

CLIMATE CHANGE AND THE RESURGENCE OF MALARIA: A REVIEW OF FUTURE ENVIRONMENTAL HEALTH RISKS

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DOI: <https://doi.org/10.5281/zenodo.18995841>

Keywords

Climate change, Malaria,
Transmission, Precipitation,
Epidemiology

Article History

Received: 05 January 2026

Accepted: 18 February 2026

Published: 13 March 2026

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Abstract

Climate change has become a global health concern in the recent time, with a great impact on the epidemiology of the diseases which are transmitted by vectors. Malaria, as a disease caused by climate sensitive Anopheles mosquitoes and parasites, Plasmodium, is in danger of becoming a major threat in areas that were once controlled or malaria-free. The dynamics of climate change and malaria transmission have a complicated intersection, which is examined in this review article in order to comprehensively examine the future environmental health risk. Using a secondary methodological approach, this assessment is based on synthesizing the existing global and regional literature comprising the empirical field data, eco-hydrological modeling, and systematic reviews to examine the exact influence of the climatic and non-climatic factors. The evidence shows that increasing temperature increases the speed of mosquito gonotrophic cycles and also reduced the extrinsic incubation period of the parasite hence maximizing the transmission potential during 25-29°C. In addition to this, changing precipitation patterns are dual-purpose, with moderate precipitation creating more breeding space and extreme incidences leading to flushing of larvae temporarily. As a result, the geographical distribution of malaria is actively displacing towards the poles and elevation, along with significantly long seasonal epidemiologic periods. More importantly, these climatic drivers are synergistically enhanced by land-use transformations, profound socioeconomic susceptibility and biological adaptations like amplified drug and insecticide resistance. The review conclusively concludes that the resurgence of malaria is an issue of critical nexus of environmental risks and biological vulnerability. In order to curb this intensifying menace, international health institutions need to start shifting swiftly towards active emergency management to proactive and climate-responsive approaches. It is paramount to incorporate artificial intelligence to create predictive early warning measures, climate-aware surveillance, advanced vaccines and resilient infrastructure to maintain world eradication efforts in a world that is fast warming.

INTRODUCTION

Malaria transmission is highly influenced by climate-sensitive mosquitoes and parasites, so changes in

temperature, rainfall and humidity will have a large impact on its spread. Evidence shows that increasing

world temperatures have already altered the geographic distribution and transmission of disease from alterations in seasons (Semenza et al., 2022). These climate-related changes are aggravated by weak healthcare systems, population growth, urbanization and socioeconomic inequalities. Collectively, these factors are raising the risk of malaria re-emerging as an important environmental and public health threat, particularly in developing nations (Megersa & Luo, 2025).

Malaria is one of the infectious diseases most evident in its relationship with climate conditions. Temperature, precipitation and humidity fluctuations directly influence the lifespan (longevity), breeding habitats availability, feeding rate and the development of parasites (Caminade et al., 2019). Recent reviews provide evidence that even modest temperature increases may shorten both mosquito and parasite development times, with altered rainfall patterns (e.g., excessive rainfall and extended drought) creating new or persistent breeding sites (Megersa & Luo, 2025). As a result, climate change is already altering the spatial distribution, seasonal timing and intensity of malaria transmission. Such changes are especially apparent in African highland areas and transition zones, which have lower acquired immunity levels among communities (Kulkarni et al., 2022; Semenza et al., 2022). Under moderate to high greenhouse gas emissions scenarios, future projections also indicate that the environmentally suitable areas for malaria vectors and parasites are likely to expand and/or shift toward higher latitudes and elevations. Such trends amplify the risk of malaria resurgence in areas where the disease had earlier declined or been successfully contained (Kulkarni et al., 2022).

But climatic factors alone cannot explain why malaria is returning. Studies from Africa and similar endemic settings show that the interplay of multiple co-existing drivers, including land use change, urbanization, insecticide and anti-malarial drug resistance through health systems fragility and low coverage of control interventions, interact with climate variables. These factors may mask or amplify the impacts of variable environmental conditions (Fouque & Reeder, 2019). Recent thorough reviews still find major knowledge gaps. The currently available evidence is sparse and geographically

patchy, with an absence of long-term, high resolution datasets linking climatic drivers to changes in malaria incidence. Low resource settings are also frequently underrepresented in research, with few climate-informed insights incorporated into disease surveillance and policymaking. Furthermore, response measures like disease-outcome based early warning systems, and climate resilient health systems have not been fully appraised (Kulkarni et al., 2022). This review is intended to fill these gaps by exploring climate change as a catalyst for the possible re-emergence of malaria as an emerging environmental health issue. The main goals are to compile and analyze existing global and regional evidence on the role of climate change in the dynamics of malaria transmission, range expansion, and seasonality. Also explore the evidence of re-emergence and re-appearance in endemic, highland, and malaria-free areas. The structure of this review begins with a description of the biological and environmental factors that link climate and malaria. It then examines the changes that have been observed and projected in the patterns of transmission and resurgence, followed by a critical assessment of the current adaptation and control strategies. Finally, it describes a framework for climate-resilient malaria control strategies in the context of global warming (Semenza et al., 2022).

Mechanism of Climate Influence on Malaria

Climate engages with both the mosquito and the *Plasmodium* parasite. Temperature, rainfall, and humidity interact to influence the mosquito population, biting rate, survival, and rate of development of the parasite, which in turn affects the basic reproduction number and seasonality (Megersa & Luo, 2025).

For most *Anopheles* and *Plasmodium* species, transmission occurs largely between 17-34°C, with maximum transmission at 25-29°C. However, above 35°C, the potential for transmission declines rapidly due to low survival rates and the inability of the parasites (Beck-Johnson et al., 2013).

The gonotrophic cycle, the time between blood-feeding and egg laying, is highly temperature dependent. As the temperature increases, the digestion rate of the blood meal and the development of eggs in the female *Anopheles*

mosquito accelerates. Consequently, the gonotrophic cycle becomes shorter, causing an increase in host-seeking and biting rates (Ukawuba & Shaman, 2022). It has been noticed that as the temperature increases, the gonotrophic cycle becomes shorter at a decreasing rate (Shapiro et al., 2017). The biting rate is a major contributor to the "force of infection" as there are increased opportunities for the mosquito to be infected with and transmit the Plasmodium parasite (Ukawuba & Shaman, 2022).

The sporogonic cycle, also referred to as the extrinsic incubation period, is the time required for the development of the Plasmodium parasite to infectious sporozoites within the mosquito. The EIP is very temperature dependent, with the rate of development increasing with higher temperatures. For instance, the EIP of *P. falciparum* can be shortened from 16 days at 21°C to less than 9 days at 34°C (Ferguson & Govella, 2023). For the mosquito to be infectious, it must survive for longer than the EIP (Christiansen-Jucht et al., 2014). Below 18°C-19°C, the sporogonic cycle is likely to be longer than the average life span of the mosquito, thus lowering the possibility of transmission (Ayanlade et al., 2022). The relationship between temperature and the rate of development for the parasite (Sporogonic Cycle) is often modeled using the degree-day concept:

$$EIP = K / (T - T_{min})$$

Where:

T = the ambient temperature.

T_{min} = threshold temperature (e.g., $\approx 16^\circ\text{C}$ for *P. falciparum*).

K = constant number of degree-days required for development.

EIP = Extrinsic Incubation Period (days)

Thermal Limits and Survival

Temperature sets the conditions for the survival of the vector as well as the viability of the parasite, which in most cases is curvilinear, peaking before sharply declining at the extremes (Ferguson & Govella, 2023). The optimal temperature for the transmission of malaria is usually between 25°C and 30°C, where both the development of the mosquito and the sporogony of the parasite are maximized; beyond this point, temperatures can become harmful to both the mosquito and the parasite, thus inhibiting transmission, shown in Fig. 01 (Li & Managi, 2022). The sporogonic stage of the parasite, for example, requires a minimum temperature of 17°C, while the adult mosquito has a short lifespan above 38°C, thus creating critical thermal limits for transmission (Khormi & Kumar, 2016).

Precipitation and breeding site

Rainfall is a strong driving force in the formation of *Anopheles* breeding sites, but its effect is nonlinear, with moderate and well distributed rainfall events being ideal for the formation and sustainability of productive habitat, while excessive and constant rainfall can lead to the destruction of the habitat through flushing and flooding (Imbahale, 2011).

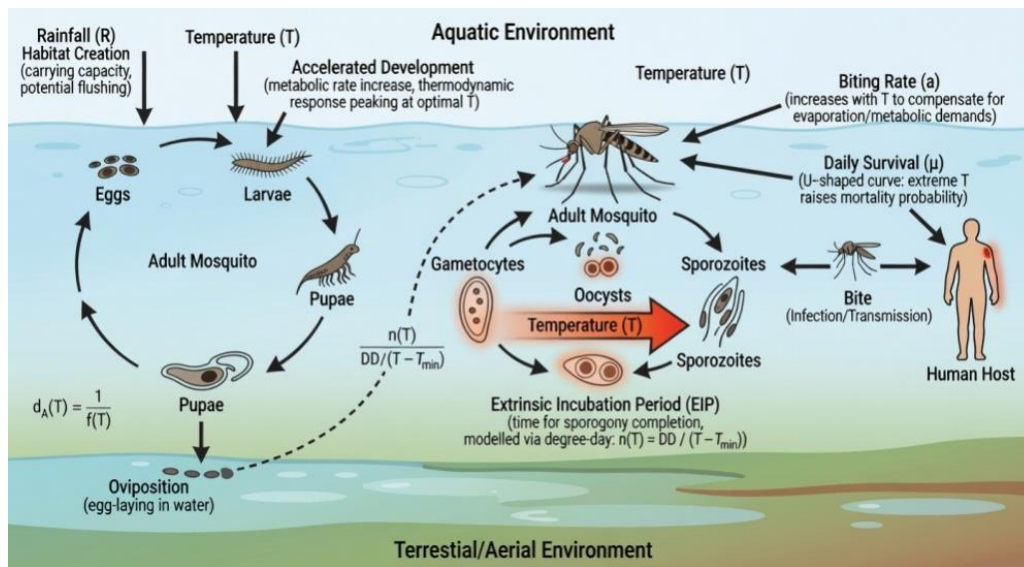


Fig. 01. Impact of ecological parameters on lifecycle of the mosquito

Creation and persistence of breeding sites

Rainfall supports aquatic habitats for the egg and larval stages, increases humidity, and is generally and positively associated with malaria, where moderate seasonal rainfall events lead to the formation of stable puddles and pools (Abiodun et al., 2016). Eco-hydrological modeling shows that rainfall, soil type, micro-topography, and vegetation are the underlying factors in the location of ponded water that persists for a sufficient period for larval development (Le et al., 2019). In areas far from permanent water bodies, the rate of transmission is strongly seasonal and follows rainfall patterns with a 1 to 2 month lag (Megersa & Luo, 2025). On the other hand, in areas near permanent water sources such as lakes or permanent rivers, low levels of transmission can be sustained throughout the year (Mala et al., 2011). In some riverine areas, the seasonality of malaria transmission is actually reversed, with the highest densities of mosquitoes recorded during the dry season when water recedes, leaving large pools of water in the riverbanks (Mbouna et al., 2019).

Heavy rainfall may wash away the breeding sites of the larvae, leading to a reduction in the number of eggs and larvae, and hence the prevalence of vectors in the short term (Megersa & Luo, 2025). Using models for the semi-arid, tropical, and sub-tropical regions, it is evident that the development of mosquitoes may be suppressed during periods of

high rainfall, which washes away the larvae, leading to a reduction in transmission in the short term (Le et al., 2019).

Drought could reduce the level of surface water, but also could create new and more productive breeding sites, especially in riverbeds, irrigation ditches, and artificial water storage. Through vegetation and soil moisture responses to high CO_2 , which could improve small and stable larval habitats even under conditions of reduced rainfall (Megersa & Luo, 2025). In coastal Kenya, high CO_2 increased habitat index and vector abundance due to increased soil moisture; additional warming decreased the lifespan of mosquitoes and parasites, but with complex effects on incidence (Le et al., 2019). Reviews of *P. vivax* in temperate biomes highlight that alterations in precipitation patterns (more extreme events and inter-event dry periods) could result in alterations in the distribution of breeding sites, which would increase transmission in some areas and decrease it in others (Alum et al., 2024).

Relative humidity (RH) is one of the key considerations in adult survival, resting, and ultimately the proportion of mosquitoes that live long enough to complete sporogony (Megersa & Luo, 2025). Laboratory and literature estimates suggest that higher humidity (above 60-70% RH) is conducive to longer mosquito life, while low humidity greatly impacts survival, even in

temperatures conducive to survival. There is an interaction between temperature and humidity, such that warm and humid conditions are conducive to increased mosquito activity, biting rates, and survival, while the probability of transmission is higher; hot and very dry conditions may result in a reduction in population despite favorable temperatures (Masse et al., 2025).

Future environmental health risk

Climate change is expected to change the distribution and seasonality of vector-borne and other climate-sensitive diseases, thus presenting new environmental health hazards. There are evidence of range shift, range extension or disruption, and large effects of extreme weather events.

Shifting Geographical Distribution

Climate change is expected to shift the risk of malaria to higher latitudes and higher elevations, especially at the margins of the present range. A very large scoping review of reviews claims that there is strong evidence that climate change will alter the global footprint of malaria, especially at the margins of the present range, because of latitudinal and altitudinal range expansion of vectors into unsuitable areas (Kulkarni et al., 2022). A global multi model, multi scenario study shows that the belt of malaria epidemic will move into temperate areas, with increased suitability at higher elevations, and that 4.7 billion more people will be at risk of malaria and dengue by 2070, especially in areas where the population is currently naïve. Empirical evidence from Africa shows that *Anopheles* have already started to migrate upslope and poleward, with a range expansion of 6.5 meters per year in elevation and 4.7 kilometers per year in latitude increase into higher latitudes from 1898 to 2016, as would be expected due to local climate warming and in association with the encroachment of malaria into new areas (Carlson et al., 2023). In temperate and highland biomes, warming is projected to extend *Anopheles* habitats into higher latitudes and altitudes, potentially threatening the re-emergence of *P. vivax* in areas that are currently considered malaria-free (Ryan et al., 2023).

Warming and related changes in rainfall distribution are projected to enhance the instability and length of

the malaria transmission seasons. A landmark African modeling study demonstrates that the length of the transmission season is as important as the expansion of the spatial area; climate projections indicate very large increases in person months of exposure due to longer transmission seasons in already malarial areas. A global inter-comparison shows that there is an increase of ~ 1.6 additional months in tropical highlands of Africa, the Eastern Mediterranean, and the Americas in malaria suitability, with larger increases in rural areas; the epidemic belt moves, and the transmission seasons extend in most areas (Colón-González et al., 2021). Continental projections for Africa forecast a shift from endemic (10-12 months) to seasonal or epidemic distributions due to climate change, with areas extending the suitability periods by months and millions of people partially vulnerable to risk by 2030-2080 (Ryan et al., 2020). In the scenario of Nepal, thermal suitability models for *Anopheles stephensi*, *Plasmodium falciparum*, and *P. vivax* project the onset of transmission in low-risk areas and the extension of the transmission season in most areas by 2030 and 2050, with some areas having shorter seasons (Bhattarai et al., 2022). High quality EIR data from sub-Saharan Africa show that temperature and rainfall seasonality are major drivers of malaria seasonality, with transmission occurring between 15-40°C and often lagging behind rainfall in highly seasonal environments, indicating that changes in seasonal patterns will directly affect transmission seasons (Yamba et al., 2023).

Extreme Weather Events

Heat waves, floods, droughts, and storms may increase or interrupt the transmission of malaria by complex processes. Based on a recent global literature review on climate and malaria, extreme weather events (floods, droughts, and strong storms) may increase or decrease the risk of malaria. Floods increase the number of breeding sites, habitat diversity, and vector population growth, leading to an increase in cases. Strong storms and heavy rainfall can decrease the number of breeding sites by destroying egg and larval habitats, thereby decreasing vector reproduction and outbreaks temporarily. Droughts may increase the range of vectors by creating new and stable breeding habitats in residual

pools and human-made water containers (Megersa & Luo, 2025). A more general assessment of infectious diseases shows that in the Colombian and Ethiopian highlands, the range of malaria has expanded to higher altitudes during warmer years, and that hurricanes, which affected vector control activities in Central America, led to the re-emergence of *P. falciparum* malaria (Semenza et al., 2022). Process-based modeling in coastal Kenya shows that, under climate change, temperature dependent reductions in the life cycles of parasites and vectors interact with soil moisture and breeding sites, such that higher temperatures and drier conditions can reduce larval habitats, while vegetation responses to CO₂ can increase soil moisture and vector abundance (Le et al., 2019).

Synergistic factors and vulnerabilities

Climate-related malaria risk escalates where environmental change, social vulnerability, and biological adaptation intersect, often turning climatically suitable areas into malaria hotspots (MacDonald & Mordecai, 2019).

Land use and land cover changes

In the Brazilian Amazon, a 10% increase in deforestation has been associated with a 3.3% increase in malaria incidence, with the greatest associations found in regions that have maintained large amounts of forest cover (MacDonald & Mordecai, 2019). More precise analyses of temporal trends suggest that even a 1% increase in deforestation could increase the number of monthly malaria cases by as much as 6% (Arisco et al., 2024). Land use change is not an isolated process but rather interacts with climatic variability, human mobility, and governance challenges. For instance, in Venezuela, the simultaneous occurrence of widespread deforestation and the collapse of socioeconomic systems has been linked to a spectacular increase in malaria cases (Fornace et al., 2021).

Socioeconomic vulnerabilities

Findings from systematic reviews suggest that socioeconomic disadvantage is a major driver of malaria transmission. Factors such as poverty, poor housing, low education, unstable livelihoods, and

weak health systems have been shown to increase the risk of infection by limiting access to preventive and therapeutic measures, as well as by increasing the risk of exposure to mosquito bites (Wafula et al., 2023). In a meta-analysis carried out in sub-Saharan Africa, people living in houses of poor construction had over double the risk of *Plasmodium* infection (OR \approx 2.1). In addition, the absence of formal education (OR \approx 1.3-1.4) and the practice of agricultural occupations (OR \approx 1.5) were significantly associated with an increased risk of infection. Lower income and lower household wealth were also associated with an increased risk (Degarege et al., 2019). Mixed-method studies also emphasize the role of wider social determinants in influencing susceptibility to malaria. Factors such as environmental degradation, risky livelihoods like swidden agriculture, irrigation agriculture, mining, and fishing, as well as migration and gendered patterns of labor, provide pathways that can exacerbate vulnerability and reduce the ability to adapt (Atusingwize et al., 2025). Large scale studies using DHS data sets have shown that children from more affluent families and those whose mothers have greater levels of educational attainment have significantly lower levels of malaria prevalence, thus emphasizing the profound structural inequalities in climate-related disease vulnerability (Anjorin et al., 2023).

Biological adaptations

Biological adaptation is also a factor in maintaining transmission. *Plasmodium falciparum* has a high rate of genetic mutation, antigenic variation, and the ability to become resistant to drugs, which allows it to adapt and survive in the presence of control efforts and changing environmental conditions (Pikor et al., 2025). On the vector side, *Anopheles* mosquitoes have shown a high degree of local adaptation to the modified environment. There is genetic selection in populations that live in contaminated urban water bodies and modified environments, especially in genes related to detoxification and other adaptive genes (Kamdem et al., 2017). Moreover, there is a high degree of over-expression of genes related to resistance in metabolism and cuticles, selective sweeps around genes related to resistance to insecticides, and possible changes in host-seeking

behavior in response to insecticide treated net (ITN) selection pressure (Kamdem et al., 2017).

Mitigation and Future Planning

Climate change is increasingly being identified as one of the most threatening factors to human health in the 21st century. Malaria is one of the most serious climate-sensitive infectious diseases that affect human populations. It is caused by five different species of *Plasmodium* parasites and is transmitted through the bite of an infected female *Anopheles* mosquito. Of these, *Plasmodium falciparum* is the most pathogenic and life-threatening form of malaria and accounts for almost 90% of all cases of the disease, especially in tropical and sub-Saharan Africa. Another form of the parasite, *Plasmodium vivax*, was once widespread in Europe, but extensive control measures following World War II, including the drainage of swamplands and the use of insecticides such as DDT, led to its eradication in many temperate regions. In the past century, economic development and advances in the prevention and control of the disease have resulted in a substantial reduction in the global distribution and endemicity of malaria, despite rising global temperatures. Although the current control efforts are directed towards the elimination of malaria, the complete eradication of the disease is not likely in many African regions under the prevailing climatic conditions. Therefore, many studies have employed climate-driven malaria models to evaluate the potential impact of future climate change on the distribution and magnitude of *P. falciparum* malaria in regional as well as global contexts shown in Fig. 02 (Caminade et al., 2019).

Mitigation of malaria and other vector-borne diseases under the impact of climate change demands the need for an integrated and adaptive control approach that combines traditional vector control methods with climate-smart public health strategies. Traditional methods of vector control such as insecticide-treated nets (ITNs), indoor residual spraying (IRS), and environmental management are still playing a crucial role in reducing the population of mosquitoes and preventing the transmission of the disease. These methods are effective in minimizing human vector contact and preventing infections when practiced consistently in the community. However, the impact of climate change variability, rising temperatures, and the development of insecticide resistance is gradually reducing the long-term efficacy of these traditional approaches, thereby demanding the need for more sustainable and climate resilient approaches. Environmental mitigation strategies such as the development of efficient drainage systems, proper waste management, and the removal of stagnant water bodies are essential in reducing the breeding sites of mosquitoes in rural as well as urban areas. Integrating environmental planning with public health strategies can greatly help in controlling the proliferation of vectors due to flooding and irregular rainfall patterns resulting from climate change. In addition, vaccination has been recognized as another complementary strategy for mitigation. The development of malaria vaccines like RTS, S/AS01 and R21/Matrix-M provides additional protection when combined with surveillance systems and vector control strategies, thus providing a multi-layered approach to the reduction of climate-sensitive malaria transmission (Fagbemi & Ubani, 2024).

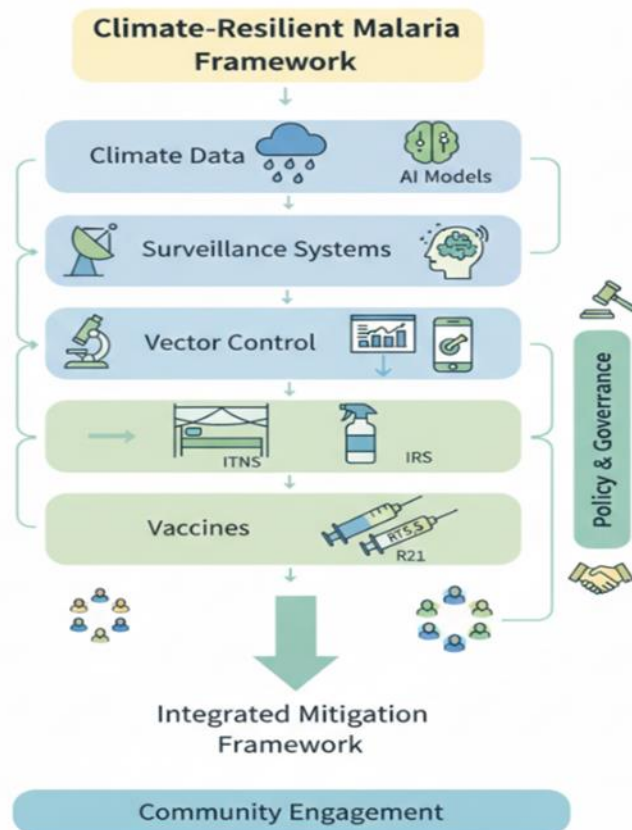


Fig. 02. Climate resilient framework and integrated management

Future strategies for implementing malaria control in the coming years are expected to focus on predictive and preventive methods rather than the traditional reactive measures. Climate informed surveillance and warning systems play a pivotal role in this regard, as they combine satellite climate information, rainfall observation, and temperature prediction to provide forecasts of possible outbreaks several months in advance. This helps health officials take preventive actions before the peak transmission rates are reached. Moreover, the convergence of artificial intelligence and machine learning technologies improves disease surveillance by enabling the simultaneous examination of climatic, environmental, and disease-related information. Predictive analysis helps forecast malaria cases several weeks before they are detected, allowing for proactive resource allocation and preparation for outbreaks, especially in developing areas (Fagbemi & Ubani, 2024).

The development of climate-resilient public health systems for malaria control is also a critical element of future malaria prevention efforts. The integration of meteorological forecasting with national health planning enables malaria control campaigns to be programmed based on seasonal climate patterns, thus increasing the effectiveness of interventions and minimizing economic losses. Online tools and decentralized data management systems also facilitate quick decision-making and localized response actions to emerging health threats. The development of climate-resilient health infrastructure is also important and includes the development of highly trained epidemiologists and vector control experts, enhanced laboratory and surveillance infrastructure, the use of mobile and cloud-based reporting systems, and the promotion of intersectoral collaboration between health, environmental, and meteorological sectors. These efforts increase the capacity of health systems to predict the expansion of malaria into new

geographic regions affected by climate change (Fagbemi & Ubani, 2024).

Long-term malaria control also requires effective policy and governance structures that align health priorities with national climate adaptation planning. Global partnerships, financial sustainability, and equal access to technological resources are also required to enable adaptive malaria control programs, especially in low- and middle-income countries that are still highly susceptible to climate-related health risks. Furthermore, community-based adaptation strategies also have an important role to play in ensuring the sustainability of efforts. Community engagement in monitoring breeding sites for mosquitoes, sharing early warning messages, and practicing preventive practices increases intervention coverage and helps to build long-term resilience against malaria transmission in a changing climate (Fagbemi & Ubani, 2024).

Key outcomes on the malarial studies

The effect of rainfall is two-fold, breeding habitats are formed by it. On the other hand, heavy or prolonged rain may cleanse larvae and lower productivity. The study in Kenya demonstrated that during rainy nights, 17.5 and 4.8% of first and fourth instar larvae respectively of the *A. gambiae* were lost through the process of flushing, mortality and ejection through pools (Paaijmans et al., 2007). Field and modelling experiments have shown that **within season rainfall pattern** i.e. timing and spacing of storms, and more significantly **time integrated surface area of pools** lasting longer than 7 days explains up to 82% of the variance in abundance of stimulated mosquito better than rainfall totals alone (Bomblies, 2012). In western Kenya and Ghana, the density of larvae of *Anopheles* is higher on rainy initial seasons, but the density of the larvae in the area rise or fall with weekly rainfall intensity according to the site, rainfall may carry out the larvae, and slight rainfall may maintain the habitats of the productive stage (Hinne et al., 2021). The incidence of malaria in Central Senegal was over 27 fold more in hamlets within a distance of 500m of operating rain-fed ponds compared to the settlements that were more than 1Km away of the breeding sites (Ndiaye et al., 2025). *Anopheles* mosquito are selective in their urban Zanzibar larval

surveys, favoring semi-permanent, concrete locations with high dissolved oxygen, and will also inhabit natural locations after heavy rainfall, however they still cannot adapt to highly polluted urban environments informing the design of targeted larviciding strategies (Hill et al., 2025). Most productive habitats in Ghana and western Kenya **are mostly man-made** (dug-out wells, irrigated furrows, reservoirs) and located in sunlit areas, grassy locations, temporary and permanent sites play a major role in the production of *Anopheles* (Hinne et al., 2021).

Massive reviews and models affirms that variations in the totals of rainfall, seasonality, and extremes modify breeding site availability and, malaria morbidity whose impacts are largely context-specific in Africa (Megersa & Luo, 2025). A model of continental hydrology on Africa shows that using realistic surface water processes (water routing on river networks) diminishes the measured area where transmissions can be stable and shows the river corridors as central tear rounding foci, showing spatial changes with climate change restructure the hydrological and ecological landscapes (Smith et al., 2020). Analysis of African climate and malaria over a long period (1981-2015) demonstrates that there are overall positive correlations between rainfall and malaria, with some areas exhibiting negative correlations in 1981-2015 which is due to flushing and other nonlinear processes (Mafwele & Lee, 2022).

In the case of *A. arabiensis* in South Africa, a temperature rainfall interaction model recreates the seasonality and suggests that the immature and adult population are regulated jointly by water availability and temperature, thus affecting the risk indications of malarial occurrence (Abiodun et al., 2016). In Ethiopia, invading urban vector *A. stephensi* can be less susceptible to seasonal rainfall changes in the dry season, 77% of larvae are produced at 23% of locations, most of which are large water cisterns, with high effects of targeting these so called super-productive habitats at 60 or above coverage (Yared et al., 2025).

Overall implication

In any given environment, the vulnerability to malaria is not only caused by the amount of rainfall

but also by the spatial and temporal sustainability of the breeding habitats, the nearness of these habitats to human settlements and the way the land use and climate change restructure the hydrological and ecological landscapes (Megersa & Luo, 2025).

This table combines empirical studies with model results to demonstrate that rainfall not only results in larval loss due to flushing effects but also provides

for population maintenance by creating habitats that provide for larval development (Paaijmans et al., 2007; Dieng et al., 2012; Ratti et al., 2022) Spatial proximity to breeding habitats has been shown to be a major predictive factor in malaria risk, with most cases occurring within 500 m of the water body (Benedum et al., 2018; Shililu et al., 2007).

Table 01: Summary of major key findings

Theme	Key Quantitative Findings	Reference
Flushing system brought about by rainfall	In rainy nights there was an increase in larval loss (17.5 and 4.8% on L1 and L4 respectively) as compared to dry nights.	(Paaijmans et al., 2007) (Dieng et al., 2012; Ratti et al., 2022; Benedum et al., 2018)
Persistence of larval Pools	The pools that have a longer life than seven days contribute 82% of the variance in the larval abundance that is stimulated.	(Bomblies, 2012) (Ratti et al., 2022; Shililu et al., 2007)
Necessity of breeding areas to water bodies	82.4% of cases are located within 500 m of ponds but none out of 1,000m	(Ndiaye et al., 2025) (Shililu et al., 2007; Benedum et al., 2018)
The Larval Abundance on the base of seasons	The prevalence of <i>Anopheles</i> larvae during the rainy season was 70.8% whilst in the dry season, it was 29.2%.	(Hinne et al., 2021). (Benedum et al., 2018) (Paaijmans et al., 2007)
Highly productive habitats	Cisterns had recovered 77% of the <i>Anopheles stephensi</i> larvae, but cisterns comprised a quarter of the survey sites	(Yared et al., 2025) (Benedum et al., 2018) (Paaijmans et al., 2007)

Future Perspectives and Mitigation

The control of malaria needs future strategies to move from response approaches to initiative strategies, which apply climate adaptive procedures. The application of machine learning and artificial intelligence technology allows scientists to analyze simultaneously the climatic environmental and epidemiological variables. These technologies can predict the transmission peaks and locate future "hotspots" weeks before the clinical detection. The national health planning needs satellite-derived meteorological data that includes rainfall monitoring and soil moisture values for appropriate timing of seasonal health interventions. The application of highly effective vaccines, such as RTS,S/AS01 and R21/Matrix-M, should be incorporated as a multi-layered strategy together with the conventional vector control. Future environmental mitigation needs to

apply spatial modeling for the management of aquatic environments, which should focus on the complex interactions of CO2 and soil moisture and the "flushing effects" of heavy rainfall. The national climate adaptation strategies need effective policy frameworks that promote collaborative actions among the health environmental and meteorological communities. The local communities in the sustainability actions need to be actively involved through breeding site monitoring and early warning information dissemination.

Conclusion

The rising number of malaria cases presents a critical area where environmental health risks intersect with biological adaptation mechanisms. The world's malaria prevalence rate saw a substantial decline between 2000 and 2015 due to increased use of

ITNs and IRS. The current study has attained the maximum level of output capacity, which poses a challenge to the healthcare system that faces rising resistance to drugs and pesticides. The 2023 IPCC report indicates a permanent rise in temperature by 1.1°C, which alters the dynamics of disease transmission. Non-linear thermal performance curves act as the driving force that influences vector biological rhythms and the Plasmodium sporogonic cycle. The extrinsic incubation period (EIP) shortens as temperatures approach the 25-29°C threshold, leading to an increased disease transmission force. The scientific evidence indicates that climate change leads to the geographical expansion of the disease's distribution, increasing the disease's range at altitudinal and latitudinal rates of 6.5 meters and 4.7 kilometers per year, respectively. Malaria is the most climate-sensitive infectious disease because it requires pandemic management approaches that take into account environmental changes rather than permanent management approaches.

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