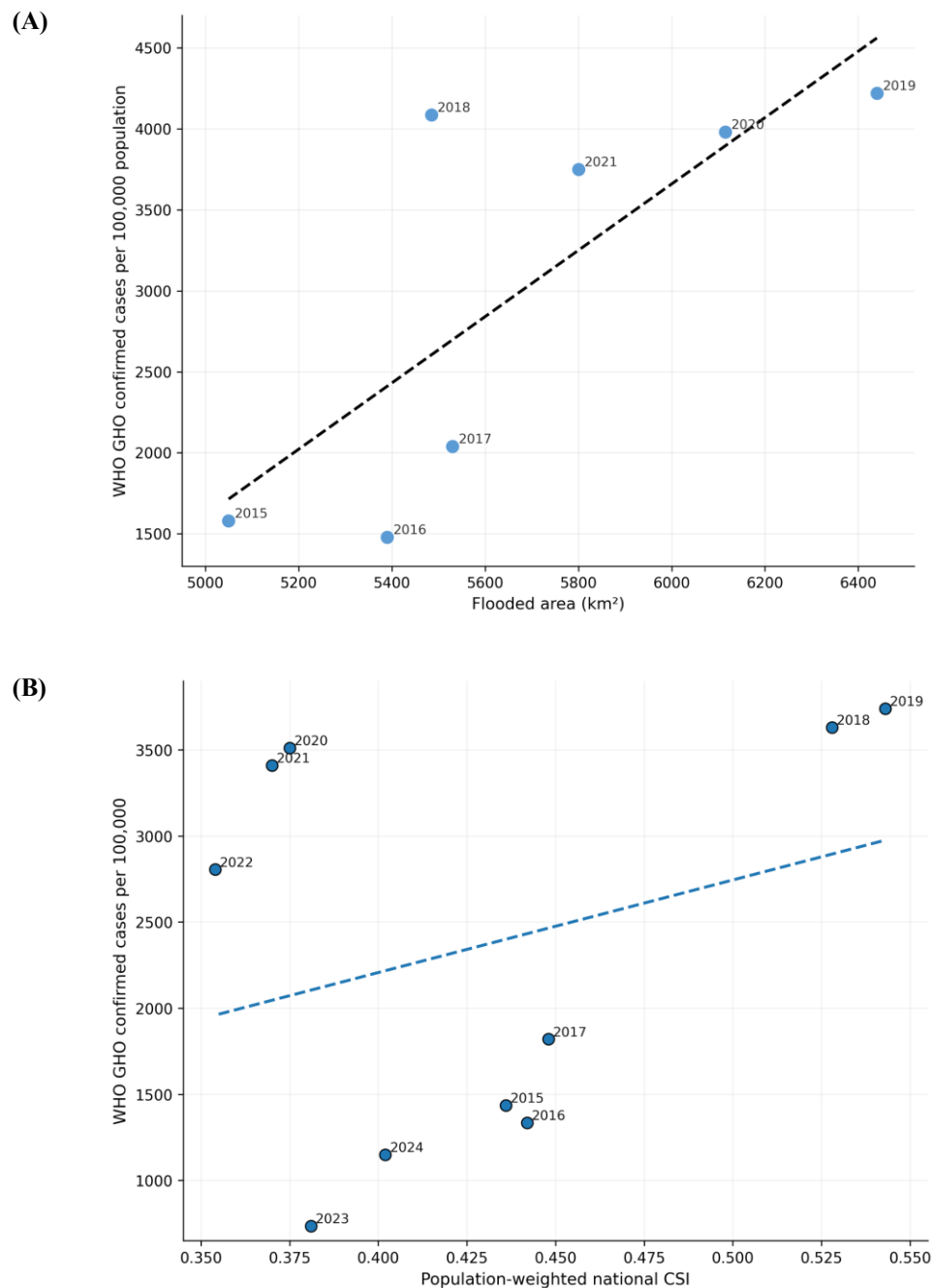


Figure 3. Scatter plots showing temporal relationships between the national WHO-GHO laboratory confirmed malaria cases vs environmental drivers in Sudan. (A) Flooded area (km²). (B) Population-weighted national CSI

Statistical correlation analyses revealed a strong, contemporaneous relationship between same-year surface water inundation and rapid malaria occurrence peaks, while broader CSI trends showed a weaker relationship. However, this variation is heavily influenced by interacting environmental, epidemiological, and humanitarian variables; therefore, given the small sample size, these lag patterns should be interpreted as indicative rather than conclusive.

Combined Analysis: Overlapping Vulnerability Strata

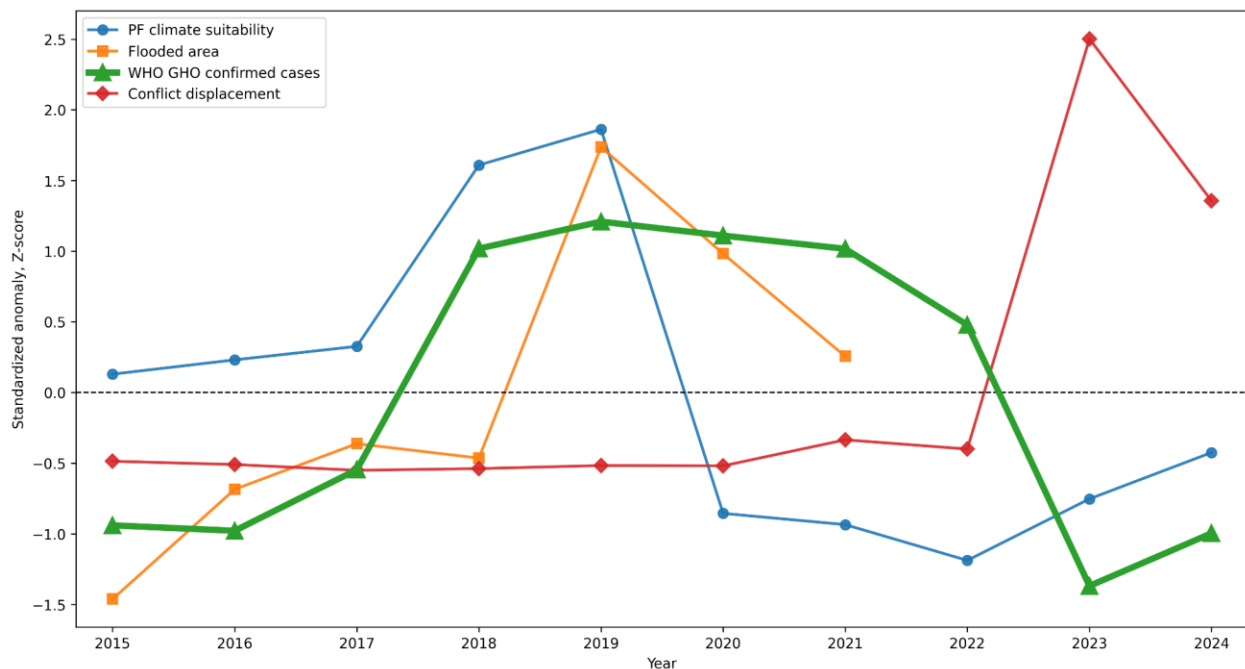


Figure 4. Combined time-series analysis of standardized values of CSI, flooded area, WHO GHO laboratory confirmed cases and conflict displacement

When examining the quantitative environmental layers with the qualitative indicators compiled within the humanitarian malaria reporting database, the interactions between climate suitability, conflict, and health system capacity become explicitly clear. The combined analysis demonstrates that malaria occurrence in Sudan is not governed by a single isolated driver, but operates as an emergent system of compounding vulnerabilities:

- **The 2015-2017 Baseline:** Despite climate suitability hovering close to or slightly above average, malaria occurrence remained below the long-term mean. During this window, flooding stayed below average, and

population displacement remained stable and below the long-term baseline.

- **The 2018-2020 Environmental Surge:** Malaria occurrence increased dramatically starting in 2018 and sustained strongly positive anomalies through 2022, with the ultimate peak observed in 2019. This epidemic wave directly mirrored environmental conditions: between 2017 and 2019, climate suitability and flooding escalated rapidly, both peaking simultaneously in 2019. Meanwhile, displacement remained low and stable between 2018 and 2020. This alignment suggests that highly favorable environmental conditions drove the transmission potential.

This is further validated by the ReliefWeb database, which identified flooding, stagnant water, and intense rainy seasons as the primary reported malaria drivers during 2019-2020.

- **The Post-2019 Climate Decline:** Climate suitability dropped sharply after 2019, staying below the long-term average from 2020 to 2024 (reaching its lowest values in 2022-2023). Flooding followed a similar post-2019 decline but remained above average until 2021. Despite this climate drop, reported malaria occurrence remained elevated through 2022.
- **The 2023-2024 Conflict-Surveillance Break:** In 2023 and 2024, displacement reached its highest positive standardized anomaly in the study period, reflecting the severe humanitarian crisis following the outbreak of civil conflict. Concurrently, official reported malaria numbers dropped below the long-term average, even as

favorable transmission conditions persisted alongside elevated CSI levels. The ReliefWeb database identified conflict as the absolute primary reported driver in both years. This simultaneous decline in reported cases alongside record displacement and elevated CSI conditions indicates a severe surveillance breakdown; the reduction in reported numbers likely reflects disrupted healthcare access, compromised diagnosis, and broken reporting networks rather than a genuine drop in transmission.

- **ReliefWeb Index Validation:** Beyond the peak years, periods of high calculated CSI (such as 2013, 2016, 2019, and 2020) closely matched qualitative reports highlighting rainfall, stagnant water, and transmission suitability. This recurring agreement confirms that the index accurately captures the temperature-dependent, humidity-related, and rainfall-driven processes governing vector transmission in Sudan.

4. Study Limitations

- **Spatial and Temporal Data Constraints & Resolution Mismatches:** A primary limitation was the reliance on national-level malaria occurrence data, which prevented subnational or state-level comparisons against climate, flooding, displacement, WASH, and health system variables. Furthermore, critical datasets suffered from truncated timelines, where malaria data spanned only 2015-2024, HeRAMS health monitoring was restricted to late 2023-mid-2025, and JRC flood data terminated in 2021. Integrating these disparate layers across differing spatial and temporal scales, collection methods, and baseline assumptions introduced underlying uncertainties. While aggregating the data to annual scales mitigated technical resolution mismatches, it likely masked critical localized transmission variability.
- **Surveillance Gaps & Qualitative Biases:** Official malaria metrics rely heavily on laboratory-confirmed case data from the WHO Global Health Observatory, meaning they are deeply dependent on diagnostic availability, healthcare access, and reporting capacity. While the custom ReliefWeb database offered crucial geographic context, humanitarian reporting is inherently inconsistent across spatial, temporal, and thematic scales and cannot be treated as a formal surveillance system.
- **Climate Suitability Index (CSI) Uncertainties:** Utilizing a simplified CSI based on the Ross-Macdonald model introduces specific analytical uncertainties. While this framework effectively links basic climatic drivers like temperature and moisture to transmission potential, its simplified structure abstracts complex biological realities. Specifically, it assumes uniform vector-parasite interaction parameters across Sudan's diverse ecological zones and relies on macro-climatic datasets. Consequently, it misses critical microclimatic refugia, such as shaded domestic spaces, irrigation ditches, or temporary water storage, where *Anopheles* mosquitoes survive extreme conditions. Consequently, while the index successfully identifies broad temporal

trends in climatic suitability, it should be interpreted as a potential suitability indicator rather than a precise quantification of local vector density.

5. Research Insights & Future Recommendations

This research establishes the value of integrating climate suitability, surface flooding, population displacement, qualitative humanitarian reports, and health system metrics within a single framework to analyze malaria occurrence in Sudan. The evidence from 2000–2024 demonstrates that tracking malaria dynamics requires evaluating environmental signals alongside security-driven disruptions to reporting infrastructure. To advance the understanding of vector-borne disease occurrence in complex humanitarian settings, future research should focus on the following priorities:

- **Securing Subnational and Granular Datasets:** Future studies must prioritize acquiring state-level and monthly malaria occurrence data to enable fine-scale seasonal modeling. Incorporating state-level displacement figures alongside continuous health system indicators—such as facility functionality, staffing levels, medical supply availability, and service disruptions—will significantly refine systemic occurrence assessments.
- **Integrating Operational Intervention Metrics:** Models assessing disease presence and burden should incorporate localized intervention coverage data, including insecticide-treated net (ITN) distribution logs, indoor residual spraying (IRS) coverage, diagnostic testing rates, and antimalarial treatments administered.
- **Enhancing Local-Scale Framework Calibration:** Analytical workflows should be refined through closer alignment with national health authorities, local research bodies, and field stakeholders. Expanding data accessibility will enable researchers to calibrate model parameters, such as the CSI, using empirical, locally sourced entomological, ecological, and epidemiological field observations.

By prioritizing subnational data acquisition and empirically calibrated climate-disease modeling, future research can more accurately isolate the environmental and anthropogenic drivers of malaria occurrence and detect obscured shifts in transmission during complex crises.

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This policy brief is based on the master's thesis, "A multi-layer malaria occurrence analysis in Sudan: Interaction between climate, conflict and health systems", completed within the Water in Changing Environment (WICE) programme at the United Nations University Hub at Lund University (Pulluoglu, S. P., 2026).

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